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A Circular Land Use Model for Reconciling Industrial Expansion with Agricultural Heritage in Italian Industrial Parks

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Abstract

Industrial park (IP) expansions in Mediterranean peri-urban areas can generate conflicts between economic development and agricultural heritage preservation. This paper develops a theoretically derived circular land use symbiosis model based on Hubs for Circularity (H4C) principles, using Fosso Imperatore IP in southern Italy as an illustrative case. This model proposes a transferable three-zone gradient design that enables the transformation of industrial–agricultural boundaries when combined with appropriate governance mechanisms and stakeholder engagement. Zone A concentrates vertical industrial development with rooftop agriculture; Zone B creates mixed agro-industrial interfaces; and Zone C enhances agricultural productivity through industrial resources. The model's components (gradient zonation, temperature–cascade matching, and bidirectional resource flows) constitute generalizable design principles. When applied to Fosso Imperatore, where farmers oppose expansion that threatens culturally significant San Marzano tomato production, the model shows how 547 tons of organic waste could generate 87,520 m^3 of methane, while industrial waste heat cascades from 150–200 °C to 25–40 °C of greenhouse heating across distances of 3 km. Implementation constraints include regulatory gaps and limited empirical data. This study operationalizes H4C through spatial design, showing how benefit-sharing mechanisms can transform stakeholder conflicts into collaboration. The model provides a replicable framework for Mediterranean contexts where industrial expansion encounters agricultural heritage.

Keywords: circular economy; industrial park; industrial symbiosis; land use planning; agro-industrial integration; stakeholder conflict

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1. Introduction

Industrial parks (IPs) have emerged as fundamental drivers of economic development across Europe, concentrating manufacturing activities within designated areas to maximize infrastructure efficiency and foster industrial agglomeration [1,2]. These planned industrial zones generate employment and economic output while offering opportunities for resource optimization through geographical proximity and shared services. However, their expansion increasingly generates tensions with agricultural communities and environmental advocates, particularly in regions where productive farmland faces conversion pressures [3]. This development–preservation tension exemplifies the broader challenge of reconciling economic growth with environmental sustainability in finite territorial contexts.

The Fosso Imperatore IP in Southern Italy exemplifies these tensions through its contested expansion into high-value agricultural territory. The Fosso Imperatore IP's proposed expansion into San Marzano tomato fields faces opposition from citizens concerned about agricultural heritage loss. In this context, "agricultural heritage" refers to the historical continuity and cultural value of agricultural territories, not to traditional or pre-modern farming methods. With three food-processing firms generating organic waste annually, this case exemplifies how Hubs for Circularity (H4C) principles might transform such territorial conflicts into collaborative opportunities [4].

While this conflict appears intractable through conventional planning approaches, emerging circular economy (CE) frameworks suggest alternative pathways. Traditional planning approaches frame industrial–agricultural relationships as inherently conflictual, requiring buffer zones and strict separation [5]. The CE paradigm provides overarching principles for regenerative resource use, while industrial symbiosis (IS) operationalizes these through inter-firm exchanges within industrial boundaries [6,7]. The recently introduced H4C concept improves IS frameworks through the integration of industrial clusters with surrounding urban and rural areas, creating regional ecosystems where energy, materials, and services flow across sectoral boundaries [8,9]. As a key element of the EU's Processes4Planet Strategic Research Agenda under Horizon Europe, H4C represents a paradigm shift from isolated industrial optimization to territorial integration [8]. H4C frameworks emphasize stakeholder collaboration [10]; however, practical spatial models for implementing H4C in contested agricultural territories remain undeveloped. These three frameworks represent an evolution in sustainability thinking from bilateral firm exchanges (IS) to industrial districts (EIP) to territorial systems (H4C), each expanding the spatial and sectoral boundaries of resource optimization.

While H4C represents an important theoretical advancement, examining its implementation alongside IS and EIP approaches highlights limitations for contexts such as Fosso Imperatore. IS research highlights the technical feasibility of resource exchanges [11,12] but operates at a firm-to-firm level and is unable to address territorial conflicts. IS finds its full application in eco-industrial parks (EIPs), which are specifically designed to facilitate the exchange of waste between firms as input [13,14]. However, it maintains rigid industrial boundaries that exclude agricultural areas, which is problematic when expansion threatens farmland. Even H4C, despite advocating urban–rural integration [8], provides only optimization models [9] and stakeholder frameworks [10] without spatial implementation strategies. Regarding conflict resolution, none of the above addresses stakeholder opposition: IS assumes cooperation between willing partners, EIP attracts voluntary participants to specifically designated zones, and H4C acknowledges conflicting objectives [9] without transformation mechanisms. Most critically for spatial design, IS treats space as a proximity distance, EIP creates fixed industrial perimeters, and H4C optimizes flows without physical reconfiguration. Indeed, while the scope expands from bilateral to regional scales, all three approaches maintain identical limitations—an inability to change contested agricultural boundaries through gradient-based spatial design.

This article addresses this gap through the development of a spatial implementation model for H4C that converts IP expansion into an opportunity for territorial circularity. This research builds on the H4C principles of cross-sectoral integration (see [8]) and recent methodological advances for data-scarce territories [4]. This research investigates three specific questions: (1) How can gradient-based spatial zonation operationalize H4C principles in agricultural territories facing industrial expansion? (2) What governance mechanisms transform the stakeholder conflicts identified in the H4C literature into collaborative development? (3) How can spatial design principles ensure that industrial growth enhances rather than displaces agricultural systems within an H4C framework?

A gradient-based spatial model is hypothesized, incorporating vertical development in industrial zones and mixed-use transitional areas. This model can create synergies between industrial and agricultural activities. Specifically, this study proposes that: (a) cascading heat utilization across temperature-matched zones can provide economically viable heating for agricultural operations while valorizing industrial waste heat; (b) organic waste flows identified in the park represent an important resource for integrated biogas systems serving both sectors; and (c) stakeholder conflicts can be changed when spatial design embeds mutual benefits rather than mere mitigation measures.

This research makes three primary contributions to H4C implementation science. First, it advances the H4C literature through the proposal of the first spatial planning model that operationalizes hub development in contested agricultural territories, connecting H4C conceptual frameworks [8] with territorial implementation. Second, it develops a gradient-based zonation framework that spatially embeds the resource flows analyzed in optimization studies [9] while addressing stakeholder dynamics [10]. Third, it provides a potentially replicable blueprint for Mediterranean regions where H4C implementation must reconcile industrial development with agricultural heritage preservation, demonstrating how spatial design can reconcile territorial conflicts into circular synergies.

The article structure follows a logical progression. Section 2 establishes the theoretical framework. Section 3 presents the methodology. Section 4 presents the H4C spatial implementation model and pathways. Section 5 discusses implications and limitations. Section 6 concludes.

2. Theoretical Framework

This research employs three theoretical lenses to analyze the shift of industrial–agricultural conflicts into collaborative opportunities through spatial design. These theories were selected because they collectively address the territorial scope (H4C), spatial configuration (gradient design), and social dynamics (conflict transformation) necessary for reconceptualizing industrial expansion. H4C theory provides the overarching framework for cross-sectoral integration on a territorial scale. Spatial design principles derived from the circular landscape literature provide the conceptual basis for gradient-based territorial integration. Stakeholder conflict transformation theory guides the analysis of how physical design can convert opposition into collaboration.

H4C represents the evolution from IS and EIPs toward territorial integration [8,9]. Unlike IS, which operates at a firm-to-firm level [6], or EIPs, which maintain rigid industrial boundaries [14], H4C explicitly theorizes resource flows across industrial, urban, and rural domains. Three H4C principles structure this analysis: bidirectional resource flows between sectors, spatial configuration as a determinant of exchange feasibility, and governance mechanisms embedded into physical design rather than imposed through external regulation.

The Fosso Imperatore case exemplifies conditions that require H4C rather than IS or EIP approaches. The contested expansion into agricultural territory cannot be addressed through inter-firm exchanges alone (a limitation of IS), nor through optimization within park boundaries (a limitation of EIPs). H4C principles position this expansion as an opportunity for bidirectional flows: agricultural organic waste is converted into industrial energy, industrial waste heat supports agricultural processes, and treated water serves both sectors [9].

Spatial design principles derived from circular landscape theory [15] challenge binary land use segregation through transitional zones that provide the conceptual basis for the three-zone gradient framework. Research on circular hubs identifies 3 km as the optimal radius for resource exchange, achieving 94.6% of the maximum CO_2 reduction potential [16].

This distance parameter directly informs the three-zone configuration proposed for Fosso Imperatore. Temperature–distance relationships prove critical for industrial–agricultural integration, with waste heat at 150–200 °C after recovery [17] being suitable for agricultural applications when matched to distance-dependent temperature decay.

The example of the Yuhang transition from opposition to collaboration [18] provides a precedent for converting stakeholder resistance into partnership through transparent benefit-sharing and participatory processes. This case informs the governance approach, although without employing game theory methods. The quintuple helix model [19] positions the environment as the nucleus rather than at the periphery, implying that industrial expansion can be reframed as an opportunity for territorial enhancement rather than a threat. This reframing principle operates through spatial strategies: vertical development to minimize land consumption, shared infrastructure to create mutual dependencies, and agricultural intensification through industrial resources.

The integration of these three theoretical dimensions provides the framework for a proposal to reconceptualize industrial expansion. While incorporating the necessary mitigation of land consumption, this model primarily focuses on spatial configurations that create positive interdependencies, transforming potential losses into mutual gains where possible. Physical design creates the foundational conditions for governance by establishing resource interdependencies, which are then managed through complementary institutional mechanisms.

3. Methodology

3.1. Research Design and Approach

This research develops a theoretically derived model following Jabareen's framework [20], where theoretical principles (H4C, gradient-based spatial design, and stakeholder transformation theory) are synthesized into transferable design components. While Fosso Imperatore serves as the illustrative case, the model itself consists of generalizable elements. The three-zone gradient principle is applicable to any industrial–agricultural interface, temperature–distance matching frameworks are transferable across contexts, and stakeholder transformation pathways are adaptable to different governance settings. The use of a single case study to illustrate the model is an established practice in the planning literature, where theoretical models are often demonstrated through specific territorial applications while maintaining transferability.

To develop this theoretical model, the research design follows three interconnected phases: theoretical grounding in H4C principles, contextual case analysis, and conceptual model development. This structure aligns with established approaches for theory building in sustainability transitions, where complex socio-technical systems require the integration of multiple knowledge domains. The conceptual framework methodology proves appropriate for developing spatial models in data-constrained contexts, where the objective is theoretical advancement rather than empirical validation [20].

The case analysis relies on documentary sources and limited primary data. While a comprehensive empirical analysis through stakeholder interviews, surveys, or detailed material flow assessments was beyond the scope of this conceptual study, the available data provide sufficient context for model development.

3.2. Case Study Context: The Fosso Imperatore Industrial Park

The Fosso Imperatore IP was selected due to the active conflict between industrial expansion plans and agricultural preservation interests. This conflict-centered selection aligns with the research objective of exploring how H4C principles might change territorial opposition through spatial design [9,10]. Following Yin's case study methodology [21], Fosso Imperatore serves as a revelatory case for examining H4C implementation in contested territories.

Located in Nocera Inferiore, Campania (40°46′47″ N, 14°37′04″ E), the park occupies a strategic position within the Agro Nocerino Sarnese plain in southern Italy (Figure 1). Situated between Naples and Salerno, the site benefits from direct access to the A30 Caserta–Salerno highway and lies near the Port of Salerno. The surrounding territory features volcanic soils enriched by millennia of Vesuvian deposits, creating one of Italy's most fertile agricultural zones.

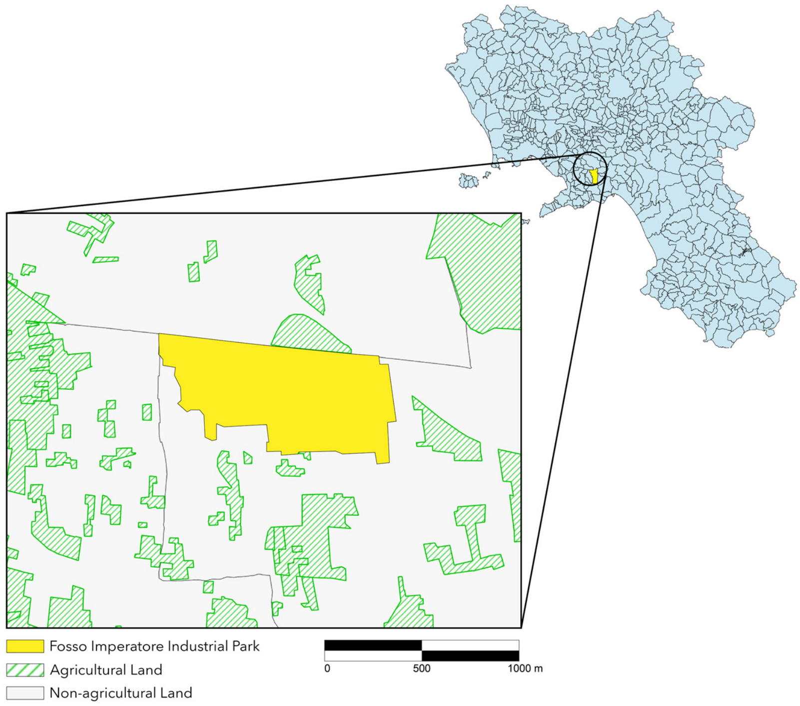

Figure 1. Location of the Fosso Imperatore IP within the Agro Nocerino Sarnese territory, Campania, southern Italy. The regional map (**right**) shows the park's position within Campania (yellow marker). The detailed view (**left**) illustrates the IP boundaries (yellow) surrounded by fragmented agricultural land (green hatched areas) and non-agricultural land (white), representing various built and developed uses. The map demonstrates the peri-urban context where the proposed expansion would directly convert adjacent agricultural parcels, although the exact expansion boundaries are not depicted, as detailed plans were not publicly available. Source: Authors.

The IP currently spans 144,846 m^2 and hosts 25 active companies across diverse manufacturing sectors. The proposed expansion of 220,000 m^2 would more than double the park's footprint. This expansion faces significant opposition from agricultural stakeholders, with the "Rete NO PIP" movement collecting 552 signatures and demanding project reconsideration. This opposition concerns direct land conversion rather than technological resistance, as the area's San Marzano DOP (Protected Designation of Origin) production system already employs modern cultivation methods, including greenhouses and advanced irrigation. Indeed, it should be noted that the DOP certification requires geographic origin and variety specifications, not organic or traditional farming practices. The municipality of Nocera Inferiore supports the expansion as being essential for regional economic development, while agricultural stakeholders view land loss as an existential threat to their production system.

The park's industrial composition creates favorable conditions for H4C implementation. Three food-processing companies operate within the current boundaries, establishing natural bridges between the industrial and agricultural sectors. Through interviews with representatives from these agro-food companies, annual organic waste generation within the park was identified as 547 tons, representing significant biogas potential. Additionally, several other outside companies have formally requested expansion space, indicating substantial development pressure that requires innovative spatial solutions.

The Fosso Imperatore context embodies the territorial tensions characteristic of Mediterranean industrial development. The site occupies peri-urban land where agricultural heritage meets industrial development pressures. This positioning, combined with the presence of the Sarno River and proximity to protected agricultural zones, creates both constraints and opportunities for circular resource flows. Therefore, this case provides an ideal setting for developing H4C implementation models that convert territorial conflicts into collaborative synergies.

3.3. Model Development Process and Data Analysis

The three-zone gradient model emerged through an iterative conceptual development process, integrating multiple data sources and theoretical frameworks. Primary data included publicly available information about the proposed expansion (although detailed spatial boundaries were not accessible), interviews with the companies within the park, and stakeholder consultation records. Secondary sources included the technical literature on IS and waste utilization. Table 1 presents the key data and parameters utilized in model development.

Table 1. Data sources and technical parameters for model development.

Category	Parameter/Source	Value/Information	Application in Model
Site Data	IP current size	144,846 m^2	Baseline condition
	Proposed expansion	220,000 m^2	Land requirement to address
	Active companies	25 (including 3 food processors)	Potential exchange partners
	Stakeholder opposition	552 signatures	Governance challenge
Resource Flows	Organic waste generation	547 tons/year	Biogas system input
	Waste heat temperature	150–200 °C after recovery [17]	Heat cascade starting point
	Biogas conversion rate	200 L CH_4/kg volatile solids [4]	Conversion factor
	Methane production	87,520 m^3/year (calculated)	Biogas output volume
	Energy equivalent	875,200 kWh/year	Electrical generation potential
Spatial Parameters	Optimal exchange radius	3 km [16]	Maximum zone extent
	Temperature decay	Exponential function [22]	Heat loss over distance
Data Limitations	GIS mapping	Not available	Limits spatial precision
	Material flow analysis	Only 3 food processors surveyed	Full park flows unknown

The conceptual development commenced with initial data mapping, identifying spatial constraints, existing resource flows, and stakeholder positions. Concept identification extracted key principles from the H4C literature, including industrial–urban–rural integration [9], gradient-based spatial transitions [15], and the bidirectional resource flows characteristic of advanced circular systems. Integration and synthesis combined these concepts with site-specific conditions to generate the three-zone spatial configuration.

This research acknowledges specific data limitations. While organic waste figures represent actual communication from park companies, they encompass only existing operations within park boundaries, not the broader territorial potential. The absence of detailed GIS (geographic information system) mapping and comprehensive material flow analyses for the surrounding area constrains spatial precision. However, these limitations align with the conceptual modeling approach, where the objective is to demonstrate H4C design principles applicable to similar contexts rather than to provide engineering specifications for immediate implementation.

4. The Proposed Circular Land Use Symbiosis Model

4.1. Spatial Configuration and Technical Parameters

The circular land use symbiosis model reconceptualizes IP expansion through a three-zone gradient design that changes the industrial–agricultural boundary from a line of conflict into a space of collaboration. This spatial configuration, as illustrated in Figure 2, challenges conventional zoning approaches by creating transitional zones that facilitate resource exchange while maintaining functional integrity for both industrial and agricultural activities.

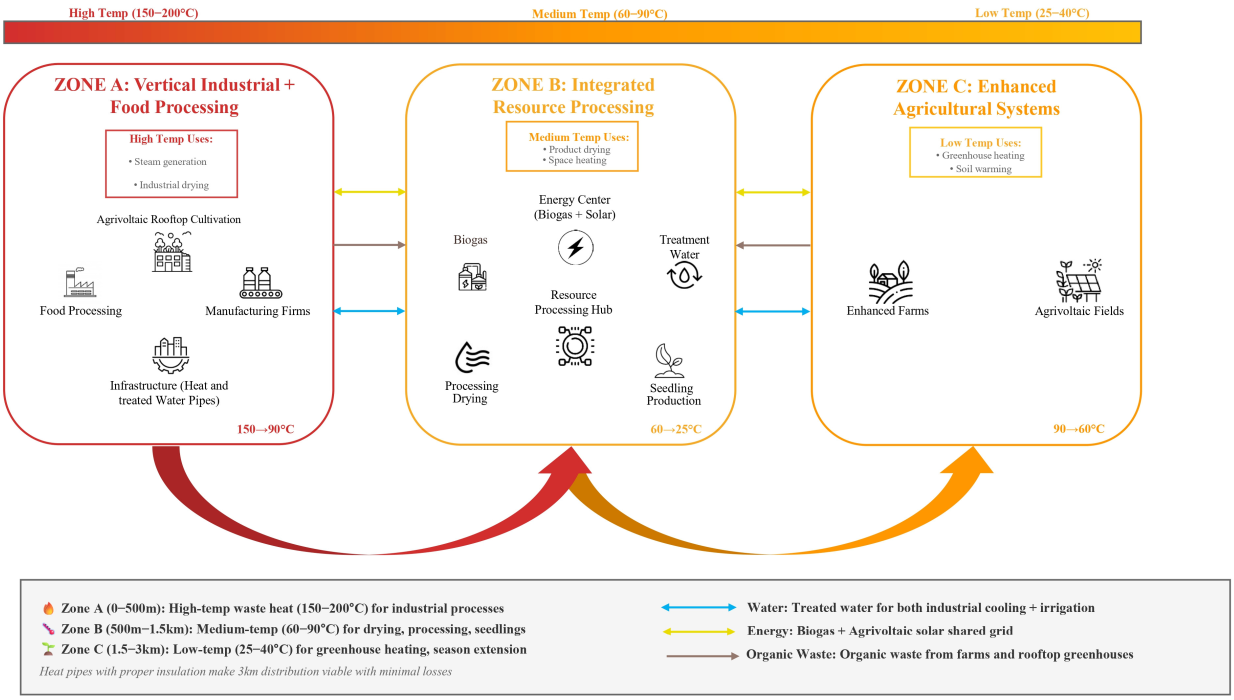

Figure 2. The circular land use symbiosis model transforms the industrial–agricultural boundary into a collaborative three-zone gradient for the Fosso Imperatore IP expansion. The model quantifies temperature cascades from high-temperature industrial processes (150–200 °C) to low-temperature agricultural applications (25–40 °C), with the biogas facility in Zone B processing tons/year of organic waste. Bidirectional resource flows include treated water for irrigation and cooling, biogas energy distribution, and organic waste collection from both industrial and agricultural sources. Optional agrivoltaic installations are shown for illustration; their adoption is voluntary. Source: Authors.

The spatial framework consists of three interconnected zones. Zone A, the vertical industrial core, accommodates high-intensity manufacturing through multi-story buildings that maximize production while minimizing land consumption. Industrial analysis indicates that metalworking and aerospace companies within the current park boundaries generate waste heat at temperatures between 150–200 °C after primary recovery systems [17]. These temperature levels are derived from combustion processes in furnaces and industrial boilers, with exhaust gases typically reaching 260 °C before heat recovery and 150–200 °C after economizer installation [17].

Zone B, the mixed agro–industrial interface, represents the model's innovative heart, where industrial and agricultural activities physically intersect through shared infrastructure. This zone alternates between built and cultivated areas at 50 m intervals, ensuring continuous integration rather than segregation. The biogas facility, strategically positioned in this zone, processes an identified amount of organic waste from the three food-processing companies. Using coefficients for Mediterranean mixed-food processing waste of 200 L CH_4/kg for volatile solids [4], and assuming an 80% volatile solid content, calculations indicate an annual methane production of 87,520 m^3. This translates to 875,200 kWh/year or approximately 110 kW of installed electrical capacity, which is sufficient to power the equivalent of 250 households.

Zone C, the enhanced agricultural buffer extending 1.5–3 km from the industrial core, intensifies agricultural production through industrial resources. Enhancement options include waste heat for greenhouses and treated water for irrigation, with renewable energy infrastructure, such as agrivoltaics, only present where voluntarily adopted by farmers based on economic benefit, not as mandatory requirements. Temperature decay calculations demonstrate the feasibility of heat cascading across this distance. Using the exponential decay Function (1) from Swarts et al. [22]:

$$T_s^* = (T_s - T_{soil})e^{-\beta L} + T_s \tag{1}$$

where the initial supply temperature T_s = 150 °C (typical for metalworking processes after primary recovery), the soil temperature T_{soil} = 10 °C, the pipe length L = 2000 m, and the heat loss coefficient β = 0.0001 m^{-1} for standard pre-insulated pipes (based on industry specifications). The delivered temperature at the periphery of Zone C equals 124.7 °C. This temperature remains suitable for agricultural drying processes and, after further cascading to 25–40 °C, provides optimal conditions for greenhouse heating throughout the 12-month growing season characteristic of Mediterranean climates.

4.2. Resource Flows and Industrial Integration

The model's operational logic centers on resource flows between zones, creating interdependencies and fostering collaborative opportunities through mutual resource dependencies. These flows follow different patterns based on resource characteristics: energy and water flow bidirectionally (Zone A sends wastewater to Zone B for treatment and receives treated water back; Zone B distributes biogas energy while receiving organic inputs). Heat cascades unidirectionally from Zone A to Zones B and C following temperature gradients. Organic matter converges from both Zones A and C to Zone B's biogas facility for centralized processing. These flows represent the typologies of possible interactions rather than fixed prescriptions, with specific pathways determined by local industrial compositions and agricultural systems. Resources are voluntarily adopted initially, but once infrastructure investments are made (the biogas facility and heat distribution networks), participating stakeholders become interdependent through sunk costs and operational reliance. Such an evolution, from voluntary participation to mutual dependence, creates the lock-in effects that sustain collaboration.

In the Fosso Imperatore application, many flows can be identified. Metalworking companies (40% of the current occupants) generate high-temperature waste heat (150–200 °C) that is suitable for Zone B processing and Zone C greenhouse heating. Food-processing firms (12% of companies) exemplify bidirectional exchange, sending organic waste to Zone B's biogas facility while receiving medium-temperature heat (60–90 °C) for pasteurization. Zone C's agricultural operations provide biomass to Zone B while receiving treated water and nutrients in return.

Water represents another flow typology. Industrial cooling processes require approximately 50,000 m^3 annually, based on interviews with company representatives. After treatment through constructed wetlands positioned in Zone B, this water meets irrigation quality standards for non-food crops, reducing the agricultural water demand by 15% during the peak summer months, which is critical when regional Water Exploitation Indices indicate stress [23].

Material flows extend beyond organic waste to include mineral by-products. Industrial by-products (aluminum shavings and mineral residues) can undergo processing for agricultural applications, such as pH adjustment, UV protection, and micronutrients. These examples illustrate the model's principle: every output represents a potential input elsewhere, with specific matches determined through local analysis rather than predetermined pathways.

4.3. Stakeholder Engagement Framework

The transformation from conflict to collaboration requires structured stakeholder engagement beyond simple consultation. Drawing from the quintuple helix model [19], the implementation framework establishes specific mechanisms for each stakeholder category.

For industrial stakeholders, the model proposes a formalized IS consortium, with rotating leadership between sectors. This consortium meets monthly to identify resource exchange opportunities, with participation incentivized through reduced waste management fees proportional to internal exchange volumes. The three food-processing companies serve as anchor participants, given their dual role as waste producers and heat consumers.

Agricultural stakeholders engage through structured dialogue mechanisms that bring together farmers from the surrounding territory. Given the area's existing greenhouse infrastructure and modern irrigation systems, these stakeholders possess both economic weight and technical capacity to participate effectively in resource exchange negotiations.

However, municipal authorities face significant regulatory gaps. Unlike regions such as Emilia-Romagna, Tuscany, and Marche, which have established APEA (Aree Produttive Ecologicamente Attrezzate) frameworks, Campania currently lacks specific regulations for ecologically equipped productive areas. Structured territorial management approaches, such as Territory Balanced Scorecard methodologies that integrate multiple stakeholder perspectives through systematic performance measurement [24], could provide frameworks for navigating these regulatory voids. This regulatory void prevents formal APEA designation and creates uncertainty for CE initiatives. The model must therefore operate within general environmental and planning regulations, lacking the streamlined procedures and incentives available in regions with dedicated APEA legislation.

Civil society engagement occurs through quarterly public forums and a permanent Citizens' Observatory with real-time access to environmental monitoring data. The conversion of the "Rete NO PIP" opposition movement into constructive participation requires transparent benefit-sharing mechanisms, such as channeling 2% of the resource exchange revenues into a community development fund, with spending priorities determined through participatory budgeting involving the original petition signatories.

4.4. Implementation Pathway and Regulatory Adaptation

Implementation proceeds through three phases that integrate technical demonstrations with systematic stakeholder engagement, converting opposition into collaboration.

In Phase 1 (Trust Building and Demonstration, months 1–12), initial implementation prioritizes visible success rather than comprehensive development. A pilot heat exchange program between a metalworking company and an adjacent greenhouse provides proof of mutual benefits. This demonstration serves dual purposes: validating technical feasibility while creating a reference site for stakeholder visits. Drawing from successful conflict transformation experiences [18], organized visits for agricultural stakeholders to witness operational benefits directly address fears and misconceptions.

Concurrently, a dedicated H4C Coordination Office emerges from existing municipal structures, comprising technical, environmental, agricultural, and community liaison working groups. This office conducts systematic consultations across affected agricultural areas, documenting specific concerns about water quality, land values, and operational safety. The "Rete NO PIP" movement transitions from external opposition to an internal advisory role, with representatives participating in technology selection and monitoring protocol development.

Regulatory mapping identifies barriers within waste classification frameworks. The European Waste Framework Directive's end-of-waste criteria provide the foundation, but Italian implementation through Legislative Decree 152/2006 allows companies to self-declare materials as by-products if they meet specific criteria, avoiding waste classification entirely. However, the regulatory framework remains confusing and incomplete, creating uncertainty for IS initiatives. The model proposes simplified pathways for intra-park exchanges, with food-processing waste that meets quality criteria receiving streamlined authorization for biogas use.

Phase 2 (Co-creation and Scaling, months 13–24) expands stakeholder participation from consultation to co-creation. Agricultural representatives participate directly in selecting biogas technology providers and heat distribution contractors, ensuring compatibility with local practices. The community evaluation of contractors prioritizes firms demonstrating environmental excellence and a willingness to employ local workers.

A formal benefit-sharing mechanism emerges through negotiated agreements. Based on the avoided disposal costs and resource values, participating companies contribute to a Territorial Enhancement Fund. With the identified tons of organic waste generating an annual value of approximately EUR 200,000 through disposal prevention and energy generation, these funds support agricultural infrastructure improvements, irrigation modernization, and transition assistance for affected operations.

Regulatory adaptation accelerates through demonstrated compliance. The distinction between waste and by-product classification becomes operational through documented resource contracts between park companies, meeting Italian legal criteria for materials produced as integral process outputs with certain further use.

In Phase 3 (Institutionalization and Continuous Improvement, months 25–36), full system integration occurs alongside governance maturation. The Citizens' Observatory, which evolved from the opposition movement, maintains continuous monitoring rights with guaranteed access to environmental data and operational parameters. Following successful precedents, authorities commit to immediate operational cessation upon verified violations, changing traditional oversight into an active partnership.

The governance structure transitions from project coordination to permanent institutional arrangements. The H4C Coordination Office becomes a standing body within the municipal administration, while the Territorial Enhancement Fund operates through participatory budgeting, involving agricultural cooperatives, industrial representatives, and citizen delegates. Formal recognition as Italy's first H4C demonstration site under the EU Processes4Planet partnership provides external validation and access to knowledge networks.

Adaptive management protocols ensure system resilience. For instance, quarterly stakeholder forums review performance metrics, address emerging concerns, and adjust operational parameters. This continuous dialogue maintains the collaborative relationships essential for long-term success, preventing the re-emergence of conflictual dynamics through sustained engagement and transparent benefit distribution.

5. Discussion

5.1. The Scale–Distance Relationship and Its Implications

The proposed three-zone gradient for Fosso Imperatore operates within distance parameters for resource exchange, yet faces fundamental tensions between scale and viability. Considering comparable systems, larger operational scales enable longer transport distances, with feasible heat distribution extending to 20 km for a capacity of 200 MW but contracting to under 5 km for smaller systems [22]. Fosso Imperatore's 110 kW biogas potential positions it at the lower end of this scale spectrum, constraining the economically viable radius for heat distribution.

This scale constraint intersects with a deeper contradiction between economic and environmental optimization. While economic feasibility limits material transport to distances where revenue exceeds logistical costs, environmental benefits can extend much further. The "critical distance" for fly ash reuse reaches 4300 km from an environmental perspective, far exceeding its economic transportability [25]. This divergence suggests that Fosso Imperatore's compact 3 km design, while economically rational, may underutilize the broader environmental benefits that are achievable through regional integration. Policy instruments that internalize environmental values, such as carbon pricing or transport subsidies for circular materials, could bridge this optimization gap.

The concept of "co-location advantage" is particularly relevant for initial implementation. Evidence from Swiss optimization models illustrates that the first 20 hectares of greenhouses can utilize waste heat at zero additional cost when directly adjacent to heat sources [26]. This implies that Fosso Imperatore should prioritize immediate adjacencies, such as rooftop greenhouses on industrial buildings in Zone A, before investing in extensive pipeline infrastructures. Such co-located demonstrations could provide the economic validation and stakeholder buy-in necessary for subsequent expansion.

5.2. Governance Infrastructure as a Foundation for Physical Infrastructure

The sequencing of H4C development challenges conventional infrastructure planning. Evidence from successful conversions indicates that governance mechanisms must precede physical investments. The Yuhang case required establishing communication channels, organizing 4000 resident facility visits, and implementing benefit-sharing arrangements before any construction commenced [18]. This "governance as primary infrastructure" principle directly contradicts Fosso Imperatore's current trajectory of proposing spatial transformation without establishing stakeholder dialogue.

The absence of systematic engagement with the opposition movement creates conditions analogous to the pre-conflict stages in failed developments. This highlights the broader challenge of managing urban–industrial metabolism, where an incomplete understanding of material and energy flows between urban systems and their environments creates governance gaps [27]. Naples' experience with wastescapes (degraded peri-urban territories resulting from unregulated development and waste accumulation) demonstrates how historical institutional failures generate community mistrust that technical solutions cannot overcome [15]. Without addressing underlying trust deficits through transparent, participatory processes, Fosso Imperatore risks replicating patterns of contested development rather than achieving collaborative transformation.

Successful governance models share the common elements of multi-stakeholder inclusion and environmental centrality. The quintuple helix framework's positioning of the environment as the nucleus, rather than as a constraint, reframes industrial development as ecological regeneration [19]. For Fosso Imperatore, this reframing could change the narrative from industrial expansion threatening agriculture to industrial innovation enhancing agricultural productivity through resource provision.

The phased implementation pathway addresses a critical gap in the H4C literature regarding the temporal dimension of stakeholder transformation. While technical studies focus on steady-state operations and governance frameworks describe mature structures, the 36-month pathway shows how contested territories evolve toward collaboration. The integration of trust-building, co-creation, and institutionalization phases with technical demonstrations provides a replicable sequence for similar contexts. This temporal framework, validated through comparable cases [18], suggests that patience and structured engagement are prerequisites for converting opposition into partnership.

5.3. Economic Viability Within Mediterranean Constraints

Quantitative evidence provides both validation and concern for the model's economic assumptions. Infrastructure investments reach EUR 1500 per meter for urban district heating networks [28], suggesting capital requirements exceeding EUR 4.5 million for pipeline infrastructure alone. However, documented payback periods of 2–3 years for greenhouse heating systems indicate potential for a rapid return on investment [26,29]. The order-of-magnitude reduction in heating costs documented in Swiss operations, from 1.08 to 0.096 CHF/kg for tomato production, highlights the compelling economics once systems are operational.

Mediterranean specificities alter these economic calculations. Water scarcity, reaching critical levels with exploitation indices of 66% in Portugal [23], elevates the water recovery value beyond Northern European contexts. The water recovery potential in Fosso Imperatore may provide greater economic benefits than heat cascading, particularly given agricultural irrigation costs during drought periods. This implies the reorientation of optimization priorities from energy efficiency, which is dominant in Northern European models, toward water circularity.

The fragmented institutional landscape characteristic of Southern European governance imposes additional transaction costs, which are absent in Northern European contexts. Tunisia's need for Inter-Ministerial Task Forces to overcome departmental silos [30] parallels Campania's fragmented authority over environmental, agricultural, and industrial development. Each resource exchange requires navigating multiple jurisdictions, potentially negating economic benefits through administrative delays and compliance costs.

Additionally, regulatory gaps compound these economic challenges. Campania's lack of an APEA framework prevents access to the streamlined procedures available in other Italian regions, forcing any attempts at implementation to navigate complex waste management regulations designed for linear disposal. Such a regulatory void creates legal uncertainties that could deter business participation and investment. The contrast with regions possessing established frameworks underlines the need for proactive policy development to enable circular transitions.

5.4. Learning from Absence: The Missing Failure Analysis

The literature's focus on successful cases obscures critical learning opportunities from failed initiatives. No documented examples address Italian agro–industrial integration attempts, whether successful or failed, creating an empirical vacuum for model validation. This absence may reflect either remarkable implementation success or, more plausibly, publication bias toward positive outcomes. Without understanding failure modes, including economic miscalculation, technical incompatibility, or stakeholder resistance, Fosso Imperatore operates with an incomplete risk assessment.

To address this knowledge gap, implementation should incorporate explicit learning mechanisms. First, establishing a monitoring protocol that documents both successes and failures during pilot phases would create the missing empirical base. Second, forming a consortium with other Italian IPs attempting circular transitions could facilitate knowledge sharing about barriers and solutions. Third, academic partnerships should prioritize publishing negative results and failed experiments to build a collective understanding of what does not work.

The contrast between designed and emergent systems provides insight into potential failure points. Kalundborg's success emerged through decades of incremental, bilateral exchanges built upon existing trust [31]. Attempts to replicate such systems through planned development often fail when imposing comprehensive designs on unprepared social contexts. Fosso Imperatore's ambitious three-zone model risks this overdesign trap by proposing system-wide change before establishing basic exchange relationships.

In order to mitigate such overdesign risks, the implementation pathway should prioritize incremental development over comprehensive transformation. For instance, initial phases should focus on single bilateral exchanges, such as one food processor providing waste to one agricultural operation, demonstrating viability before scaling. The three-zone model should serve as a long-term vision, guiding individual projects, rather than an immediate blueprint. Success metrics should emphasize relationship building and trust development alongside technical performance. This adaptive approach allows the system to evolve organically while maintaining strategic direction, combining Kalundborg's emergent success factors with intentional design principles.

5.5. Adaptive Implementation Strategy

The analysis indicates that successful implementation requires the fundamental resequencing of proposed activities. The initial focus must shift from comprehensive spatial planning to targeted demonstration projects, exploiting existing co-location advantages. A single successful exchange, perhaps between one food processor and an adjacent agricultural operation, could provide proof of concept while building stakeholder trust.

Regulatory adaptation must proceed in parallel rather than await regional framework development. The creative interpretation of existing instruments, including temporary use permits, experimental designations within current zoning, or voluntary inter-company agreements, could provide a legal foundation for pilot projects. These demonstrations could then inform regional APEA development, positioning Fosso Imperatore as a living laboratory for policy innovation rather than as a victim of regulatory absence.

Monitoring progress toward circularity requires standardized indicators that capture the complexity of urban–industrial metabolism. Recent reviews of international standards for ecological indicators provide frameworks for assessing smart urban metabolism with the potential to guide performance measurement in H4C contexts [32].

The integration of digital technologies offers particularly promising avenues for optimizing resource flows and stakeholder coordination. Lessons from Urban Agenda Partnerships show how digital tools can enhance urban metabolism efficiency, suggesting applications for real-time monitoring and the adaptive management of industrial–agricultural exchanges [33].

Policy implications extend across multiple governance levels. At the regional level, developing APEA legislation adapted to southern Italian contexts represents an urgent priority. Such frameworks should acknowledge existing industrial–agricultural interfaces while providing flexibility for innovative configurations such as gradient zones. At the municipal level, authorities might explore interim measures, including experimental designations or voluntary agreements, that enable pilot demonstrations within current regulations. These early implementations could inform subsequent regulatory development based on practical experience rather than theoretical projections.

The three-zone gradient model retains conceptual value as a long-term territorial vision. Its primary contribution lies not in specific technical configurations but in challenging binary thinking about industrial–agricultural relationships. The model proposes spatial continuity rather than segregation, opening an imaginative space for reconceiving territorial development in regions where traditional zoning has reached social and environmental limits. This approach proves particularly relevant for Mediterranean contexts where water scarcity makes resource recirculation essential, year-round cultivation justifies infrastructure investments, high-value protected products (DOP) incentivize enhancement over replacement, and dense peri-urban patterns enable efficient resource exchange within a 3 km radius. These territorial specificities, combined with fragmented governance requiring negotiated solutions, make the model especially applicable to those regions facing similar development pressures. This conceptual innovation, more than any technical specification, provides the foundation for turning Southern European IPs from sites of conflict into spaces of collaboration.

However, the model does not eliminate the fundamental land conversion challenge but rather transforms it from a binary opposition to negotiated optimization. Vertical development in Zone A and a mixed-use configuration in Zone B reduce but do not eliminate agricultural land consumption. The model acknowledges that some conversion remains inevitable, even with vertical development. The maintenance of a partial agricultural function in transition zones and enhanced productivity in the remaining areas create a pragmatic compromise that addresses industrial needs while minimizing agricultural losses. This represents a realistic approach, recognizing that absolute preservation often leads to conflict deadlock, while managed transition with compensation mechanisms enables workable solutions.

6. Conclusions

This research addressed the challenge of reconciling industrial expansion with agricultural heritage preservation by developing the first spatial planning model that operationalizes H4C principles for contested territories. Unlike traditional approaches that rely on buffer zones or compensation mechanisms, the three-zone gradient design proposed for the Fosso Imperatore IP shows how territorial conflicts can be converted into collaborative opportunities through innovative spatial configurations and resource exchange mechanisms. Through this proposed framework, the H4C literature may advance from abstract principles to implementable spatial configurations. Successful adaptation to other regions requires the careful consideration of local agricultural systems, regulatory frameworks, and social trust levels.

As a conceptual modeling study, this analysis is limited by the scope of available data, organic waste figures from only three companies rather than comprehensive material flows, illustrative parameters rather than detailed economic analyses, and documentary sources rather than extensive stakeholder engagement. These constraints are consistent with theoretical model development, where the objective is to establish frameworks for future empirical validation rather than comprehensive implementation analysis.

Future research should prioritize three areas—comprehensive GIS-based material flow analysis, detailed techno-economic modeling, and systematic stakeholder engagement—to validate the conceptual framework through empirical evidence.

The significance of this research lies in illustrating that industrial development and agricultural preservation need not be mutually exclusive. The model reconceptualizes spatial boundaries as productive interfaces rather than lines of separation, providing a pathway for territories facing similar conflicts, thus turning the zero-sum logic of land use competition into positive-sum resource synergies.

The path from a conceptual model to operational reality requires patient, incremental progress through pilot demonstrations, transparent benefit-sharing, and sustained stakeholder dialogue. Through such careful implementation, IPs can evolve from sources of territorial conflict to catalysts for circular transformation.

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Abbreviations

The following abbreviations are used in this manuscript:

IP	Industrial Park
H4C	Hubs for Circularity
EIP	Eco-Industrial Park
IS	Industrial Symbiosis
CE	Circular Economy
APEA	Aree Produttive Ecologicamente Attrezzate
Rete NO PIP	Rete No Piano Insediamenti Produttivi
GIS	Geographic Information System
DOP	Denominazione di Origine Protetta (Protected Designation of Origin)

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