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Systemic analysis of urban sustainability indicators: A case study of the city of Moundou, Chad

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Abstract: Contemporary cities are shaped by the intricate interplay of material and immaterial flows operating within non-linear urban metabolisms. In the face of escalating global challenges—most notably climate change and rapid urbanization—their governance has become increasingly complex, exposing the limits of conventional sectoral approaches to urban sustainability decision-making. This complexity is especially pronounced in sub-Saharan African cities, where limited adaptive capacity, financial constraints, and weak governance hinder effective responses to ongoing transformations. In this context, a systemic approach to urban governance offers a compelling framework for strengthening public decision-making. This study applies the MICMAC method (Matrix of Crossed Impacts—Multiplication Applied to a Classification) to identify patterns of influence and dependency among variables. It then uses dynamic systems modeling via Vensim (version 8.2.1) to simulate interactions among twenty interdependent indicators of urban sustainability. The systemic analysis highlighted the strategic relevance of the following indicators: rational land use, accessibility and mobility, urban vegetation density, flood management, and access to health services. Six structuring feedback loops were also identified: the spatial-functional loop, ecological resilience loop, civic cohesion loop, regulatory-economic loop, social inclusion loop, and health–productivity loop. These dynamic interrelations highlight the need for systemically informed urban governance capable of enabling integrated and evidence-based decision-making for sustainable urban development.

Keywords: *Causal interdependencies, Indicators, Sub-Saharan Africa, Systemic analysis, Urban sustainability.*

1. Introduction

The evolution of urban sustainability assessment frameworks has emerged as a pressing global priority, galvanizing governments, international organizations, planning bodies, and academic institutions; their converging efforts are progressively reshaping both normative and operational paradigms [1-3]. This momentum is unfolding amid complex, interrelated social, economic, environmental, and geopolitical transformations that challenge conventional planning models and underscore the urgency of reconfiguring evaluative approaches to meet contemporary urban demands [4-6]. The increasing complexity of urban systems renders static or sectoral analyses obsolete, necessitating a reconceptualization of the urban fabric as a dynamic, adaptive system characterized by evolving feedback loops, self-organization, and emergent properties [7-11]. Cities, therefore, function as complex adaptive systems wherein adaptability and adaptive learning mechanisms shape development trajectories in response to shifting internal and external stimuli [4, 7, 12-14]. These dynamics are embedded in multi-scalar interdependencies among subsystems—spanning governance, infrastructure, material flows, and socio-economic processes—the interactions of which generate non-linear, path-dependent transformations [15-17]. Consequently, urban analysis must transcend compartmentalized

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approaches in favor of systemic perspectives that acknowledge the co-evolution of interlinked components and their mutual transformations [18]. These interdependent processes give rise to emergent dynamics that reconfigure spatial and functional urban structures in unpredictable and often irreversible ways [18-23]. Urban adaptability is rooted in decentralized mechanisms of change and institutional learning, which continuously reshape both technological infrastructures and governance frameworks, revealing the intrinsic self-organization of the city as a socio-technical system in perpetual evolution and recomposition [24]. Moreover, the non-linearity of urban dynamics generates cascading effects across city subsystems, where minor disruptions may catalyze significant transformations, while large-scale interventions may yield only marginal or unintended outcomes [25]. Understanding these dynamics necessitates a critical integration of interdependencies into planning and governance strategies, attuned to variations in institutional and socio-economic resilience across diverse territorial and institutional contexts [26, 27]. Sectoral or reductionist approaches, therefore, fall short of addressing the magnitude and complexity of contemporary urban challenges, demanding systemic, integrative frameworks sensitive to structural entanglements and multi-scalar dynamics, which can more accurately capture the complexities of urban evolution and guide responsive, context-specific interventions [28-30]. This paradigm shift calls for a transition from fragmented, static urban imaginaries towards relational analyses that place inter-subsystem interactions at the core of urban inquiry, thereby paving the way for adaptive governance frameworks that embrace urban transformation as a situated, evolutionary process.

The transition of cities toward sustainability has emerged as a critical priority for development stakeholders, catalyzing increasing recognition of indicators as pivotal tools for guiding this transformation [31]. Indicators are indispensable for setting objectives, realigning priorities, and ensuring the effective monitoring and evaluation of urban performance within distinct local contexts [32-37] forming the foundation of urban sustainability assessment frameworks [38]. However, traditional assessments have predominantly relied on sector-specific indicators—such as environmental, economic, or social metrics—often in isolation, thereby overlooking the intricate interdependencies between these dimensions [2, 3, 39-42]. This reductionist approach has led to significant analytical fragmentation, impeding a comprehensive understanding of urban dynamics. For example, evaluating healthcare service performance independently from waste management fails to account for potential synergies or trade-offs between these sectors [31]. Moreover, indicators not grounded in a systemic comprehension of urban dynamics risk misaligning public policies with the complex realities of local contexts [43]. The prevailing sectoral methodology, largely descriptive in nature, also falls short in capturing the dynamic interrelations among variables, undermining the efficacy of indicators in guiding integrated and adaptive urban policies [39]. As Haou, et al. [31] observe, although sustainability indicators increasingly address local challenges, their failure to explicitly analyze interdependencies limits the identification of feedback loops and actionable leverage points [31]. Scholars have further stressed that disregarding feedback mechanisms in evaluation processes can lead to unintended consequences, potentially jeopardizing long-term sustainability [44, 45]. In light of these limitations, a growing body of research advocates for a paradigmatic shift towards a more integrated, systemic approach to urban sustainability assessment [46]. This emerging paradigm, underpinned by a network of interconnected indicators, enables a more holistic understanding of urban complexity, thereby providing more robust tools for sustainable planning and governance. Advanced quantitative methods—such as system dynamics modelling [47, 48]. Structural Equation Modelling [15]. Bayesian network analysis [49] and causal regression modelling [18]—are central to this evolution. These methodologies not only facilitate the modelling of causal relationships among indicators but also help uncover feedback loops and leverage points critical for advancing integrated urban governance [44]. Transitioning from fragmented sectoral indicators to a cohesive system of interlinked metrics thus fosters a more nuanced understanding of how interventions in one domain—such as transportation—can generate ripple effects in other essential areas, including public health and environmental quality.

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As Haou, et al. [31] contend, the acceleration of socio-economic and environmental transformations, combined with the complex and multifaceted nature of urban challenges in Sub-Saharan Africa (SSA), necessitates the adoption of a systemic approach to sustainability assessment. The region is currently experiencing an unprecedented demographic surge, with an annual growth rate approaching 4% and nearly 60% of its population under the age of 25, a trend expected to persist throughout the 21st century [50, 51]. This rapid growth places immense pressure on already fragile infrastructure and insufficient basic services, which are increasingly unable to meet the rising demands of urban populations [52, 53]. Numerous studies underscore the widening gap between demographic dynamics and the capacity of public authorities to deliver quality social services, ensure adequate housing, promote sustainable transport, and effectively manage urban land [52-55]. These structural tensions exacerbate the overburdening of existing infrastructure, accelerating the degradation of urban ecosystems and amplifying biodiversity loss, alongside the fragmentation of remaining natural spaces [31]. Rather than representing a mere symptom, informality acts as a compounding factor, undermining both the economic viability and functional coherence of urban territories by fostering precarious land-use patterns and complicating institutional regulatory frameworks [56]. One of the primary obstacles to urban sustainability in SSA, as highlighted by Haou, et al. [4] is the fragility of urban governance frameworks—characterized by decision-making asymmetries, institutional dysfunctions, and bureaucratic inertia—which critically hinder the ability of public authorities to design and implement effective urban policies [4]. Furthermore, despite being one of the lowest global contributors to CO_2 emissions [4]. SSA remains acutely vulnerable to climate change, owing to its limited adaptive capacities and the deteriorating resilience of its infrastructure [4, 57]. This vulnerability intensifies climate-related risks, such as recurrent flooding in major cities like Bamako, Abidjan, Dakar, N'Djamena, and Moundou [54-63]. These interconnected challenges position SSA at a pivotal crossroads—not only in terms of its own development trajectory but also for the broader socio-economic and environmental balance of the planet [64, 65]. Indeed, the development path that SSA adopts in the coming decades will determine both its capacity to transition towards urban resilience and its impact on global sustainability dynamics. Consequently, rather than being perceived merely as a region of vulnerability, SSA must be recognized as a dynamic laboratory for reimagining urban development models within extreme constraints. The solutions emerging in this context—ranging from local poverty alleviation initiatives and nature-based strategies to novel governance frameworks—offer mechanisms capable of catalyzing transformative change on both local and global scales [66-68]. However, given the intrinsic complexity of these challenges, a strictly sectoral approach remains inadequate. To navigate this transition successfully, it is imperative to adopt integrated analytical frameworks that capture the interconnections between climate, urbanization, social inequality, and economic growth, and to develop robust decision-support tools that enhance urban resilience in the face of future crises [35].

This research contributes to ongoing academic debates *on* the development of innovative methodologies for the systemic assessment of urban sustainability, *through a case study of the city of Moundou, Chad*. Moundou serves as a microcosm of the profound structural challenges faced by Chadian cities—and, more broadly, those in Sub-Saharan Africa—particularly with respect to unregulated urban sprawl, inadequate provision of basic services, degradation of fragile urban ecosystems, and low resilience to climatic shocks [69]. While rooted in a local context, the study aims to offer an analytical framework with broad applicability to other urban territories in SSA confronted with similar constraints. In this context, the article introduces an innovative approach for modelling the causal interdependencies among urban sustainability indicators—an underexplored systemic perspective within the existing literature on sustainability in Sub-Saharan Africa. Building upon the 20 urban sustainability indicators developed by Haou, et al. [4] the study pursues three interrelated objectives: (i) to analyze the influence-dependence dynamics among sustainability indicators in order to identify those that exert high, moderate, or low systemic impacts, thereby highlighting key leverage points for transformation; (ii) to model the structural interdependencies among these indicators to represent the

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causal relationships connecting them, thereby facilitating the prioritisation of interventions and the formulation of a robust decision-making framework for sustainable urban governance; and (iii) to examine feedback loops to uncover circular causality logics and self-reinforcing or inhibiting mechanisms that are likely to shape the sustainability trajectory of the urban system.

By advancing a systemic approach, this study aims not only to deepen our understanding of the underlying mechanisms governing urban sustainability in the city of Moundou, but also to equip policymakers with a robust, context-sensitive decision-support tool. Given the mounting demographic pressures and escalating climate vulnerabilities, the development of comprehensive, systemic assessment tools capable of effectively steering strategic transitions towards more sustainable urban futures constitutes an urgent scientific imperative and a critical prerequisite for fostering informed and resilient urban governance.

2. Materials and Methods

2.1. Study Site

Moundou, the economic capital and second-largest city of Chad, is situated between latitudes 08°31′ and 08°40′ North and longitudes 16°00′ and 16°10′ East, approximately 480 km southwest of the national capital, N'Djamena. Geopolitically, the city is bordered to the north by the sub-prefecture of Déli, to the south by the Logone River—a key hydrographic axis that significantly influences both urban morphology and economic dynamics, to the east by Lake Taba, and to the west by the sub-prefecture of Bah and Lake Wey. Administratively, Moundou is subdivided into four districts, encompassing 32 neighborhoods [70].

Strategically positioned within a dense transport corridor, Moundou is served by major arterial roads linking it to southern Chadian cities such as Doba, Koumra, and Sarh, while also ensuring transnational connectivity to Bangui (Central African Republic, 641 km) and N'Gaoundéré (Cameroon, 400 km). This infrastructural integration has transformed Moundou into a vital commercial gateway for regional trade and mobility. As a direct consequence, the city's population has risen markedly—from approximately 100,000 in 1993 to an estimated 240,000 in 2023 [31]. While this demographic surge reflects the city's growing economic attractiveness, it also intensifies critical challenges related to urban infrastructure provision, institutional governance, and environmental resilience, posing a significant threat to the sustainability of the city.

This case study focuses on five neighbourhoods of the city of Moundou—Dombao, Djarabé 1, Doumbeur 2, Gueldjem 2, and Guelbé (see Figure 1) —selected according to five criteria defined by [31]. The geographical location of these neighbourhoods was mapped using geospatial analysis conducted with ArcGIS software (version 10.4), based on shapefile datasets provided by the National Research Centre for Development, headquartered in N'Djamena, Chad.

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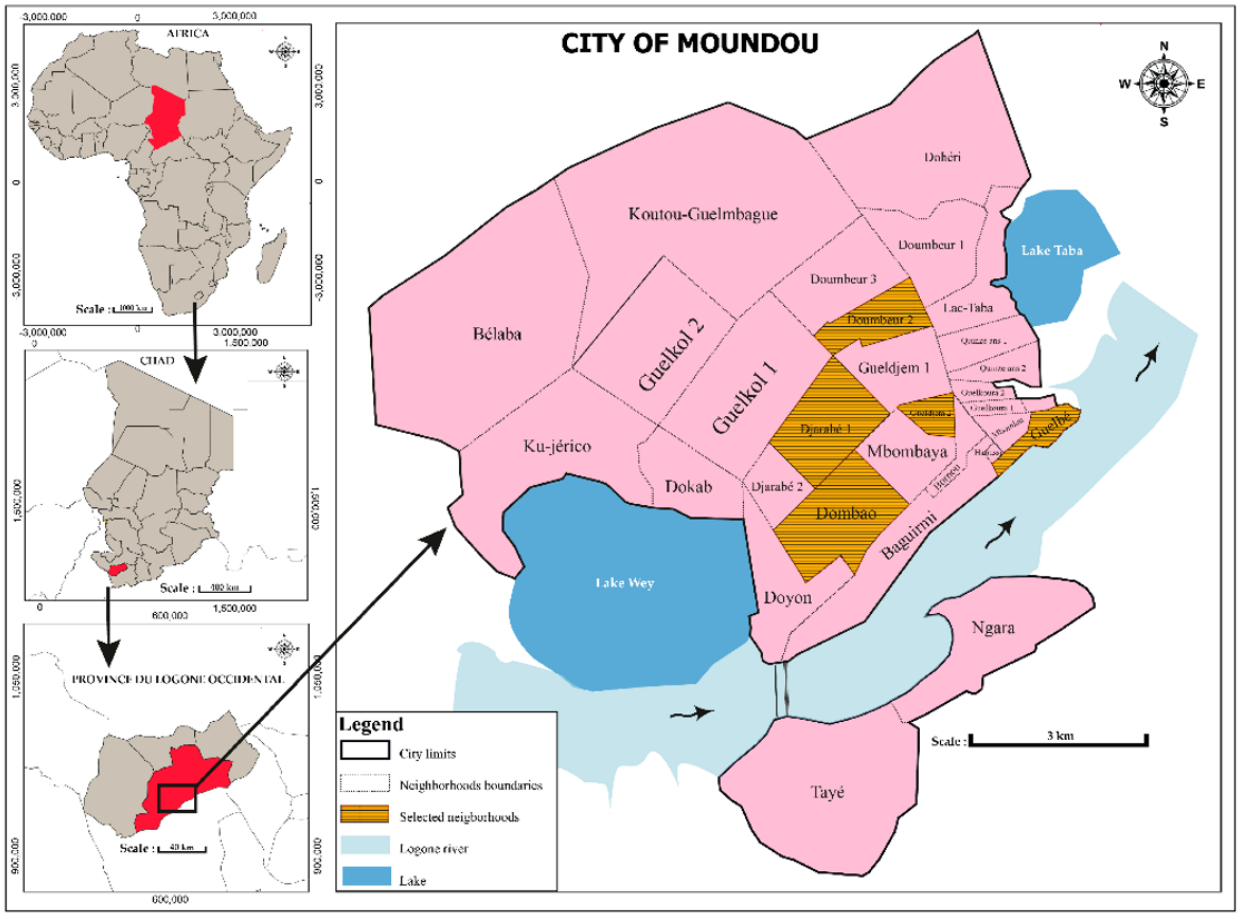

Figure 1.
Geographical location of the city of Moundou.

2.2. Research Methods

2.2.1. General Methodological Framework

In this study, we adopted an inductive-deductive methodological approach. This approach integrates an inductive phase, aimed at empirically extracting pertinent indicators from field-collected data, with a deductive phase, designed to formulate and test hypotheses concerning the causal relationships among these indicators, notably through systems analysis.

The inductive process facilitates the development of a nuanced contextual understanding deeply rooted in the specific realities under investigation, beginning with empirical observations and data [71]. Conversely, the deductive phase draws upon existing theoretical frameworks to construct testable hypotheses and to structure the analysis, thereby enhancing both the rigor and the potential generalizability of the findings [72].

This dual dynamic, widely endorsed in complex research within the social sciences and urban studies, enables a comprehensive examination of the intricate interactions characterising urban environments by reconciling the richness of qualitative and quantitative data with a structured theoretical reasoning [73, 74]. Furthermore, it guides the selection and sequencing of the specific analytical methods detailed below.

2.2.1. Methodological Foundations and Analytical Innovation

This article builds upon the twenty sustainability indicators developed by Haou, et al. [4] that emerged from a participatory process involving diverse stakeholders actively engaged in sustainable

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urban development initiatives in Moundou, Chad. The innovative dimension of this study lies in its ambition to transcend conventional assessments by conducting a comprehensive analysis of these indicators, with particular emphasis on their intricate causal interrelationships. This approach aims to assess urban sustainability through a systemic, multi-dimensional framework, thereby offering a more nuanced and holistic perspective. In particular, this contribution represents a novel scholarly effort within the Sub-Saharan African context, where the dynamics of urban sustainability are still insufficiently studied. By adopting a systemic approach, the article proposes a meticulous delineation of the interactions between indicators, distinguishing, on the one hand, those that serve as drivers—indicators characterized by a profound influence on the system—and, on the other hand, those that function as responsive indicators, whose impact is comparatively weaker.

As background, the 20 indicators proposed by Haou, et al. [4] were selected through a rigorous methodological process, structured around four stages and placing a strong emphasis on the active involvement and meaningful participation of stakeholders:

1) *Revision and Prioritisation of Urban Sustainability Issues and Objectives:* the initial phase consisted of a comprehensive analysis of the specific sustainability challenges and objectives pertinent to the city of Moundou. This step drew upon multiple methodological approaches, including an in-depth review of existing strategic documents and urban development plans. To complement this desk-based analysis, twenty-two focus group discussions were conducted with key local development stakeholders, including representatives of neighbourhood development associations, youth groups, women's cooperatives, community leaders, economic actors, and local NGOs. This participatory process culminated in a collectively defined and prioritized set of sustainability issues and objectives, which were formally validated in collaboration with Moundou's municipal action committee.

2) *Analyzing Indicator Needs*: at this stage, a structured questionnaire comprising two main components was employed to assess both the current use of indicators and the existing gaps in indicator needs among key stakeholders. To ensure methodological rigor and the relevance of the findings, the survey was administered exclusively to members of the Action Committee, which included subject-matter experts, officials from various technical departments, and policymakers.

3) *Selection of Optimal Indicators:* At this stage, two complementary methodological approaches were employed to guide the selection of optimal indicators. The first approach follows the framework developed by Gudmundsson, et al. [75] which assesses indicators based on ten criteria grouped into three categories: representational criteria (validity, reproducibility, and sensitivity), operational criteria (measurability, data availability, and adherence to ethical standards), and decision-support criteria (transparency, interpretability, alignment with overarching goals, and relevance for policymaking) [75].

The second approach, proposed by Munier [76] initially involves analyzing the effects, impacts, and weightings of each indicator [76]. These parameters are subsequently incorporated into a confrontation matrix. Based on this matrix, the Simplex algorithm—implemented in Microsoft Excel (version 2004)—was applied to compute the objective function and derive the optimal weighting coefficients for the indicators. This rigorous and systematic procedure ultimately led to the selection of 31 optimal indicators.

4) *Validation of Indicators:* the 31 optimal indicators selected were subsequently subjected to a formal validation process conducted by a panel of experts. Drawing upon the content validity methodology proposed by Ayre and Scally [77] the panel—comprising three academic researchers, three urban development specialists, two heads of municipal technical departments, and the municipal delegate for urban planning—assessed each indicator by classifying it into one of three categories: *essential*, *useful but not essential*, and *not necessary*. This systematic validation process led to the refinement of the initial list, culminating in a final selection of 20 indicators distributed across five thematic dimensions (Figure 2).

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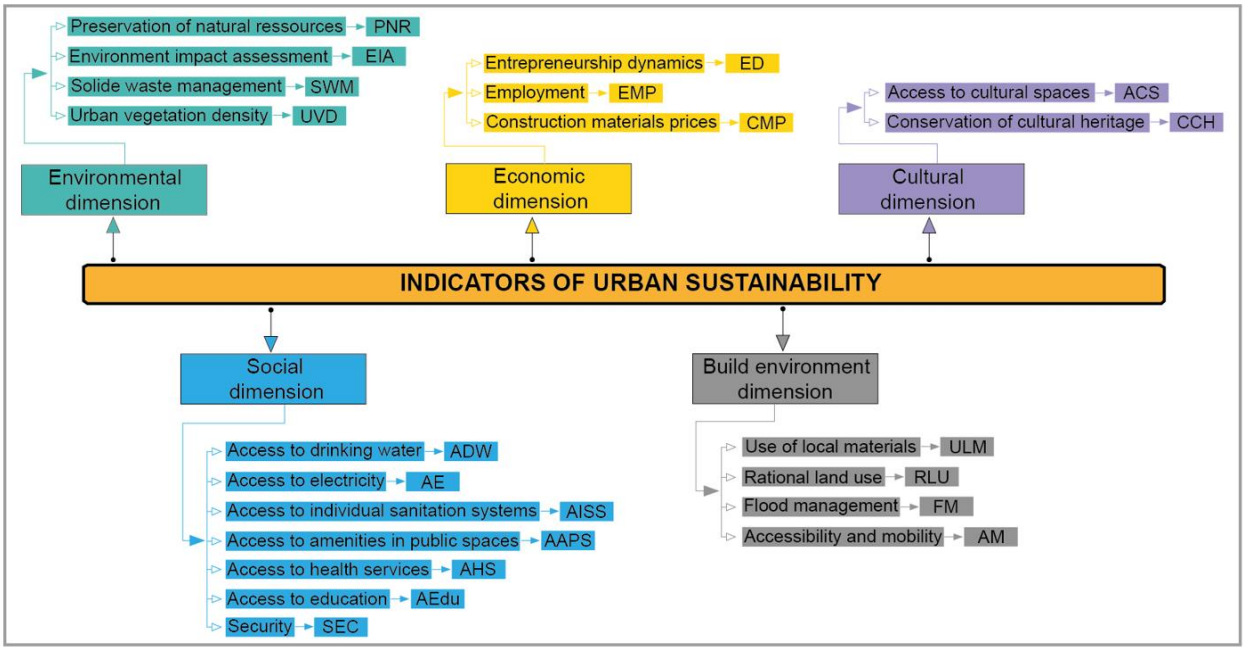

Figure 2.
Classification of the Twenty Urban Sustainability Indicators Across Five Interrelated Dimensions. (Source: authors, 2021).

2.2.2. Data Collection

The data underpinning this study are derived from reputable institutional sources, including the INSED databases, the Development Committee, the Mairie de Moundou, Initiative Développement, and the technical service directorates of provincial delegations. The temporal focus on the 2017–2021 period was selected following a meticulous evaluation of data availability and completeness, ensuring both consistency and robustness for subsequent analysis. Notably, datasets from periods preceding 2017 and following 2021 are characterized by substantial discontinuities and significant gaps across numerous critical indicators, which severely hinder their integration into a comprehensive, systemic analysis of causal interdependencies. This strategic temporal selection, therefore, safeguards the integrity of the findings and the validity of the inferences drawn from the applied methodology. Table 1 provides an overview of the data sources.

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Table 1.
Data sources.

Institutions	Concerned indicators	Justification of data sources
National Institute of Statistics and Demographic Studies (INSED), Development Planning Delegation	Access to health services	INSED is the official body for national demographic and socio-economic data collection, providing standardized, reliable statistics for socio-economic analysis. The Development Planning Delegation ensures that data align with urban development strategies at both national and local levels.
	Access to education	
	Security	
	Entrepreneurship dynamics	
	Employment	
Development Committee, Mairie de Moundou	Rational land use	The Development Committee oversees urban and economic development policies. It provides data derived from territorial surveys, monitoring reports, and strategic urban planning initiatives, which are crucial for evaluating urban dynamics and supporting sustainable infrastructure planning in Moundou.
	Accessibility and mobility	
	Access to cultural spaces	
	Conservation of cultural heritage	
	Construction materials prices	
	Use of local materials	
	Access to amenities in public spaces	
Provincial Technical Services of Provincial Delegations, Mairie de Moundou, Initiative Développement	Preservation of natural resources	These institutions are responsible for the technical planning and management of urban infrastructure and natural resources. The data they provide are sourced from fiel observations, environmental impact assessments, urban planning documents, and monitoring reports. Initiative Développement further supports the collection of data related to waste management and flood control projects.
	Environmental impact assessment	
	Solid waste management	
	Access to individual sanitation systems	
	Urban vegetation density	
	Flood management	
Public Utilities and Distribution Companies	Access to drinking water	As key managers of essential services, these organisations provide precise data on infrastructure, service availability, and utilities access, sourced from administrative records and performance reports
	Access to electricity	

2.2.3. Normalization of Indicators

The twenty fundamental indicators selected for this study are characterized by heterogeneity in their units of measurement, rendering direct comparison impractical. To ensure analytical coherence and facilitate a rigorous systemic assessment, it is essential to harmonize these indicators to a common scale. This preliminary step, crucial for any integrated modeling effort, is based on a methodical normalization process aimed at converting raw values into comparable scores using established statistical methods, thereby facilitating cross-analysis and highlighting structural correlations [78].

Among the most frequently employed normalization methods in the scientific literature, five approaches stand out: Z-score standardization [79]. Min-Max normalization [78] logarithmic transformation [80] interval-weighted normalization [81] and ranking-based standardization [82]. Each technique offers specific advantages depending on the type of data, the statistical distribution of the variables, and the analytical objectives pursued. However, Min-Max normalization is prevalent in numerous empirical studies, both for its algorithmic simplicity and its ability to preserve the relative range of inter-indicator variations [78]. It also serves as a methodological benchmark for major institutions, such as the United Nations Development Programme (UNDP) in developing the Human Development Index (HDI) [83] and the African Development Bank for calculating the Gender Equality Index (GEI) in Africa [84]. In this study, the choice of Min-Max normalization is driven by a dual requirement: ensuring interdimensional comparability of the indicators while maintaining the integrity of their relative distribution. Normalized values are thus projected onto the [1] range, where 0 represents the lowest observed performance and 1 the highest, thereby facilitating an intuitive and rigorously comparable interpretation of all variables. To operationalize this component of the analysis, Formula (1) was employed as presented below.

$$Xi = \frac{x - \min(x)}{\max(x) - \min(x)}$$

Where:

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Xi : is the normalised value of the indicator
X : is the actual (raw) value of the indicator before normalisation

2.2.4. Cross-Impact Matrix Multiplication for the Systemic Classification of Urban Sustainability Indicators

In this study, we employed the MICMAC method (Cross-Impact Matrix Multiplication Applied to Classification) to model the structural interdependencies among urban sustainability indicators. Originally developed for strategic foresight analysis, this method has progressively emerged as a critical tool for analyzing complex systems, owing to its capacity to reveal both direct causal relationships and feedback effects [85-87]. As such, it enables the identification of key leverage points and supports enhanced urban governance through a nuanced understanding of interdependence chains.

Its methodological value lies in its dual capacity to simultaneously capture (1) driving power, defined as an indicator's capacity to influence other variables within the system, and (2) dependence, understood as its sensitivity to variations triggered by other indicators. This dual reading provides a systems-based analytical framework for classifying variables according to their structural role within the broader urban system architecture: (i) driving indicators (high influence, low dependence); (ii) relay indicators (moderate influence and dependence); (iii) dependent indicators (low influence, high dependence); and (iv) autonomous indicators (low influence, low dependence).

Formally, the method is based on the construction of a cross-impact matrix $M = [m_{ij}]$, in which each coefficient $M = [m_{ij}]$ reflects the intensity of the impact exerted by indicator (i) on indicator (j), according to the following predefined scale:
Mij = 0: No influence
Mij = 1: Negligible influence
Mij = 2: Low influence
Mij = 3: Moderate influence
Mij = 4: Strong influence
Mij = 5 : Very strong influence

Subsequently, we computed both the influence and dependence indices. The influence index of indicator *i* is defined as the sum of its effects on all other variables in the system, while the dependence index of indicator *j* reflects the total influence it receives from the others. These two indices are computed using equations (2) and (3), respectively.
(2) The influence index of indicator *i* is defined as the sum of the values in the *i*-th row of the impact matrix, expressed as:

$$I_i = \sum_{j=1}^{n} M_{ij}$$

(3) The dependence index of indicator *j* is given by the sum of the values in the *j*-th column, expressed as:

$$D_j = \sum_{i=1}^{n} M_{ij}$$

This mathematical formalization serves, on the one hand, to objectify the relational dynamics among indicators, and on the other hand, to support a strategic reading of the analyzed urban system. It thus offers a rigorous foundation for the definition of informed action scenarios and the prioritisation of interventions in the field of urban sustainability.

2.2.5. System Dynamic

To capture the systemic interdependencies among urban sustainability indicators, this study adopts the System Dynamics (SD) approach. System Dynamics is an interdisciplinary analytical framework grounded in systems thinking and structural modelling, designed to explore complex phenomena [88]. It is widely employed by researchers to model, interpret, and elucidate evolving behaviours, feedback

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loops, multidimensional interactions, and causal relationships that typify complex systems. According to Mitchell [89] the term *complex system*: a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution [89].

System dynamics analysis relies on the representation of cause-and-effect relationships through reinforcing or balancing feedback loops. These loops serve to model internal feedback mechanisms and flow trajectories, thereby enabling a more precise understanding of the dynamics arising from interactions within the system [90]. One of the initial steps in this methodology involves the construction of a Causal Loop Diagram (CLD), which provides a visual interpretation of the interrelations between indicators via directional links [86]. The orientation of causal directions is determined based on the influence levels of indicators as identified in the MICMAC matrix. In other words, comparing the linkage index values (li) allows for the inference of a directional relationship between two indicators (X) and (Y) in the studied system. If the influence index (Ii) of indicator (X) on indicator (Y) is strictly greater than that of (Y) on (X), it indicates that (X) exerts a positive influence on (Y) within the modelled system dynamics.

Furthermore, we examined the feedback mechanisms that regulate system behavior. Reinforcing loops (positive feedback) amplify initial changes, potentially triggering self-reinforcing dynamics and tipping points. Conversely, balancing loops (negative feedback) act as regulatory mechanisms, restoring systemic equilibrium through corrective processes [91]. To formalize these components, we employed the Vensim PLE software (version 8.2.1).

2.2.6. Conceptual framework and Hypotheses

The conceptual framework constitutes the organisational backbone of our urban sustainability model, enabling a coherent articulation of the various dimensions of sustainable development at the urban scale. It provides an analytical structure conducive to representing the causal interrelationships among indicators through a systemic approach. Drawing on the conceptual frameworks proposed by Gudlaugsson, et al. [92] and Musango, et al. [93] and incorporating the empirical findings of Haou, et al. [4] we developed a robust conceptual foundation (Figure 3) that structures the dynamic organisation of the five dimensions of urban sustainability. This framework served as the basis for formulating hypotheses reflecting the causal relationships among the 20 indicators. Each hypothesis is grounded in the analysis of interactions between the dimensional blocks, which are conceived as interdependent subsystems within the broader urban system, whose cross-cutting and feedback effects shape the trajectory of the city's sustainable development.

Hypothesis 1 (Environment vs. Social): The condition of the urban environment—including the preservation of natural resources, the management of solid waste, environmental assessment practices, and vegetative density—exerts a decisive influence on the social dimensions of urban life. A healthy environment promotes improvements in public health, mitigates health-related risks, enhances access to potable water, and elevates the quality of public spaces. Together, these elements constitute the foundational pillars of social well-being.

Hypothesis 2 (Social vs. Economic): The level of access to essential social services—namely education, healthcare, sanitation, electricity, and security—constitutes a structural foundation of urban economic performance. A socially well-equipped population is more capable of participating actively in the labour market, engaging in entrepreneurship, and enhancing local economic dynamics. Consequently, investments in human capital are a critical precondition for sustaining the vitality and resilience of urban economic activities

Hypothesis 3 (Economic vs. Built Environment): Economic dynamics—particularly employment levels and entrepreneurial expansion—directly influence the capacity to transform the physical fabric of the city. A robust urban economy enables sustained investment in infrastructure, improves the quality and accessibility of housing, facilitates more efficient land use, and informs the selection of appropriate

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construction materials. In this regard, economic development serves as a structuring lever for enhancing the built environment.

Hypothesis 4 (Built Environment vs. Culture): The configuration of the built environment—including mobility systems, flood management, material availability, and spatial organisation—fundamentally conditions access to cultural spaces and the preservation of heritage. A spatially well-structured city fosters the emergence of vibrant cultural venues, nurtures local identities, and embeds heritage within contemporary urban dynamics. Thus, the built environment functions as a vector for cultural transmission.

Hypothesis 5 (Culture vs. Social): The valorisation of culture and the conservation of urban heritage strengthen social cohesion, identity anchoring, and perceived security. Equitable access to cultural spaces plays a transversal role in fostering social connectedness, particularly in urban contexts marked by socio-ethnic diversity and rapid urbanisation.

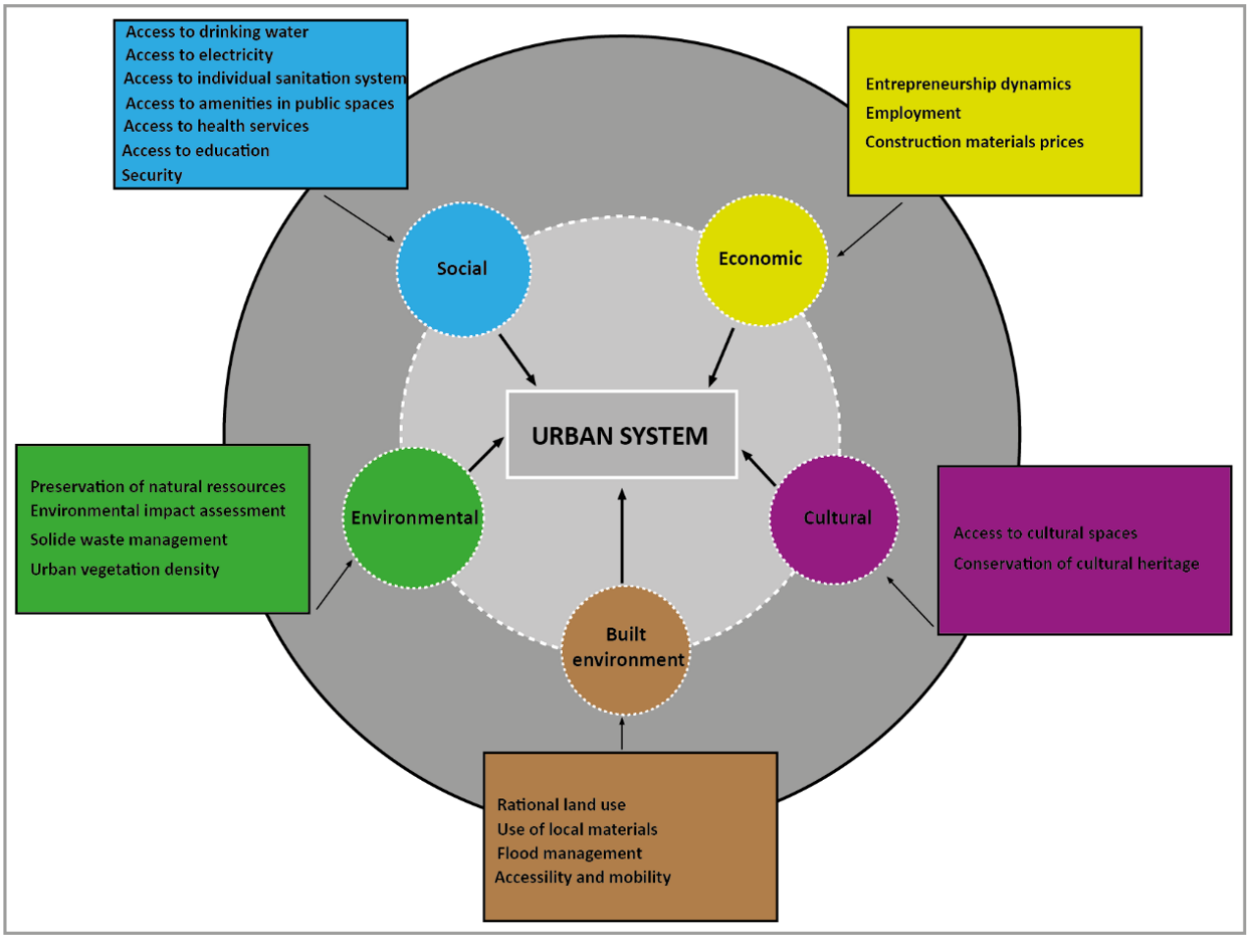

Figure 3.
Conceptual framework.

3. Results

3.1. In-depth Analysis of Normalized Performance Data

The normalisation of indicators over the 2017–2021 period, as presented in Table 2, reveals a nuanced and heterogeneous landscape, where incremental gains coexist with persistent structural vulnerabilities. The conservation of natural resources displays a relatively stable trajectory (0.517 in

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2017, fluctuating between 0.505 and 0.530), indicating a sustained—albeit modest—commitment to ecological priorities. In a similar vein, the performance of environmental impact assessments (ranging from 0.480 to 0.520) suggests a gradual yet perceptible incorporation of environmental considerations into local governance frameworks.

In contrast, the domain of basic infrastructure reflects pronounced volatility, symptomatic of deep-seated systemic deficiencies. Access to potable water deteriorated slightly (from 0.308 in 2017 to 0.290 in 2021), while access to electricity remained persistently low (between 0.280 and 0.330), underscoring chronic challenges in energy provision. Although sanitation services experienced a temporary improvement in 2020 (0.350), the subsequent decline (0.330 in 2021) points to the fragility and underinvestment characterising this essential sector. The availability of essential services follows a similarly erratic path. Healthcare access fluctuated between 0.340 and 0.380, reflecting a structurally under-resourced medical system. Education access exhibited an uneven progression—rising from 0.385 in 2017 to 0.400 in 2018, only to fall to 0.370 in 2021—revealing a persistent mismatch between growing demand and constrained supply. These inconsistencies exacerbate socio-spatial inequalities and hinder the fulfilment of human development potential. From an economic standpoint, the indicators expose a pattern of structural inertia that impedes inclusive growth. Entrepreneurship declined over the period (from 0.286 in 2017 to 0.260 in 2021), while employment rates stagnated within a narrow range (0.220 to 0.260), signalling an economic environment unfavourable to innovation and job creation. Concurrently, the steady rise in the cost of construction materials (from 0.429 to 0.520) reflects inflationary pressures likely to erode housing affordability and hinder sustainable urban expansion.

Table 2.
Analysis of Normalised Performance Data.

Indicators	2017		2018		2019		2020		2021	
	Row value	Min-max Norm.	Row value	Min-max Norm.	Row value	Min-max Norm.	Row value	Min-max Norm.	Row value	Min-max Norm.
Preservation of natural ressources	61	0.517	63	0.530	60	0.505	62	0.520	59	0.495
Environment Impact assessment	50	0.500	48	0.480	52	0.520	49	0.490	51	0.510
Solid waste management	35	0.417	38	0.450	36	0.430	39	0.470	37	0.440
Urban vegetation density	45	0.500	44	0.490	46	0.510	43	0.480	47	0.520
Access to drinking water	40	0.308	42	0.330	39	0.300	41	0.320	38	0.290
Access to electricity	30	0.286	33	0.315	30	0.295	34	0.330	29	0.280
Access to individual sanitation system	48	0.327	50	0.340	46	0.320	49	0.350	47	0.330
Access to amenities in public spaces	50	0.385	52	0.400	49	0.380	53	0.420	50	0.390
Access to health services	38	0.354	37	0.345	39	0.370	36	0.340	40	0.380
Access to education	55	0.385	57	0.400	54	0.375	56	0.395	53	0.370
Security	42	0.338	44	0.350	41	0.330	45	0.370	40	0.320
Entrepreneurship dynamics	25	0.286	27	0.310	24	0.270	26	0.290	23	0.260
Employment	33	0.236	36	0.260	32	0.230	34	0.250	31	0.220
Construction materials prices	80	0.429	85	0.450	90	0.490	88	0.470	95	0.520
Use of local materials	60	0.333	63	0.350	59	0.320	61	0.340	58	0.310
Rational land use	52	0.340	55	0.360	51	0.330	54	0.350	50	0.320
Flood management	49	0.380	50	0.390	48	0.370	51	0.400	47	0.360
Accessibility and mobility	57	0.309	55	0.300	58	0.320	54	0.290	59	0.330
Access to cultural spaces	47	0.309	49	0.330	46	0.300	48	0.320	45	0.290
Conservation of cultural heritage	53	0.260	52	0.250	54	0.270	51	0.240	55	0.280

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Urban planning remains an area of sustained concern. Indicators of accessibility and mobility exhibit only modest and inconsistent progress (0.309 in 2017, fluctuating between 0.290 and 0.330), thereby revealing persistent inadequacies in transport infrastructure. Flood management, after a slight improvement in 2018 (0.390), declined to 0.360 in 2021, underscoring continued exposure to climate-related hazards.

Cultural and heritage dimensions remain significantly marginalised. Access to cultural spaces declined (from 0.309 to 0.290), while heritage conservation indicators, though marginally improved (from 0.260 to 0.280), remain alarmingly low—reflecting a broader disregard for urban cultural identity.

3.2. Cross-Impacts Matrix Analysis

Figure 4 presents the spatial distribution of the 20 indicators within the MICMAC matrix, based on their systemic influence (y-axis) and dependency (x-axis). This mapping enables a nuanced interpretation of each variable's strategic weight and structural role within the urban system.

In the upper-left quadrant, driving indicators such as *Rational Land use*, *Flood Management*, and *Access to Electricity* exhibit high influence coupled with low dependency. Their structural autonomy positions them as critical levers of urban transformation, capable of initiating cascading effects across the system. These variables function as strategic catalysts, often setting the direction of systemic change.

Conversely, the upper-right quadrant comprises relay indicators—including *Access to Education*, Access to *healthcare Services*, *Solid Waste Management*, and *Accessibility and Mobility*—that combine high influence with high dependency. Their dual position reflects both their centrality in mediating systemic interactions and their vulnerability to shifts in the broader configuration. These indicators constitute dynamic hubs within the system, simultaneously shaping and being shaped by upstream and downstream variables.

The lower-right quadrant includes dependent indicators such as *Entrepreneurial Dynamics*, *Preservation of Natural Resources*, Access to amenities in public spaces, and *Environmental Impact Assessment*. These variables exert limited influence yet demonstrate significant dependency, thereby functioning more as systemic outcomes than drivers. For instance, entrepreneurial vitality is contingent on a favorable structural environment—including education, infrastructure, and energy provision—revealing its embeddedness within macro-level institutional and governance frameworks.

Finally, indicators situated in the lower-left quadrant, such as *Cultural Heritage Conservation*, *Access to Individual Sanitation Systems*, Security, and *Access to Access to cultural spaces*, exhibit both low influence and low dependency. While seemingly peripheral in terms of strategic leverage, these variables play a critical role in sustaining the symbolic and cultural dimensions of urban sustainability. Their contribution to spatial equity, intergenerational continuity, and collective identity warrants their careful consideration within any integrative policy framework.

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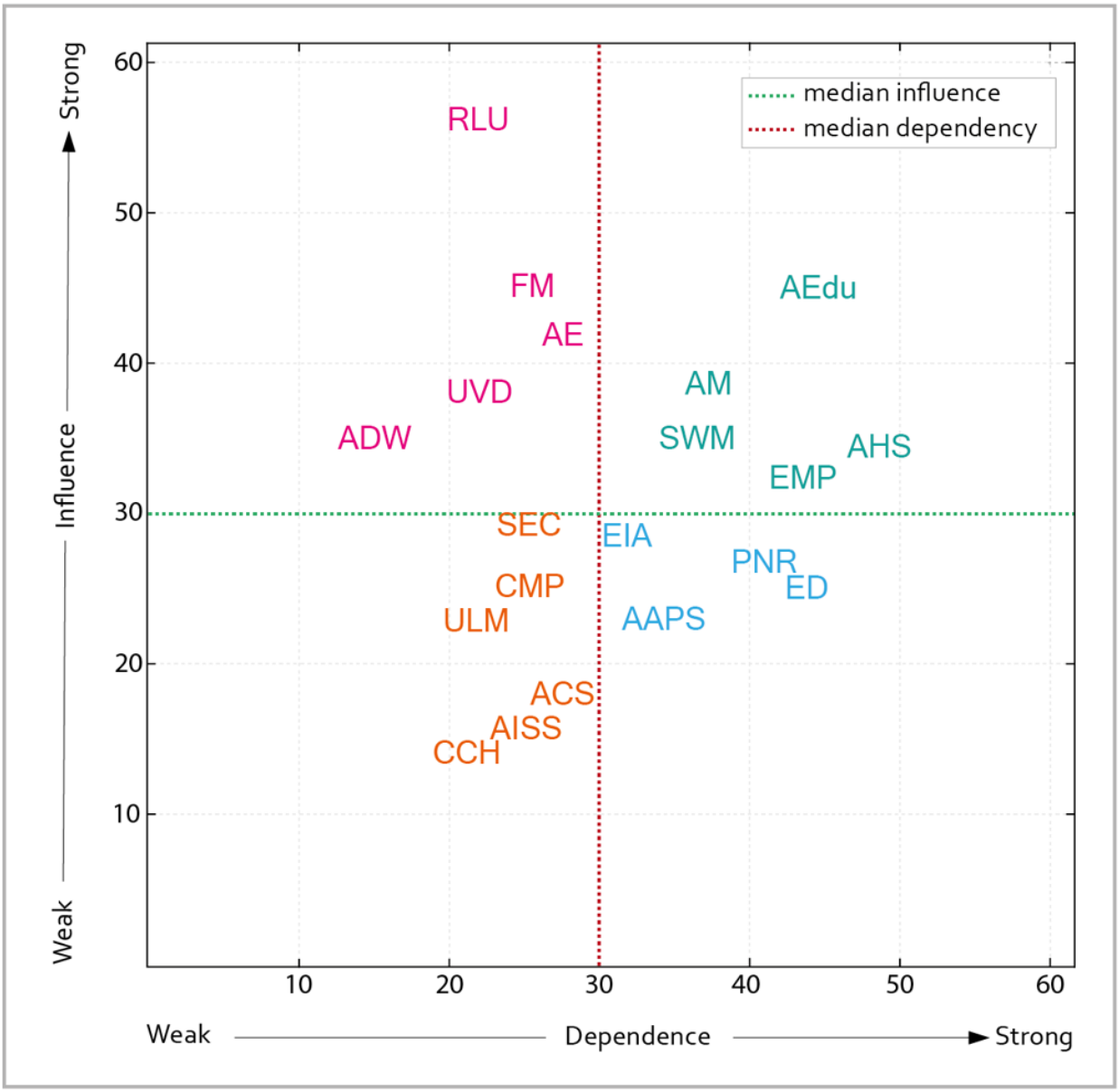

Figure 4.
Spatial distribution of the 20 indicators within the MICMAC matrix.

3.3. Dimensional Analysis of Influence Scores

Figure 5 depicts the distribution of influence scores across distinct dimensions of urban sustainability. A systemic reading of these scores reveals a multilayered and hierarchically ordered configuration of interdependent domains. The social dimension, with a cumulative influence score of 224, clearly emerges as the central node within the urban sustainability framework. This notable dominance underscores the pivotal role of basic services—namely drinking water (Ii = 35), electricity (Ii = 42), education (Ii = 45), and healthcare (Ii = 34)—which lie at the intersection of collective wellbeing imperatives and governance priorities.

The social dimension's predominance reflects its dual role: it acts both as a catalyst for urban resilience and as a locus of systemic fragility, heavily contingent on the performance of public policies

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and the infrastructure underpinning environmental, economic, and spatial domains. It thus operates simultaneously as a point of convergence and a tension nexus within the sustainability framework.

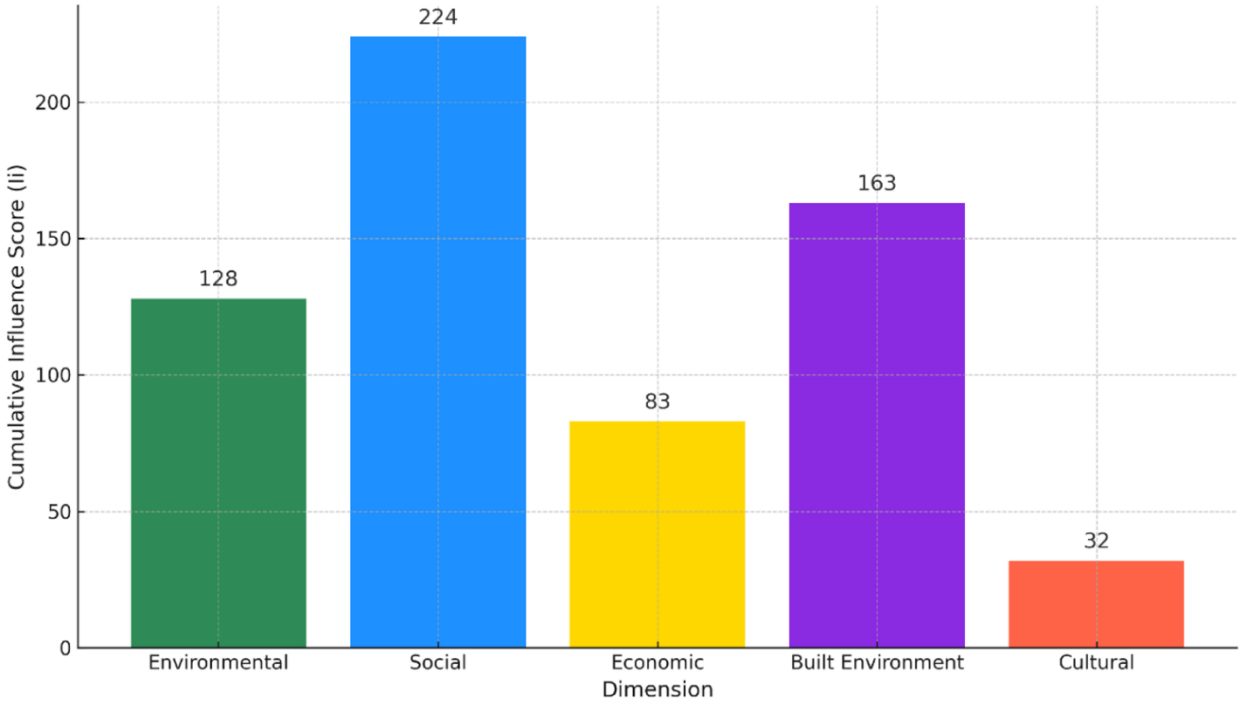

Figure 5.
Infkuence scores per dimension.

In contrast, the environmental dimension, with an influence score of 128, occupies a structurally significant yet functionally autonomous position within the urban sustainability system. The indicators comprising this dimension—such as the preservation of natural resources (Ii = 27), environmental impact assessments (Ii = 28), and solid waste management (Ii = 35)—primarily operate as enabling conditions for the broader framework, establishing foundational ecological parameters without eliciting reciprocal influence. This autonomy reflects the ontological distinctiveness of natural resources: systematically marginalised in political discourse, yet structurally indispensable to urban functioning.

The built environment dimension, scoring 163, acts as a pivotal interface between the social, economic, and environmental spheres. It operationalises the aspirations of the other domains by transposing them into spatial configurations and actionable infrastructures. Indicators such as the use of local materials (Ii = 23), rational land use (Ii = 56), flood management (Ii = 45), and accessibility and mobility (Ii = 39) function as strategic vectors of transformation, enabling the concretisation of multidimensional sustainability goals. In this mediating role, the built environment bridges ecological imperatives with societal demands, offering a physical platform for coherent policy integration.

The economic dimension, with a comparatively low influence score of 83, demonstrates a reactive posture in relation to the other domains. Despite the recognised importance of entrepreneurship dynamics (Ii = 26) and employment (Ii = 32), the economic sphere appears structurally subordinated to the prerequisites defined by the social, environmental, and built environment dimensions. Rather than catalysing independent transformation, it adapts to externally induced shifts, thereby constraining its potential to autonomously advance sustainable development trajectories.

Finally, the cultural dimension, with a minimal influence score of 32, remains conspicuously peripheral. Indicators such as access to cultural spaces (Ii = 18) and the preservation of cultural heritage

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(Ii = 14) underscore the systemic neglect of cultural considerations in urban sustainability paradigms. This marginalisation highlights a persistent failure to integrate cultural dimensions into urban planning, despite their centrality in fostering identity, belonging, and territorial cohesion. The omission of cultural foundations in development strategies risks engendering transformations devoid of symbolic anchoring or collective meaning, ultimately threatening the legitimacy and durability of urban transitions.

3.4. General Analysis of the Causal Interdependencies among Urban Sustainability Indicators

Figure 6 delineates the systemic architecture underpinning the complex web of interrelations among the twenty urban sustainability indicators, advancing an integrated and systems-oriented analytical approach. This configuration is structured around five thematic spheres—environmental, social, economic, built environment, and cultural—each represented by red dashed circle, symbolizing the foundational dimensions of urban sustainability. While analytically delineated for heuristic clarity, these spheres exhibit substantial zones of conceptual overlap, thereby reflecting the intrinsic permeability of sectoral boundaries within contemporary urban systems.

The interactions across spheres are illustrated through a network of directional arrows that trace causal linkages, thereby foregrounding the holistic and interdependent nature of the urban system. These connections defy linear or unidirectional simplification; instead, they embody a circular, multidirectional, and recursive dynamic that is emblematic of complex adaptive systems. Much like causal loop diagrams, these linkages exemplify patterns of mutual conditionality and co-evolutionary feedback processes that continuously modulate the trajectories of urban transformation.

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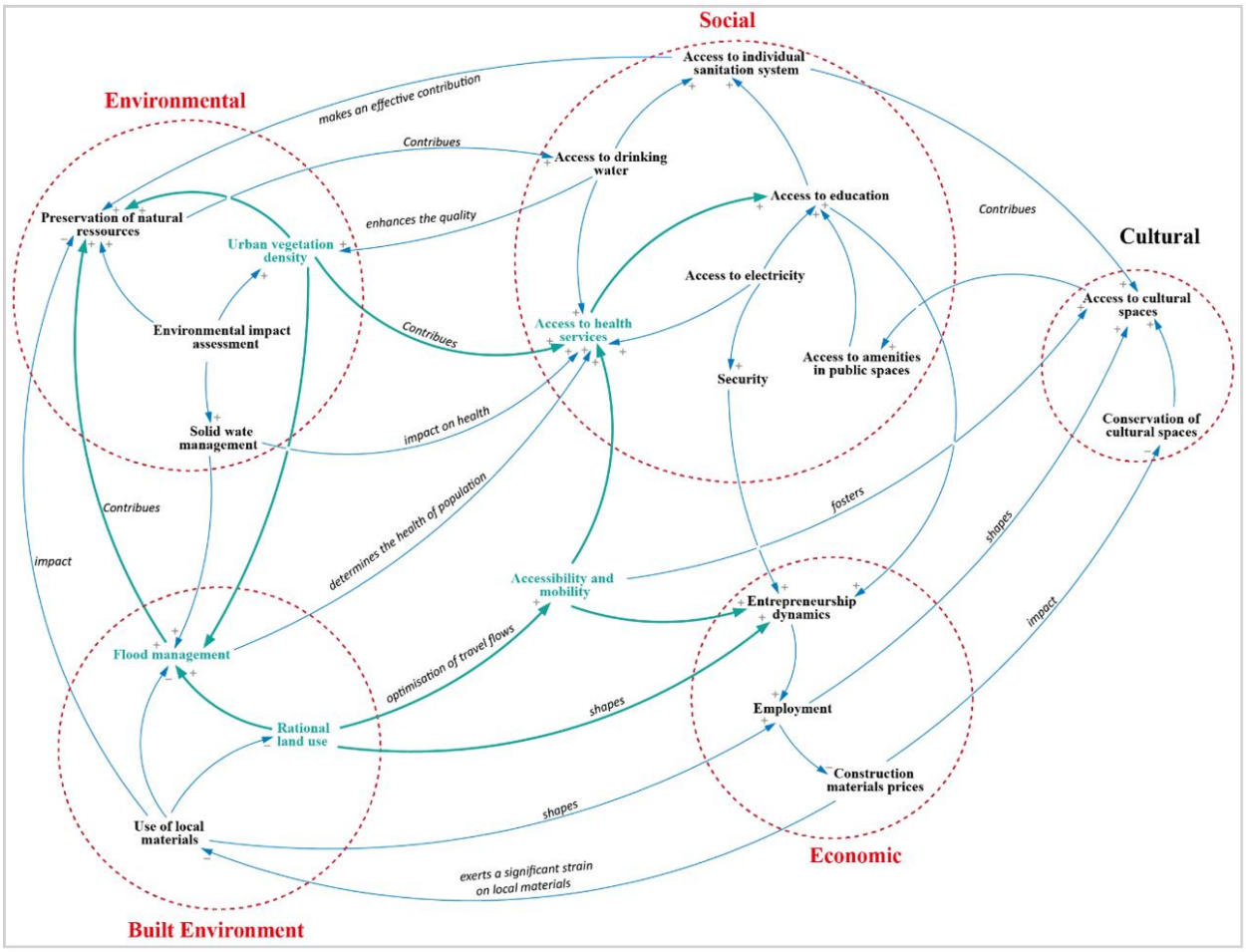

Figure 6.
Causal architecture of the twenty indicators.

A thorough analysis of the systemic architecture reveals the emergence of several strategic nodes that perform a critical regulatory function within the network of urban interactions. These nodal points fulfil a triadic role: they absorb, reconfigure, and redistribute externalities, thereby exerting a decisive influence on both the functional organisation and the overall performance of the urban system. Their dynamic centrality positions them as critical leverage points in steering systemic resilience and sustainability trajectories.

Among these high-impact indicators, *Rational Land Use* emerges as a foundational lever in orchestrating spatial, ecological, and socio-economic dynamics. It plays a pivotal role in mitigating natural hazards—particularly urban flooding—preserving ecological integrity, and offering critical insights for enhancing urban mobility and fostering entrepreneurial dynamism. As such, rational land use drives profound systemic transformations across the entire urban fabric. Far from being a mere technical variable, this indicator functions as a structural operator that mediates the interplay between the built environment and ecological processes, effectively translating spatial configurations into tangible sustainability outcomes.

A second strategic node, *Accessibility and Mobility*, serves as a critical interface linking the physicality of the built environment with its intangible impacts on social, cultural, and economic life. By enabling equitable access to essential services—such as healthcare, education, and employment—this indicator operates as both a vector of social inclusion and a catalyst for territorial economic activation. It

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enhances the fluidity of exchanges, stimulates micro-entrepreneurial initiatives that facilitate job creation, and contributes to the functional integration of peripheral urban areas. As such, it exemplifies the intricate entwinement of infrastructural provision and social dynamism within the broader urban system.

A parallel axis of systemic influence is embodied by *Urban Vegetation Density* (UVD), an indicator that functions as a critical—yet frequently undervalued—ecological and social vector. UVD exerts measurable influence across multiple domains, including the preservation of natural resources, flood regulation, and access to health services. This wide-ranging impact underscores the multifunctionality of ecological infrastructure, which supports climate regulation and enhances public health. In contrast to grey infrastructure—typically characterised by mono-functional and technocratic applications—green infrastructure delivers compound benefits that encompass hydrological stability, cultural identity, and climate resilience. In urban contexts marked by institutional fragmentation or fiscal constraints—as is the case in many African cities—investment in vegetated urban spaces represents a strategic intervention with low political and economic risk and high cross-sectoral returns.

The fourth critical node pertains to access to health services, whose systemic effectiveness depends on a constellation of interdependent variables, including access to potable water, electricity provision, solid waste management, and urban vegetation density. In turn, this dynamic enhances access to education, which itself exerts a systemic influence within the urban fabric by acting as a key driver of entrepreneurial activity and, consequently, a catalyst for job creation. This configuration transcends conventional sectoral compartmentalisation and calls for a cross-cutting, territorially grounded, and fundamentally holistic public health strategy. From this systemic perspective, health infrastructure is no longer conceived in isolation but emerges as a property of the urban ecosystem, shaped by intricate socio-ecological interdependencies.

The system also reveals the presence of indicators that are highly influenced yet exert minimal influence themselves. Notably, *Access to Cultural Spaces* and *Conservation of Cultural Heritage* appear structurally dependent on other domains—social (e.g., access to public amenities), economic (e.g., employment levels, construction material costs), and the built environment (e.g., mobility systems). This pronounced dependency indicates a critical weakness in the self-regulatory capacity of the cultural subsystem, thereby undermining its potential to contribute to autonomous and sustainable development trajectories. In the Sub-Saharan African context—where cultural resources serve not only as reservoirs of collective identity but also as engines of community resilience and endogenous development—this structural vulnerability necessitates the urgent reintegration of cultural dimensions into urban sustainability frameworks. The marginal positioning of culture within systemic leverage points exposes a persistent blind spot in contemporary urban theory and practice—one that demands rectification through a more epistemologically inclusive and territorially contextualized planning paradigm.

Lastly, *Preservation of Natural Resources* emerges as a transversal pillar that undergirds the entire architecture of sustainability. Its effectiveness hinges on the interplay of social parameters—such as access to sanitation systems, flood management capacity, and the implementation of environmental assessments. This preservation dynamic, in turn, contributes to improving access to safe water and thereby reinforces the overall regulatory capacity of the urban system.

3.5. Feedback Loops Analysis

Figures 7 to 12 elucidate the feedback architecture that governs the interplay among urban sustainability indicators. These interdependent networks reveal recursive feedback loops—nonlinear pathways through which affected indicators retroact on their sources, either amplifying or attenuating the initial dynamics. Such latent and nonlinear feedback mechanisms are pivotal for decoding emergent systemic behaviours and anticipating inflection points, regime shifts, or path-dependent lock-ins.

(Figure 7 illustrates the systemic feedback architecture underpinning the interactions among rational land use (RLU), accessibility and mobility (AM), access to education (AEdu), entrepreneurial dynamics, and employment (EMP) within the urban context of Moundou. The model delineates a

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potentially virtuous feedback loop whereby the Rational land use (RLU) enhances accessibility (AM), thereby facilitating access to educational services (AEdu), particularly for peripheral populations. Improved educational access strengthens human capital, which in turn stimulates entrepreneurial initiatives and broadens employment opportunities (EMP). These socioeconomic improvements eventually empower a growing number of household heads to secure land tenure.

However, within the specific socio-economic context of Moundou—characterised by limited urban planning capacity—the intensification of landownership aspirations and the ensuing proliferation of land parcel acquisitions exert adverse effects on rational land governance. Mounting land pressure, compounded by underperforming regulatory institutions and the widespread expansion of informal land transactions, leads to spatial fragmentation and unregulated settlement patterns. These developments undermine the systemic coherence essential for sustainable and inclusive urban planning.

Figure 8 illustrates the systemic feedback loop, delineating the dynamic interrelations among solid waste management (SWM), urban vegetation density (UVD), flood management (FM), environmental impact assessment (EIA), preservation of natural resources (PNR), and access to education (AEdu). This framework reveals a cascade of circular causalities with the potential to foster self-reinforcing mechanisms conducive to an ecological transition.

In Moundou's specific context—characterised by rapid urbanisation, limited institutional capacity, and under-resourced urban management systems—ineffective solid waste governance, in the absence of robust collection, sorting, and disposal mechanisms, frequently leads to the obstruction of drainage channels and stormwater infrastructure. This dysfunction directly undermines flood mitigation efforts, thereby heightening the vulnerability of peripheral neighbourhoods, which are often informal and structurally underserved.

An increase in urban vegetation density, in turn, strengthens the empirical foundation of environmental impact assessments (EIA), rendering them more contextually grounded and analytically robust. These evaluations constitute critical inputs for the design of natural resource preservation (PNR) strategies—an urgent imperative in Moundou, where ecosystem degradation is intensifying under the combined pressures of informal urban expansion and demographic growth.

The preservation of natural resources enhances environmental curricula and improves access to quality education (AEdu), particularly by fostering ecological literacy and citizenship. This elevation of educational standards reinforces local capacities for adopting sustainable practices—especially in waste management—thus completing the systemic feedback cycle.

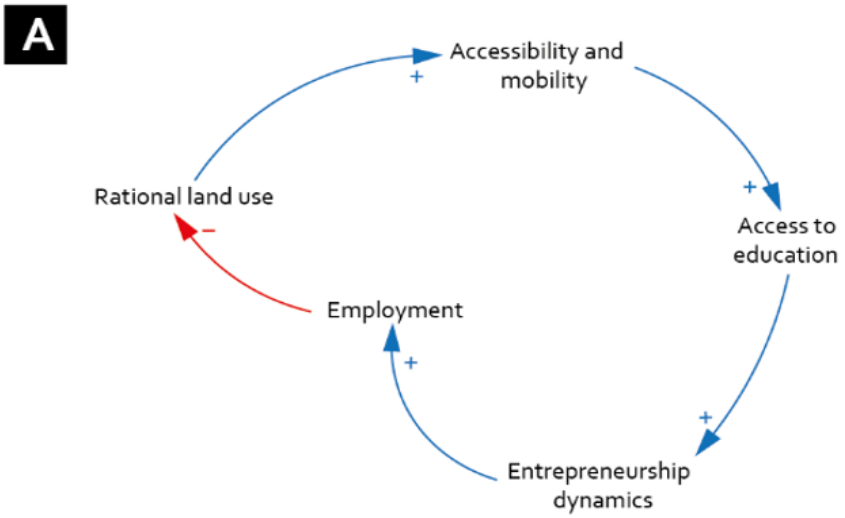

Figure 7.
Spatial-fuctional loop.

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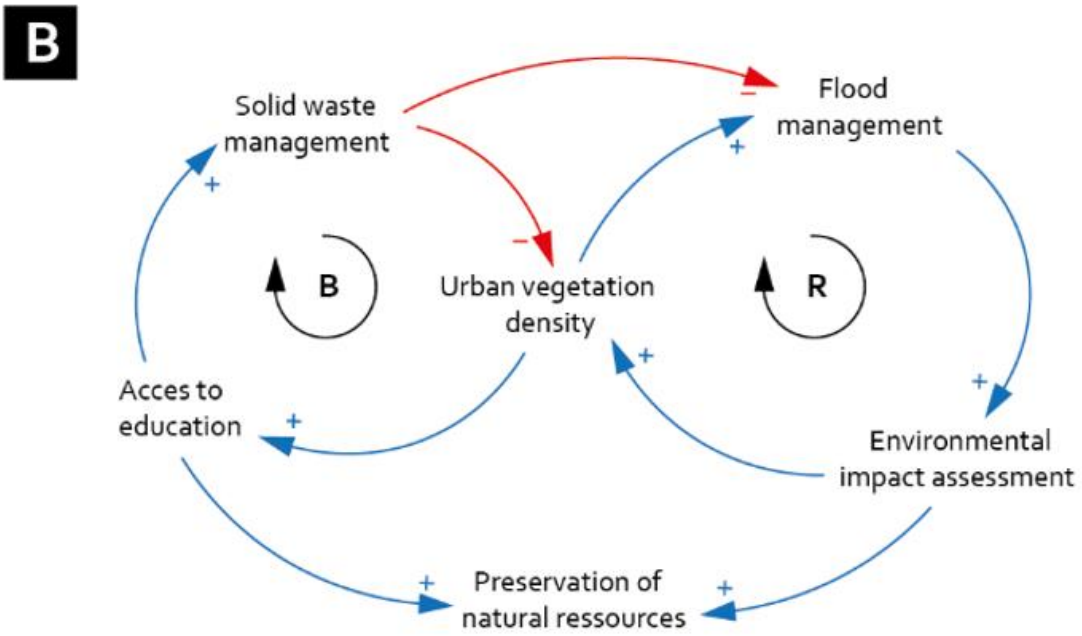

Figure 8.
Ecological resilience loop.

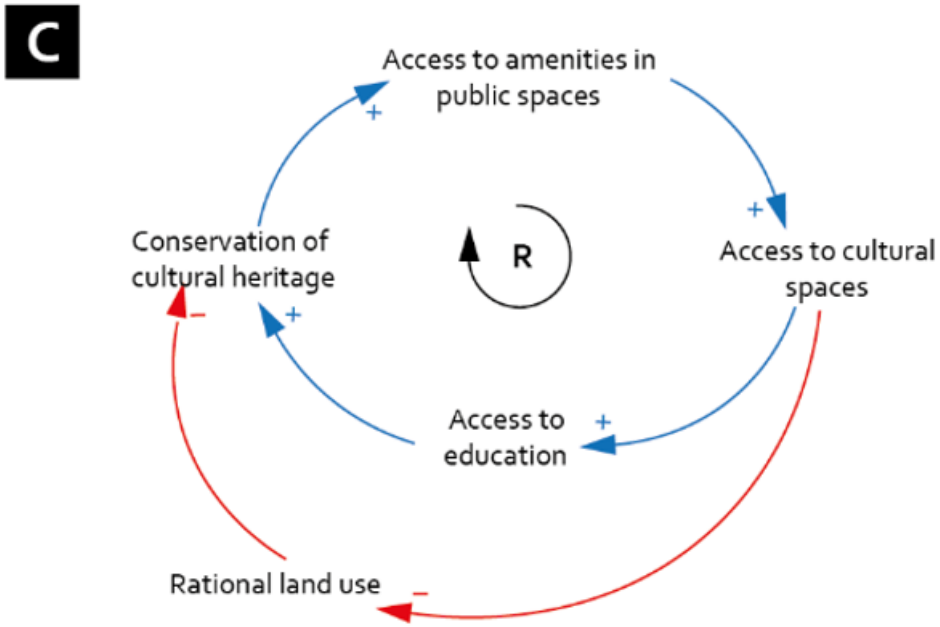

Figure 9.
Civic cohesion loop.

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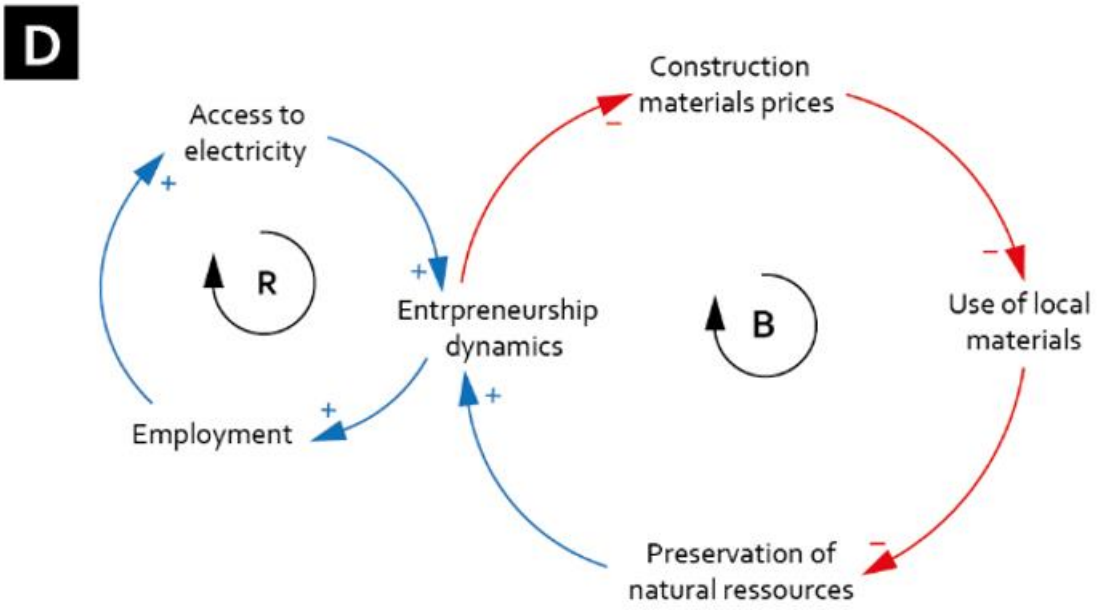

Figure 10.
Regulatory-economic loop.

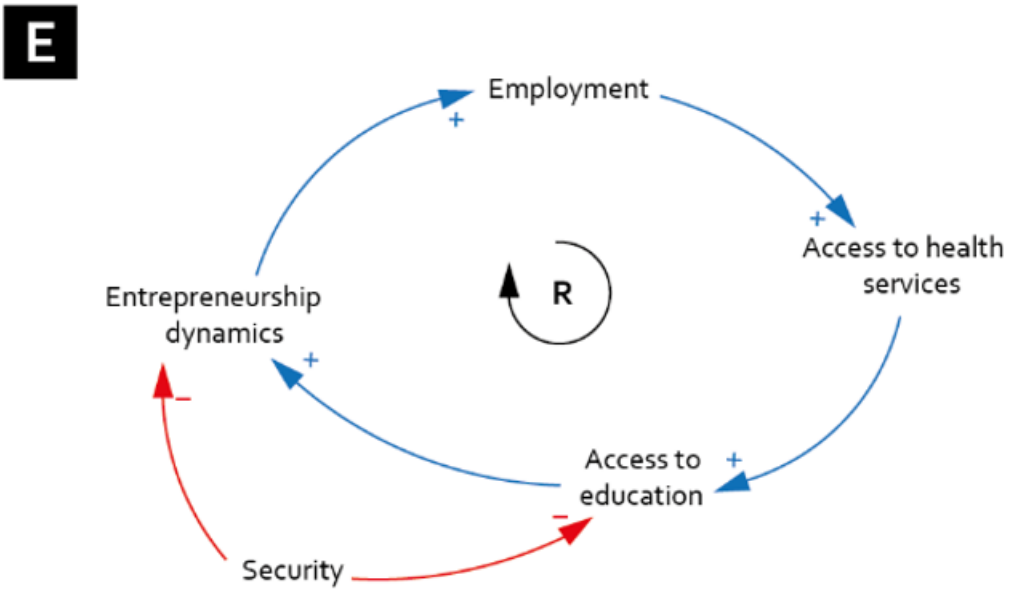

Figure 11.
Social inclusion loop.

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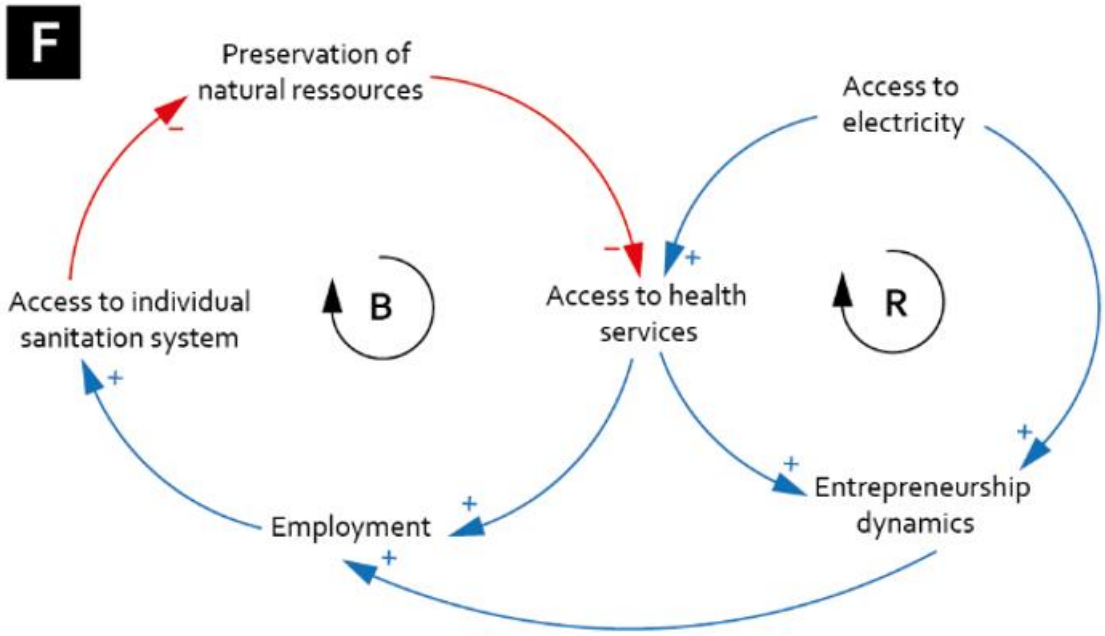

Figure 12.
Health-productivity loop.

Figures 7-12. Feedback loops.

Figure 9 illustrates a feedback loop grounded in citizenship and collective identity, wherein access to amenities in public spaces (AAPS) transcends its conventional role as physical infrastructure to become a strategic lever for social inclusion and community cohesion. High-quality public spaces that incorporate cultural functions (ACS) foster social interaction, stimulate civic education (AEdu), and reinforce collective identity. This, in turn, promotes the valorisation of cultural heritage (CCH), initiating a catalytic and mutually reinforcing dynamic that strengthens both the sense of belonging and civic engagement.

However, within the urban context of Moundou, this virtuous cycle remains fragile and is frequently disrupted by multiple structural and socio-spatial constraints. The quality and accessibility of public spaces are often compromised by territorial inequalities, insufficient maintenance, and limited investment in cultural infrastructure. Moreover, increasing land pressure—driven by unplanned land use and the informal expansion of the urban fabric—impedes the preservation of cultural heritage and weakens the symbolic function of public spaces. These tensions are further exacerbated by the marginalisation of cultural policies, thereby limiting the capacity of public spaces to act as catalysts for social resilience and cultural sustainability.

Public and cultural spaces should therefore not be perceived merely as physical settings, but as fundamental instruments of socialisation and vital vectors for reinforcing social bonds. Strengthening their role in fostering inclusive and cohesive urban development requires proactive governance, integrated planning, and sustained investment in territorially embedded cultural initiatives.

Figure 10 depicts a complex feedback mechanism interweaving reinforcing dynamics. Access to electricity (AE) serves as a foundational lever of urban transformation, enabling the emergence of local entrepreneurial dynamics (ED). These, in turn, catalyse the development of both formal and informal economic activities, thereby fostering employment growth (EMP). The resulting improvements in socio-economic conditions intensify the demand for basic infrastructure and domestic energy, consolidating a virtuous feedback loop centred on electrification.

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Entrepreneurial dynamism and expanded employment opportunities exert increasing structural pressure on the housing market, consequently driving demand for construction materials. In the absence of adequate regulatory oversight, this pressure triggers a surge in construction material prices (CMP). In response, the use of local materials (ULM) emerges as an adaptive strategy—provided it is supported by regulatory frameworks that ensure quality, durability, and alignment with local urban resilience strategies.

However, without robust regulatory systems and environmental safeguards, the unregulated exploitation of local materials can undermine the preservation of natural resources (PNR). Unsustainable extractive practices—such as uncontrolled quarrying, deforestation for timber, or excessive clay extraction—may result in severe environmental degradation, including soil erosion, biodiversity loss, and the depletion of non-renewable resources.

Thus, while the use of local materials presents a promising pathway for inclusive urban development, it must be integrated into a coherent and forward-looking framework of environmental governance. In this regard, adaptive public policies that reconcile economic stimulation with ecological preservation are essential to ensure the long-term sustainability of urbanisation processes.

Figure 11 depicts a system of complex feedback loops—both positive and negative—among five core indicators of sustainable urban development in Moundou: Employment, Access to Health Services (AHS), Security (SEC), Access to Education (AEdu), and Entrepreneurial Dynamics (ED). This systemic configuration reveals the multidirectional interactions that shape the city's socio-economic and security trajectories.

When optimal mechanisms and enabling conditions for local wealth creation—promoted by municipal authorities—are effectively operationalised, they can foster entrepreneurial dynamism, which, in turn, expands employment opportunities for the working-age population. The resulting financial capacity of employed household heads acts as a structuring lever, generating income that facilitates improved access to health services and mitigates health-related inequalities. Enhanced health outcomes, in turn, strengthen school attendance and access to education. A more educated population becomes a catalyst for creativity and innovation, contributing to the diversification and consolidation of entrepreneurial activities.

However, within Moundou's specific urban context, a persistent climate of insecurity significantly disrupts this virtuous cycle. Insecurity directly impedes entrepreneurial momentum by fostering an environment that is hostile to local investment, urban innovation, and the long-term viability of small-scale economic initiatives—thereby reinforcing a self-perpetuating negative spiral.

Accordingly, beyond the creation of favourable economic conditions, the imperative of urban security must be acknowledged as a foundational prerequisite for any sustainable transformation of socio-economic dynamics.

Figure 12 presents a dynamic systems feedback loop capturing the interdependencies among environmental, health, and economic variables in the city of Moundou.

In Moundou's urban context, limited access to individual sanitation systems constitutes a major driver of environmental degradation. Inadequate infrastructure leads to the unregulated discharge of human waste into the immediate surroundings, thereby contaminating vital natural resources—particularly groundwater, soil, and urban biodiversity. This degradation undermines the preservation of natural ecosystems and fosters the proliferation of unsanitary living conditions.

Such ecological imbalance is directly correlated with a rise in waterborne and hygiene-related diseases—including cholera, typhoid fever, and dysentery—which places increasing pressure on already fragile and under-resourced health systems. A negative feedback loop is thereby established: deficient sanitation infrastructure exacerbates environmental degradation, which in turn heightens public health vulnerabilities.

Concurrently, access to electricity emerges as a strategic enabler of two interrelated dynamics. On the one hand, it enhances the functionality and resilience of health services by enabling the refrigeration of vaccines, the operation of medical equipment, and the provision of adequate lighting in healthcare

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facilities. On the other hand, it serves as a catalyst for entrepreneurial activity, supporting income-generating ventures in commerce, artisanal production, and urban services.

These entrepreneurial dynamics gradually translate into local job creation. Improved employment prospects—particularly through access to stable and decent work—enhance the financial capacity of household heads to invest in individual sanitation solutions, such as the construction of latrines, the installation of septic systems, or the acquisition of household waste management mechanisms.

Accordingly, a second, virtuous feedback loop emerges, contributing to the preservation of environmental quality. This intricate interplay between environmental, economic, and health dimensions underscores the imperative of adopting an integrated approach to urban sustainability—one in which investments in foundational infrastructure not only address immediate ecological and health challenges, but also generate broader, mutually reinforcing development outcomes.

4. Discussion, Limitations and Research Perspective

This study initially employed the MICMAC methodology to analyse the patterns of influence and interdependence among twenty urban sustainability indicators. Subsequently, a dynamic modelling framework, implemented via Vensim software, was used to simulate the causal relationships among these indicators and to identify the most salient feedback mechanisms. The findings reveal substantial variability in the relative influence of specific indicators and in the multidimensional interactions they generate, which exhibit marked asymmetry. Furthermore, the emergent feedback loops not only uncover latent opportunities but also expose structural tensions, thereby offering a more nuanced and integrative perspective on the complexities of urban dynamics.

4.1. Normalization of Indicators: An Illustration of Mixed Progress

The results derived from the standardisation of indicators over the period 2017–2021 reveal contrasting dynamics across the various dimensions of urban sustainability, simultaneously highlighting noteworthy progress and enduring structural vulnerabilities. At first glance, indicators relating to the preservation of natural resources and the integration of environmental concerns into public policy exhibit relative stability—arguably a sign of growing awareness of ecological challenges among local authorities, likely spurred by the intensification of extreme climatic events [94]. However, this apparent environmental resilience fails to obscure the alarming deficiencies observed in other essential sectors. The data reveal chronic shortcomings in basic infrastructure: access to potable water, electricity, and individual sanitation systems continues to stagnate, and in some instances, regresses markedly. These underperformances underscore the structural fragility of public utilities and reflect a persistent incapacity to meet growing demand, driven by the combined pressures of demographic growth, accelerated urbanisation, and chronic underinvestment—both public and private. In this regard, Haou, et al. [31] emphasise that budgetary allocations to these essential services remain critically inadequate, owing to local governance systems operating with extremely limited fiscal leeway [31]. Similar deficiencies are also evident in the fields of health and education, where access indicators fluctuate erratically and point to a provision that is both insufficient and spatially uneven—ill-equipped to address the mounting needs of urban populations. This systemic mismatch exacerbates socio-spatial inequalities and constitutes a major impediment to sustainable human development [95].

The analysis also reveals alarming economic warning signs. Indicators related to entrepreneurship exhibit a marked decline, falling from 0.286 in 2017 to 0.260 in 2021, while those associated with employment remain low and persistently volatile, fluctuating between 0.220 and 0.260 throughout the period under review. These findings reflect the stagnation of local economic momentum, constrained by an environment unfavourable to private investment, chronic institutional instability, and a sustained lack of effective public incentives. This interpretation aligns with the observations of Doudjidingao [96] who argues that the deterioration of the business climate undermines entrepreneurial dynamism and hinders any meaningful progress in employment access [96]. Emerging from these socio-economic vulnerabilities, the assessment of indicators related to the built environment reveals troubling

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instability in accessibility, urban mobility, and flood management—symptomatic of deficient urban planning and a pronounced shortfall in resilience mechanisms against climatic hazards. This situation amplifies the exposure of urban populations to environmental risks and obstructs the emergence of controlled and equitable urbanisation dynamics [62]. Furthermore, the extremely poor performance in access to cultural amenities and heritage preservation highlights a concerning marginalisation of local cultural assets within planning policies, reflecting both a weak valorisation of urban identity and an institutional disengagement from levers that are nonetheless essential to social cohesion and the consolidation of a shared sense of belonging [4].

4.2. The Causal Interdependencies of Urban Sustainability Indicators: Complex Cascading Effects

The causal architecture revealed by the analysis highlights a dense network of interdependent indicators, within which certain variables emerge as critical structural nodes shaping the overall urban dynamic. Among these, the indicator related to rational land use functions as a systemic leverage point, exerting cascading effects across multiple domains—including accessibility and mobility, flood risk management, and entrepreneurial development. This catalytic role positions rational land use at the core of urban performance structuring, insofar as it determines the spatial allocation of services, facilitates multimodal mobility, and underpins environmental resilience. These findings resonate with an established body of literature that identifies land-use efficiency as a key determinant of urban morphology, spatial accessibility, and ecological sustainability [97, 98]. In African contexts marked by sprawling informal urbanization and weak regulatory frameworks, land governance emerges not merely as a technical concern but as a foundational prerequisite for mitigating compound negative externalities, ranging from environmental degradation to infrastructure dysfunction [72]. A rational and anticipatory land management strategy is therefore not ancillary but constitutive of any integrated approach to urban sustainability, particularly in cities navigating the triple challenge of demographic pressure, climate vulnerability, and institutional fragmentation [98].

In parallel, the systemic analysis underscores the pivotal role of accessibility and mobility as a strategic leverage point within the urban sustainability architecture. Far from being a merely operational variable, mobility exerts a cascading influence on a wide array of interdependent indicators, including access to healthcare and education services, the vitality of entrepreneurial ecosystems, and the inclusiveness of cultural infrastructures. This centrality aligns with the conceptualizations of Sietchiping, et al. [99] and Zreik, et al. [100] who frame mobility not only as a means of physical displacement but as a structural enabler of opportunity that shapes the contours of urban equity [99, 100]. In a context such as Moundou—marked by fragmented spatial development, infrastructural discontinuities, and the marginalization of peripheral zones—enhancing mobility systems has the potential to unlock systemic ripple effects across multiple governance domains, from social service delivery to spatial justice. As such, it constitutes a critical entry point for reconfiguring urban trajectories toward greater inclusiveness, functionality, and resilience.

In continuity with the previously established systemic perspective, the analysis reveals the structural centrality of access to healthcare services within the architecture of urban sustainability. Far from being reducible to the mere presence of medical infrastructure, this indicator emerges as the complex outcome of multisectoral interdependencies, involving access to clean water, electricity supply, solid waste management, and the density of urban vegetation. Such a configuration underscores the limitations of compartmentalized, sector-specific approaches and calls for the implementation of an integrated, territorially grounded public health strategy that operates across multiple scales and accounts for the social, ecological, and infrastructural determinants of well-being. This conception aligns with research in urban health that regards healthcare infrastructure not as isolated entities, but as emergent properties of complex socio-ecological systems [101]. Consequently, the strengthening of health resilience cannot overlook the necessity of systemic interventions throughout the entire urban fabric, wherein green infrastructure, energy access, and sanitation act as essential co-mediators of health equity.

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In parallel, the analysis foregrounds the transversal role of Urban Vegetation Density as a foundational pillar of urban resilience. In a Sahelian city such as Moundou—where escalating climate variability and the degradation of natural buffers exacerbate environmental vulnerabilities—urban greening emerges as a cost-effective and culturally embedded adaptation strategy. This perspective aligns with the work of Thoms and Köster [94] and Gudlaugsson, et al. [92] who highlight the multifunctionality of urban green spaces as anchors of climate resilience, public health, and social cohesion [94]. Far from being a sector-specific intervention, Urban Vegetation Density operates as a systemic variable that permeates multiple strata of the urban metabolism—ranging from ecological integrity and hazard mitigation to improvements in urban health. The dynamic interplay between environmental protection and Access to Health Services reveals the bidirectional feedback loop linking ecosystem functionality and human well-being, thereby reinforcing the imperative of integrated socio-ecological planning [102].

Yet, one of the most salient insights emerging from this systemic modelling is the limited structural influence of the cultural dimension. Indicators such as *Access to Cultural Spaces* and *Heritage Preservation* appear to be highly dependent on other subsystems—economic (employment, construction material costs), social (access to public services), and Built environment (Accessibility and mobility). This pronounced dependency reflects a weak integration of cultural aspects into urban policies, often rooted in the lack of investment in cultural infrastructure, limited support for cultural expression, and inadequate promotion of local identities—factors that could otherwise exert systemic influence on urban development. Such a deficit constitutes a persistent blind spot within prevailing sustainability frameworks, thereby constraining the transformative potential of culture in shaping autonomous and durable development trajectories [103]. In the Sub-Saharan African context—where cultural assets serve not only as repositories of collective identity but also as vectors of community resilience and endogenous innovation—this marginalization underscores the urgency of reintegrating the cultural dimension into urban sustainability paradigms. The omission of culture from systemic leverage points reveals a deeper institutional and epistemological oversight—one that must be rectified through more inclusive, context-sensitive planning frameworks grounded in local cultural rationalities and socio-spatial specificities [31].

4.3. The Feedback Architectures of Urban Sustainability Indicators: A Non-Linear Systemic Perspective

Figures 7 to 12 highlight the feedback mechanisms underpinning the dynamics of urban sustainability in Moundou. Rather than conforming to a linear understanding of causality, these feedback loops reveal a non-linear architecture in which each indicator, far from being a passive receptor, interacts dynamically with the factors influencing it—modulating, amplifying, or inhibiting the initial effects.

The first two loops underscore how territorial and environmental dynamics can positively self-reinforce within a systemic framework of sustainable urbanisation. Spatial and functional loop (Figure 7) operates as a key mechanism for mitigating urban inequalities by enhancing access to public facilities, improving urban mobility, and fostering synergies among education, employment, and social inclusion. These systemic effects are well documented in the literature on spatial justice and the redistributive capacities of urban planning in evolving African cities [97]. In a context such as Moundou—where spatial disparities are intensified by informal expansion and the underdevelopment of peripheral zones—an integrated spatial logic is critical to reconfiguring urban trajectories in a sustainable manner [69]. Concurrently, Ecological resilience loop (Figure 8) refers to the capacity of the urban system to absorb climate shocks through effective waste management, the preservation of urban ecosystems, and hydrological regulation. The nexus between waste management, resilience, and ecological governance is underscored in recent studies on Sub-Saharan African cities, including those by Okorondu, et al. [101] and UNEP [83] which demonstrate that the intersection between urban vegetation density, flood management, and the preservation of natural resources can yield positive externalities for public health and urban sustainability [83]. In synergy, loops A and B highlight the imperative for territorial

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planning strategies that integrate the principles of functionality, equity, and resilience, in alignment with the objectives of the 2030 Agenda and the Sendai Framework for Disaster Risk Reduction.

In a framework more attuned to identity dynamics and economic tensions, (Figure 9) and (Figure 10) reveal the inherent complexities of urban governance in rapidly expanding contexts. The significance of cultural facilities and public spaces (Figure 9) extends beyond strictly infrastructural considerations, as it encompasses the symbolic recognition of social groups, the fabric of communal life, and the consolidation of local social capital through education. Haou, et al. [31] underscore the structuring role of such spaces in African cities, where they function as vectors of active citizenship and urban cohesion. In Moundou, a multicultural city shaped by historical identity tensions, these spaces serve as essential points of social mediation [31]. However, this inclusive dynamic is undermined by the ambivalent effects of unregulated economic growth (Figure 10). In the specific context of Moundou, job creation opportunities remain limited, and commercial activities are largely unregulated. As a result, the rising cost of construction materials encourages the overexploitation of local resources, thereby threatening the conservation of natural assets—including cultural resources. UN-Habitat [97] further confirms that the absence of land market regulation mechanisms in secondary African cities exacerbates social vulnerabilities, particularly among youth and women [97]. The interplay of these two loops highlights the urgent need for adapted forms of urban governance, grounded in participatory approaches and the proactive regulation of local economic dynamics, as advocated by Biloa and Gaarde [104] in their research on inclusive land management [104].

Feedback loops E and F delve deeper into the systemic interrelations between human capital, essential services, and social stability. Figure 11., highlights a virtuous cycle linking employment, health, education, and security, which forms the very foundation of an integrated approach to human development, as conceptualised in the 2023 UNDP report [105]. In a context such as Moundou, characterised by chronic underinvestment in basic social services, these interconnections transcend fragmented sectoral approaches and promote a systemic perspective in public policy.Figure 12., in turn, illustrates how access to individual sanitation systems serves as a catalyst for improving public health and, indirectly, economic productivity. The relationship between health, infrastructure, and economic performance is well documented, particularly in the work of Buckley and Kallergis [106] who argue that sanitation deficits constitute a structural barrier to achieving the SDGs in African cities [106]. For instance, the lack of sanitation systems negatively affects the preservation of natural resources, which, in turn, impacts public health. Together, these two loops underscore the urgent need for increased investment in essential public goods—not only to meet fundamental human needs but also to establish the structural foundations for inclusive sustainability. In this regard, they align with the recommendations of the Economic Commission for Africa (ECA), which calls for the integration of social, health, and economic dimensions into sustainable urban development strategies, supported by a multi-stakeholder governance framework grounded in human rights [107].

4.4. Limitations and research perspective

Despite the methodological and empirical contributions of the present research, several limitations must be highlighted in order to delineate its scope and inform future avenues for investigation. The first limitation pertains to the contextual boundaries of the study, which focuses exclusively on the city of Moundou. While this locality provides a relevant basis for exploring urban dynamics in Sub-Saharan Africa, the socio-economic, institutional, and cultural particularities of this context constrain the immediate generalization of the results to other urban configurations in the region. An inter-urban validation, through comparative studies that include other African cities with contrasting morphologies, trajectories, and governance regimes, would help to strengthen the external robustness of the proposed model.

The second limitation lies in the static nature of certain datasets employed. Despite the dynamic approach adopted through systemic modeling, the quality, availability, and periodicity of contextual data remain uneven, partially restricting the model's ability to capture the diachronic evolution of indicators.

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Future integration of more extensive time series, derived from longitudinal databases or participatory monitoring systems, would pave the way for more refined prospective simulations and the evaluation of alternative urban development scenarios.

Finally, although the adopted systemic approach facilitates the identification of structuring feedback loops, it does not yet fully integrate the political, institutional, and emotional dimensions of urban decision-making. The articulation between the modeling rationality of complex systems and the multiple, often conflicting rationalities that govern urban fabric remains both a theoretical and operational challenge. Future research would benefit from exploring the interfaces between systemic modeling and deliberative processes, particularly by incorporating participatory approaches or territorial collective intelligence systems.

5. Strategic Recommendations for Local Authorities and Urban Development Practitioners

In light of the systemic dynamics revealed by the causal analysis of twenty urban sustainability indicators, it is crucial to move beyond fragmented, sector-specific interventions towards an integrated governance model, anchored in the activation of structural levers. The intricate interdependence of these indicators highlights the urgent need for transversal and adaptive governance frameworks that optimize system-wide interactions and catalyze lasting urban transformations.

(1) *Reconceptualizing Land Use Planning as a Systemic Governance Lever:* The pronounced influence of the Rational Land Use (RLU) indicator, which demonstrates the highest systemic impact, calls for a fundamental recalibration of land management policies. Local authorities must transcend technocratic or cadastral paradigms to establish regulatory frameworks that prioritize spatial continuity, functional integration, and environmental and ecological resilience. This requires the revision of urban master plans and development schemes, the enforcement of land regulation mechanisms that are inclusive and adaptive, and the implementation of both preventive and incentive-based instruments. Rational land use should be redefined not merely as a technical constraint but as a transformative strategic enabler capable of triggering positive feedback across the urban system.

(2) *Operationalising a Triptych of Strategic Action: Accessibility and Mobility, Access to Health Services, and Entrepreneurial Dynamics*: The systemic interdependencies among accessibility and mobility, access to health services, and entrepreneurial dynamics constitute a transformative triptych for sustainable urban development. These domains are not only mutually reinforcing but also pivotal in shaping inclusive and resilient urban systems. Accordingly, urban policies must be strategically designed to harness cross-sectoral synergies. For instance, enhancing accessibility and mobility through sustainable transport strategies can stimulate entrepreneurial activity by improving access to markets and employment opportunities, while simultaneously fostering urban health by reducing environmental burdens and facilitating access to care. This integrated approach provides a framework for advancing social equity, economic vitality, and public well-being in tandem.

(3) *Institutionalizing the Preservation of natural ressources and Urban Green Infrastructure as a Pillar of Resilience:* The intersectoral influence of Preservation of natural ressources and Urban Vegetation Density highlights its potential as a key structuring component of urban ecosystems, with implications including public health, flood mitigation, cultural preservation, and waste management. Urban municipalities must integrate ecological infrastructures within formal planning instruments and regulatory frameworks. Incentive mechanisms should support the greening of both public and private spaces, while local knowledge systems related to landscape maintenance and biodiversity stewardship must be recognized. Urban nature should no longer be regarded merely as ornamental or residual, but rather as a central pillar of socio-spatial regeneration and climate adaptation.

(4) *Reframing Environmental Risk Governance as Public Health Infrastructure*: The systemic convergence between flood and solid waste management demands a paradigm shift in environmental governance. These functions should not be confined to technical departments, but rather integrated into

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the core of urban planning as key enablers of collective well-being. Intersectoral coordination platforms and inclusive participatory mechanisms are essential for institutionalizing a culture of environmental stewardship. Investment in these infrastructures should be seen not merely as reactive mitigation, but as a proactive strategy advancing environmental justice and long-term public health resilience.

(5) *Anchoring Sustainability Policies in Endogenous and Cultural Dynamics*: Although certain indicators—such as the use of local materials, the conservation of cultural heritage, or fluctuations in construction material prices—may exert limited quantitative influence, their qualitative significance is considerable. These elements constitute the cultural, symbolic, and material bedrock of sustainable urbanism in Sub-Saharan Africa. Public policy must institutionalise endogenous practices, vernacular knowledge systems, and informal production circuits—not as obstacles to modernity, but as essential resources for resilient innovation. Embracing hybrid urban modernities—rooted in cultural specificity yet oriented towards the future—enhances both the legitimacy and the effectiveness of urban governance.

6. Conclusions

This study employs the MICMAC method to analyse the influence and dependency relationships among twenty-four urban sustainability indicators. It also applies dynamic systems modelling—using Vensim software (v. 8.2.1)—to map their interrelationships, with the city of Moundou serving as the case study. Through an in-depth examination of indicators structured around five thematic dimensions—social, economic, environmental, cultural, and built environment—the research reveals contrasting urban dynamics, structural asymmetries, and strategic inflection points. These findings offer insights that are both context-specific and transferable to other secondary cities in Sub-Saharan Africa. The main results of this study are as follows.

6.1. Performance Analysis of Urban Sustainability Indicators

Performance analysis reveals that Moundou's urban system is characterised by deeply entrenched structural vulnerabilities. Despite some positive trends—particularly in the conservation of natural resources—most indicators, notably those related to access to water, sanitation, electricity, healthcare, and education, remain critically weak. This uneven progress underscores a misalignment between planning strategies and institutional frameworks. Furthermore, pronounced socio-spatial inequalities persist, especially in the distribution of basic services, while economic indicators—including employment and entrepreneurship—exhibit alarming stagnation. The underdevelopment of mobility infrastructure, compounded by inadequate flood management, highlights the fragility of the city's urban fabric in the face of rapid demographic growth and climate-related risks.

6.2. Key Insights From The Systemic Analysis

The systemic analysis of the model reveals strategic prominence of four indicators : rational land use, accessibility and mobility, Urban vegetation density, access to health services. These indicators emerge not only as central nodes within the broader system of interrelations but also as high-leverage entry points with the potential to catalyse cross-sectoral improvements. Rational land use, for example, enhances spatial efficiency and underpins territorial equity ; improved mobility fosters socio-economic inclusion and connects fragmented urban areas ; access to health services strengthens both individual well-being and collective resilience; and natural resource preservation safeguards ecological capital vital for long-term urban viability. These indicators are not isolated levers, but deeply embedded components of dynamic feedback loops. Their systemic position enables them to initiate cascading effects across multiple domains, reinforcing virtuous cycles that link environmental integrity, social equity, and economic productivity. Thus, they constitute priority targets for policy intervention, particularly in rapidly urbanising contexts where strategic governance is often constrained by limited resources

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6.3. Key Insights Derived from The Analysis of Systemic Feedback Loops

The systemic analysis reveals six major feedback mechanisms that structure the dynamics of urban sustainability:

The systemic analysis reveals six major feedback mechanisms that structure the dynamics of urban sustainability :

- *Spatial–functional loop*: Rational land use enhances mobility and access to education, thereby generating economic opportunities and reinforcing inclusive territorial development.
- *Ecological resilience loop*: Effective solid waste management mitigates flood risks and bolsters the ecological robustness of urban systems through the preservation of natural resources.
- *Civic cohesion loop*: Access to public and cultural spaces fosters identity, social interaction, and civic education, thereby strengthening social cohesion and cultural sustainability.
- *Regulatory–economic loop*: Access to electricity stimulates entrepreneurship and employment, yet also contributes to housing pressure—necessitating robust land-use governance to prevent economic distortion.
- *Social inclusion loop*: Employment, health, education, and security interact in a virtuous cycle that promotes social equity, reduces vulnerability, and reinforces urban stability.
- *Health–productivity loop*: Sanitation infrastructure improves public health, which in turn enhances labour productivity, thereby reinforcing both healthcare systems and economic vitality.

Ultimately, this study contributes to narrowing the knowledge–action gap by offering actionable recommendations to policymakers, urban planners, and scholars dedicated to fostering more inclusive, resilient, and sustainable urban futures—both in Moundou and, more broadly, across Sub-Saharan Africa.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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