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Beyond Sustainability: Paradigms for Complexity and Resilience in the Built Environment

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Abstract: Conventional approaches in architecture and urban planning still rest on modernist, deterministic assumptions that downplay the nonlinearity and deep uncertainty that characterize contemporary cities. Sustainability, although crucial, has often been operationalized through incremental, efficiency-oriented checklists that struggle to address systemic transformation. This conceptual theory synthesis reframes the built environment as a complex adaptive system and interrogates three paradigms that have arisen in the wake of the sustainability turn: resilience planning, adaptive planning, and regenerative design. Drawing on an integrative, narrative review of interdisciplinary scholarship, the article maps these paradigms onto a functional "what–how–why" theoretical scaffold: resilience specifies what socio-technical capacities must be safeguarded or allowed to transform; adaptive planning sets out how planners can steer under conditions of deep uncertainty through sign-posted, flexible pathways; and regenerative design articulates why interventions should move beyond mitigation toward net-positive socio-ecological outcomes. This synthesis positions each paradigm along an uncertainty spectrum and identifies their complementary contributions.

Keywords: complex systems; urban resilience; adaptive planning; regenerative design; built environment; climate resilience; sustainable futures

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Academic Editor: Jianming Cai

Received: 8 May 2025
Revised: 4 June 2025
Accepted: 5 June 2025
Published: 8 June 2025

Citation: Mannucci, S. Beyond Sustainability: Paradigms for Complexity and Resilience in the Built Environment. *Urban Sci.* **2025**, *9*, 212. https://doi.org/10.3390/urbansci9060212

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1. Introduction

As the consequences of climate change become increasingly pronounced [1], cities are among the most vulnerable and crucial hotspots for transformative action. They face a confluence of unprecedented challenges. These include rising temperatures [2], sea-level rise [3], shifting rainfall patterns, socio-economic fluctuations, and deep uncertainty [4] stemming from the complex interplay of exogenous and endogenous factors, which cannot be addressed through assumptions of stationarity [5].

Climate change is intensifying both the frequency and severity of environmental stressors affecting cities. According to the IPCC Sixth Assessment Report [6], over 3.3 billion people live in contexts that are highly vulnerable to climate impacts. Urban areas are already experiencing more frequent and intense heat waves, floods, and infrastructure disruptions. For instance, economic losses from climate-related natural disasters have exceeded globally USD 320 billion in 2024 [7]. In Europe alone, hydrological events account for 28% of insured natural hazard losses, with single urban floods costing up to EUR 800 million (Copenhagen 2011) and damages projected to increase 3.7-fold by 2100 under RCP 8.5 if no extra measures are taken. Heatwaves already kill more Europeans than any other weather disaster (about 70,000 excess deaths in 2003) and, without adaptation, annual heat-related fatalities could climb up to 30,000 (1.5 °C) [8].

As Skrimizea et al. [9] point out, the Anthropocene era, defined by transformative changes in the Earth's ecosystems driven by human activities, significantly increases both complexity and uncertainty. These transformations are not just more pronounced but also inherently unpredictable due to their interconnected and evolving nature, demanding adaptive approaches rather than purely predictive or reactive ones.

The built environment, understood here as a complex adaptive system, is at the forefront of these Anthropocene challenges, as it integrates ecological, social, and economic dimensions that interact dynamically across multiple scales. Consequently, the planning debate has recognized the necessity to shift from traditional deterministic methodologies toward adaptive practices capable of navigating uncertainty and complexity [10–12].

However, the operative frameworks within architecture and urban planning often remain anchored in deterministic legacies, hindering the step forward from theory into practice. These assumptions were once aligned with a broader mechanistic worldview, where the built environment was conceptualized as stable, knowable, and optimizable through top-down interventions and formal design solutions. Adopting a technical-rational model, planners sought to promote societal progress by shaping a physical environment rooted in certainty. Embodying modernist, functionalist, and materialist ideologies, it peaked in the 20th century. The continued influence of this paradigm is visible not only in the physical fabric of urban forms but also in the instruments and procedures still widely used in design practice that remain grounded in notions of stationarity [13,14].

Failing to acknowledge the dynamic and evolving character of cities over time presents a critical limitation. This becomes especially evident when urban challenges are considered across longer temporal horizons, where traditional engineering approaches often fall short in addressing unpredictable and uncertain conditions that may compromise the effectiveness of planned interventions [15,16].

While sustainability, entering planning agendas in the late 1980s, did not arise directly as a critique of architectural determinism, it offered a holistic lens that emphasized environmental, social, and economic interdependences [17]. However, despite its transformative ambitions, sustainability efforts often remained embedded in predict-and-control logic, prioritizing mitigation over adaptation and resilience, and focusing on minimizing harm rather than fully addressing the complexity and deep uncertainty of urban systems [18,19].

Today, urban and architectural planners draw on three chief paradigms to cope with climate extremes—resilience planning [20], adaptive planning [21], and regenerative design [22]. While these paradigms hold great potential, they are often criticized as buzzwords [9,23,24]. Resilience highlights not just how cities withstand shocks but how they adapt, evolve, and potentially improve [25]. The adaptive planning paradigm places uncertainty at the core of the planning process, treating it not as an obstacle but as a catalyst for action. Rather than attempting to eliminate uncertainty, this approach embraces it as a dynamic element that informs and shapes planning decisions. On one hand, modeling and monitoring help reduce uncertainty by deepening scientific and professional insight into the system. On the other hand, uncertainty itself becomes a resource, guiding the development of adaptive hypotheses that inform and refine planning and monitoring efforts over time [26]. Regenerative development calls for the active renewal of ecosystems and social contexts, shifting the goal from "*do not harm*" to "*do good*", reframing the built environment in complexity science [27] as an open, adaptive system subject to nonlinearity, uncertainty, and emergent spatial and social patterns [28].

Positioned as a conceptual article [29], this article revisits the planning paradigms that underpin contemporary planning discourse, exploring how they differ, how they intersect, and how they build a solid theoretical core that planners can rely on to move beyond sustaining the status quo to embracing change, recovery, and proactive renewal.

In order to do so, this study first traces the historical trajectory from determinist modernism to sustainability, the initial disruptive idea that challenged a fuel-based mechanistic worldview. Using a literature overview works on resilience, adaptive planning, and regenerative design, with a "what–how–why" alignment that offers planners a theoretical core for future empirical testing for applicative planning efforts that embrace the complexity and resilience of the built environment. Three paradigms are presented to move beyond that limit, each filling a specific gap and presenting a theoretical scaffold that lays the ground for future empirical studies on planning for complex urban systems under uncertainty, moving beyond the current limitations.

Urban resilience provides the "what", maintaining core functions amid disturbance. Adaptive planning delivers the "how", reflecting iterative, sign-posted choices that remain robust across multiple futures. Regenerative design supplies the "why", turning unavoidable change into net-positive socio-ecological evolution. Additionally, this article provides a conceptual bridge between the planning practice that evolved from the deterministic perspective and methods to support decision-makers in designing plans for complex, uncertain systems that can be adapted over time, setting the stage to move from theory to practice.

The manuscript is organized accordingly: Section 2 provides the theoretical framework to carry out this study; Section 3 retraces the road from determinism to sustainability; Section 4 reframes cities as complex adaptive systems, introduces the uncertainty spectrum, and analyses resilience (what), adaptive planning (how) and regeneration (why); Section 5 discusses the conceptual theory synthesis; and Section 6 highlights the future directions and the limitations of this work.

2. Theoretical Framework of the Study

This study is structured according to Jaakkola's conceptual theory synthesis [29] to integrate current understanding across multiple theoretical perspectives relevant to the built environment's resilience and adaptive transformation. A conceptual theory synthesis article utilizes broad narrative reasoning to highlight overarching patterns and relationships. In this study, the literature analysis is an instrument, not an end. While the line between a review and a theory synthesis can be thin, as Jaakkola highlights, the literature overview is used to build up a coherent narrative according to the theoretical scaffold the authors present. The aim is to integrate an extensive set of theories and phenomena from different theoretical perspectives.

As proposed by Jaakkola, the conceptual integration across multiple theoretical standpoints can be articulated into three points as follows:

1. Starting point;
2. Choice of domain;
3. Choice of theory for organizing the key aspects of the selected domain(s).

For this study, the starting point (1) is the recognition that planning and designing the built environment in the face of climate extremes, socio-ecological disruption, and deep uncertainty requires moving beyond the traditional sustainability paradigm. However, it is indeed the first paradigm that provides a holistic view that recognizes multiple factors influencing each other. This manuscript begins by identifying the limits of modernist approaches, particularly their reliance on predict-and-control rationalities that prove insufficient [14]. This motivates the need for an alternative conceptual basis to integrate complexity thinking with planning theory. The choice of domain (2) is planning the built environment under uncertain and dynamic conditions. This synthesis draws on literature that treats cities as complex adaptive systems and already influences architectural or urban planning practice. Three streams satisfy those criteria: urban resilience, adaptive planning,

and regenerative design thinking. As for the choice of organizing theory and the key aspects of the selected domains (3), the integration rests on the two lenses shown in Table 1.

Table 1. Key aspects of the selected domains.

Lens	Rationale in this Study
The built environment as a complex adaptive system	This study reframes the built environment as a complex adaptive system, showing where deterministic planning models fall short. It traces the evolution of planning paradigms, beginning with sustainability, the first to challenge modernist determinism by introducing a holistic, long-term socio-environmental-economic perspective, while demonstrating why new approaches are needed to cope with nonlinearity and deep uncertainty.
"What–how–why" functional spine	Urban resilience specifies what must be safeguarded (core socio-technical functions). Adaptive planning explains how those functions can remain robust or be adjusted under changing conditions. Regenerative design articulates why change should lead to net-positive outcomes.

Literature Search and Selection Methodology

As previously discussed, theory synthesis papers aim to link previously unconnected theories and identify the "*big picture*". In Jaakkola's terms [29], a theory synthesis review "*unravel[s] the components of a concept or phenomenon*" and deliberately focuses on conceptual commonalities (even excluding elements that are incommensurable). Furthermore, conceptual theory synthesis papers must be grounded in a clear research design, with explicit justification of theory and source selection (as discussed in the previous subsection). For this study, that means focusing on pre-defining the scope and then purposely selecting sources that contribute meaningfully to the point made in the study.

For this reason, a narrative review was adopted for the literature selection [30]. As Sukhera highlights [31], a narrative review allows researchers to both outline what is already known and add their critical reading of the literature. It positions the field as it currently stands, suggests where it might go next, and spotlights fresh ideas or angles that standard summaries miss. Because of this, this approach works for topics that are still thinly studied as well as for areas crowded with research that need a new perspective. There is no fixed structure for a narrative review as it serves the purpose of the study, and while this flexibility is particularly useful for the scope of this study, it is limited by the exclusion criteria in the literature. To build up this narrative review, following the three steps of the conceptual article discussed in the previous section, works and recent studies in each paradigm were identified through a combination of database searching (Scopus, Google Scholar), and snowballing for the identification of more studies, once a relevant source was found.

3. From Modernism to Sustainability: A Historical Trajectory

To understand the conceptual need for alternative planning paradigms, it is crucial to revisit the intellectual trajectory that brought sustainability into planning discourse. This section traces the evolution from modernist determinism to sustainability, examining how their embedded assumptions still shape contemporary planning approaches. While sustainability introduced a holistic and long-term perspective, it remains entangled in predict-and-control thinking, limiting its capacity to engage with the uncertainty, complexity, and nonlinearity that characterize today's urban challenges [32].

3.1. Modernism, Determinism, and the Birth of Sustainability

Although the sustainability paradigm formally emerged in the late 20th century in response to escalating environmental degradation, its conceptual foundations were seeded earlier, developing alongside critiques of modernist planning, architectural determinism, and the socio-environmental consequences of industrial urbanization [33]. Understanding this evolution requires first revisiting the cultural and ideological context that shaped planning practices in the post-war era.

As Vandevyvere and Heynen discuss [34], modernist thought was closely linked to the rise of fossil fuel technologies [35]. Post-WWII planning led to extensive suburban expansion and large-scale reconstruction projects [36]. This period was marked by rapid reconstruction driven primarily by modernist planning philosophies that prioritized efficiency and functionality. Although these redevelopment initiatives profoundly reshaped cities, they sometimes produced adverse outcomes, fragmenting the urban fabric and undermining social cohesion and environmental integrity. Planning strategies during this era heavily emphasized rapid alterations in land use, urban densification, and a reliance on car-oriented infrastructure [37]. Rooted in the principles of certainty, this paradigm aimed to contribute to social advancement through a top-down approach that left no room for failure or flexibility [38].

The pursuit of planning as a technical exercise was not only a reaction to post-war urgency but also a broader aspiration to emulate the determinism and objectivity of Newtonian physics [39]. However, the technical-rational mindset promoted by modern architecture provided only a narrow perspective on the complex and layered realities of urban environments. Sustainability first surfaced as a counter-reaction to the environmental damage and social rigidities left by industrial modernism and top-down planning. Those early critiques set the stage for the more explicit green politics and policy debates that gathered pace during the environmental protests of the 1960s and 1970s.

3.2. Sustainability and Its Limits

During the second half of the 20th century, planning was re-examined as the environmental movement gathered strength and sustainability gained international prominence. The 1972 Stockholm Declaration [40] was the first multilateral accord to couple environmental safeguards with economic development, a linkage later reinforced by the Brundtland Commission's report, Our Common Future (1987) [17], which defined sustainable development as meeting present needs without limiting the options of future generations. In practical terms, planners began to target lower carbon emissions, greater energy and resource efficiency, expanded green infrastructure, and stronger commitments to social inclusion and urban equity [41]. The underlying intent was to harmonize three core dimensions: environmental protection, economic viability, and social well-being; often depicted as the three integrative "pillars" of sustainability [42]. This framework helped bring long-term thinking and systems awareness into planning practices [43].

However, in the 1990s, sustainability shifted from a largely conceptual ideal to a driver of policy and day-to-day practice. Publication of the IPCC's first assessment report in 1990 [43] underscored the magnitude of global climate risks and the costs of inaction, prompting calls for a truly interdisciplinary approach to sustainability [32].

Sustainability has often been characterized as a boundary object, a concept that enables coordination across disciplines and stakeholder groups despite holding different meanings in different contexts [44]. Its ability to unite diverse agendas has made it powerful, but also semantically diffuse. This conceptual flexibility, on the one hand, is useful for building a common semantic across different fields; on the other hand, it has also enabled the depoliticization of sustainability goals and the dilution of their transformative potential [45].

Early sustainability frameworks assumed that continued economic growth would provide the means to solve ecological and social problems [46]. In practice, many sustainability initiatives focused on incremental mitigation of impacts, doing "*less bad*" [47]. As Reed [48] observed, sustainable design in the built environment had become "*primarily an exercise in efficiency*" aimed at reducing damage, whereas what is needed is a shift to "*participate with the environment*" in a way that creates positive ecological outcomes [49]. As humanity overshoots planetary boundaries [50], mere harm reduction may no longer suffice. Calls for restoration and regeneration gained traction by the mid-2010s [51]. The philosophical limitations of sustainability are closely tied to its modernist roots. Classic models operate within a mechanistic worldview [52], conceptualizing the environment as a set of discrete parts to be managed through technical optimization. Yet contemporary challenges reveal that cities are open, dynamic, and deeply embedded in planetary systems. Scholars argue that sustainability's limitations stem from this inadequate epistemological foundation [48].

Despite its widespread adoption in development and planning frameworks such as the Sustainable Development Goals (SDGs) [53] or the New European Bauhaus [54], the practical application of sustainability in urban planning reveals significant limitations. Gibson [55] emphasizes that sustainability assessments often become procedural checklists, constrained by data availability and institutional inertia. Rather than catalyzing transformation, they reinforce status quo practices. This requires clear criteria, explicit trade-off rules, and robust, context-sensitive processes. However, as Gibson [55] points out, the dominant "*three pillars*" model can obscure the systemic and cross-dimensional nature of urban problems, reducing sustainability to a checklist of sectoral goals and benchmark indicators.

In response, scholars and practitioners have emphasized the need to reframe sustainability as a principle-based, adaptive process that accommodates uncertainty, invites participation, and aligns with the systemic nature of urban change [56]. This implies that the pursuit of sustainability cannot remain locked within predictive or efficiency-oriented paradigms. It must be embedded in planning approaches that are dynamic, reflexive, and oriented toward transformation rather than preservation. There is no unified agreement within urban planning on what constitutes a truly sustainable built environment. The concept of sustainability in this context is interpreted in various ways: it may refer to the resilience and vitality of the city as a complex system, the overall well-being of its residents, or the ecological capacity to support urban life. For some, sustainability is primarily understood in economic terms—as the city's ability to reach a qualitatively enhanced stage of socio-economic, demographic, and technological development that reinforces the stability of its urban system over time. Others take a more expansive view, framing sustainability around intergenerational justice, social equity, and participatory governance [57].

While sustainability remains a vital normative reference, its capacity to respond to today's challenges depends on complementing it with paradigms that fully engage complexity. Resilience, adaptation, and regeneration offer conceptual and operational avenues to address sustainability's blind spots. Before these can be unpacked, however, it is necessary to reframe cities not as static systems to be optimized, but as complex, adaptive environments.

4. Embracing Complexity: The Built Environment as an Adaptive System

By the late 20th century, the built environment was reframed through the lens of complexity theory [58]. Accelerating global change prompted scholars to revisit the epistemological foundations of planning and to explore approaches informed by the dynamic, nonlinear nature of the built environment. As Partanen [59] notes, socio-economic shifts and the fragmentation of urban form significantly exposed the limitations of rationalist models

that had relied on predictability and hierarchical control. The rise of post-Fordist dynamics in the 1970s, marked by globalization, regional competition, and constant economic flux, reshaped cities into discontinuous territories held together more by infrastructure than by coherent planning [60]. These shifts undermined the validity of top-down approaches and helped usher in a broader epistemological transition in planning. Jane Jacobs had already anticipated this in 1961, describing cities as "*problems of organized complexity*", composed of interrelated factors forming an organic whole [61,62].

Within this context, complexity theory provided a new conceptual framework that acknowledged the limitations inherent in traditional planning methods. This thinking positions cities as dynamic, nonlinear systems characterized by emergent behaviors, unpredictability, and continuous change. As such, the built environment can no longer be effectively managed through traditional deterministic or reductionist methodologies that assume linear causality or stable equilibria [63,64]. Instead, complexity theory highlights the significance of self-organization, wherein coherent patterns and structures spontaneously emerge from decentralized interactions among numerous individual actors, each making decisions based on partial knowledge and localized incentives. This self-organizing principle fundamentally challenges the assumption of centralized planning control, suggesting planners adopt the roles of enablers or facilitators rather than absolute controllers [65]. This underscores the importance of understanding cities as interconnected networks operating across multiple scales, where local actions can have profound, often unpredictable impacts at broader systemic levels [66]. The issue of scale is central to the analysis of complex systems, particularly given the difficulty of defining clear system boundaries.

As Partanen observes [59], in a universe where absolute limits are largely absent, the challenge lies in generating knowledge across different scales when the notion of a delineated "system" becomes ambiguous. Nevertheless, it is possible to observe relatively persistent and stable configurations within this flux. These emergent patterns can be approached analytically as if they possess a provisional or functional existence—what Richardson [67] refers to as "*limited existence*". In practice, some degree of reductionism, temporarily bracketing a system from its broader context, is often necessary to render research feasible. Such provisional framing allows scholars to describe and analyze a subsystem while still acknowledging its embeddedness in wider networks.

Moreover, adopting complexity theory involves transitioning from traditional positivist methodologies towards reflective, post-positivist approaches. This means acknowledging reality as inherently uncertain and probabilistic, necessitating continuous epistemological reflection transitioning from static frameworks to dynamic, adaptive methods capable of continuously responding to emergent conditions and evolving patterns. Complexity theory acts as a bridge between quantitative methodologies prevalent in natural sciences and systemic, dynamic approaches typical in social sciences. By the late 20th century, these ideas were reinforced by the rise of the "*wicked problems*" concept, introduced by Rittel and Webber [68].

The rise of wicked problem awareness further underscored the need for more flexible, iterative planning, acknowledging that scientific and technocratic approaches alone are insufficient for addressing complex planning issues, primarily because of the inherent uncertainty, complexity, and value divergence these issues entail. They are not merely complicated; their wickedness lies precisely in the uncertainty around their definition, potential solutions, and the differing values and priorities among stakeholders. Indeed, Head [69] argues that it is precisely this uncertainty, regarding problem boundaries, future conditions, causal mechanisms, and stakeholder perspectives, that renders wicked problems resistant to traditional deterministic methods. Consequently, an explicit exploration of uncertainty is crucial.

4.1. Framing Uncertainties: Planning Under (Deep) Uncertainty

Given the inherent limits of prediction, it is impossible to state whether the future will be definitively certain or uncertain [70]. Building upon the concept of wicked problems, it becomes clear that their inherent complexity is intrinsically linked to different forms of uncertainty. While traditional planning methods rely on known variables that can be quantified and managed through statistical or probabilistic methods, wicked problems often involve uncertainties that surpass these capabilities.

Philosophers have wrestled for millennia with where our knowledge ends and ignorance begins, but the modern debate on this spectrum of (un)certainty is usually traced to Frank Knight's seminal 1921 essay. Knight drew a clear line between risk, situations where the odds can be estimated, and uncertainty, where they cannot [71]. Across different fields, scholars have developed numerous ways to describe and organize uncertainty. Risk analysts, for instance, routinely distinguish between aleatory and epistemic uncertainty: the former reflects the intrinsic randomness of the world or system being studied, whereas the latter reflects gaps in our data understanding. Other authors focus on *where* an unknown enters the picture. In contrast, still others concentrate on *how much* is unknown, arranging ignorance along a spectrum that runs from near-certainty to complete indeterminacy [72,73].

Kwakkel et al. [4] provide a straightforward classification of uncertainties. The authors define uncertainty as a multidimensional concept, where the dimensions are essential to determine how to cope with uncertainties. The dimensions are defined as location (e.g., context factors, parameters, inputs in a model), nature (e.g., epistemic, stochastic), and level, ranging from determinism to total ignorance.

All dimensions are crucial, but understanding the levels of uncertainty can be extremely important for planners to choose adequate planning approaches and tools and the boundaries they want to set for the analyses.

The levels are divided into: Level 1 ("shallow"), where uncertainty applies when probabilities can be attached to each outcome. Level 2 ("intermediate") uncertainty arises when the set of possibilities is known and can even be rank-ordered by plausibility, but the numerical distance between them cannot be stated. Level 3 ("deep") uncertainty still allows us to list candidate futures, yet disagreement or ignorance prevents any ordering at all. Level 4 ("recognized ignorance") is the most intractable: we cannot even enumerate the possibilities, although we remain aware that surprises are always possible. Figure 1 synthesizes these four levels, the associated system types, and the planning paradigms that best cope with each uncertainty level.

The built environment, understood as a complex and adaptive system, inherently embeds deep uncertainty. Roggema and Chamski highlight [74] that urban professionals are increasingly confronted with complexities and uncertainties that demand not only technical expertise but also new skills. Traditional prediction-based models struggle in this context, and there is a growing recognition that new approaches, capable of embracing systemic flux, are essential. In this emerging era, where climate change, biodiversity loss, social unrest, and resource scarcity intersect, planners can no longer rely solely on fixed strategies or linear projections. Instead, they must prepare for a dynamic environment where scenarios unfold unpredictably.

De Roo emphasizes that conventional planning approaches, often grounded in technical rationality, are insufficient for addressing the spontaneous and autonomous changes that increasingly characterize urban systems [26]. Contemporary planning requires a spectrum of rationalities, spanning from technical to communicative, depending on the degree of uncertainty planners are facing. As illustrated in Figure 2, this spectrum tracks the move from predictive and scenario-based methods in feedback systems to collaborative approaches in

open network settings, and finally to adaptive, monitor-and-adjust logics in complex adaptive systems. Under conditions of low uncertainty, traditional goal-oriented, control-based planning remains effective; however, in situations marked by high uncertainty, planners must shift toward more adaptive and learning-based strategies [26].

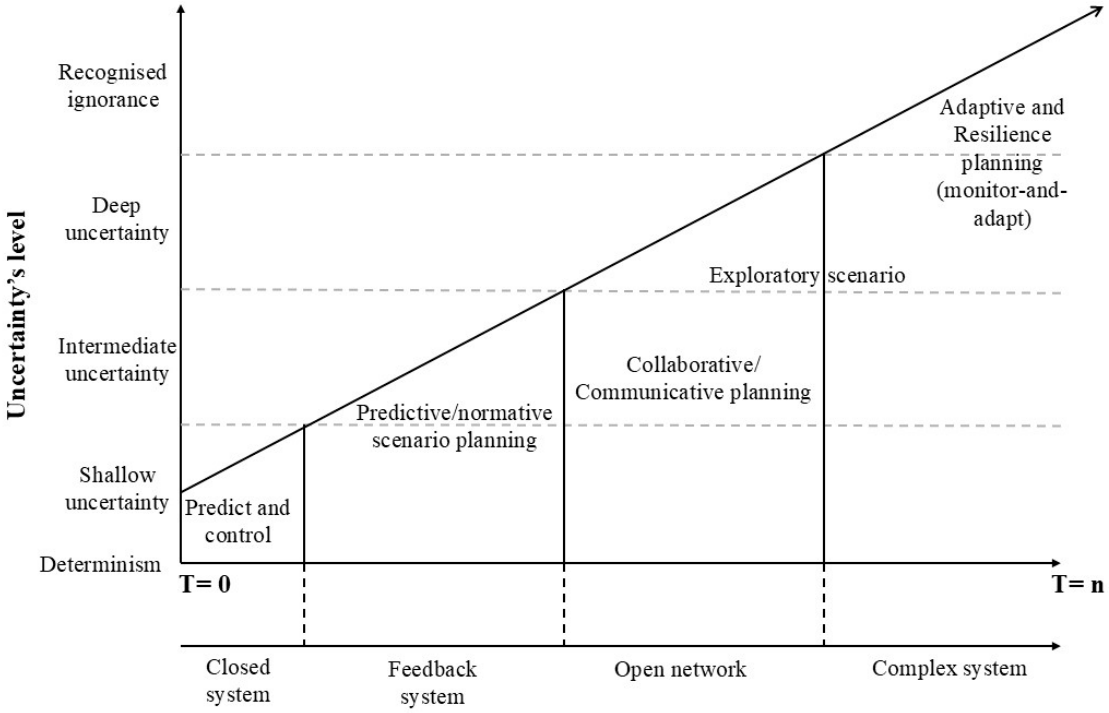

Figure 1. Uncertainty levels, system categories, and planning approaches. The vertical axis adopts Walker et al.'s [72] and Kwakkel et al.'s [4] four-level scale (determinism → recognized ignorance). The horizontal slices follow De Roo's system: typology-closed, feedback, open network, complex adaptive. Planning paradigms shift accordingly: predict-and-control in deterministic settings; predictive/normative scenario planning in feedback systems; collaborative/communicative approaches in open networks; and adaptive and resilience planning (monitor-and-adapt) under deep uncertainty and recognized ignorance. Adapted from Walker et al. [72]; De Roo [39]; Kwakkel et al. [4].

In this regard, De Roo [75] proposes the "*spectrum language*", which frames planning rationalities along a continuum, from factual realities, where technical rationality and predictability prevail, to agreed realities, where uncertainty demands collective sense-making and adaptive behavior. Recognizing that deep uncertainty challenges not only what we know (epistemology) but also how we act (axiology), planning practices must embrace flexibility, experimentation, and responsiveness rather than seek static solutions. Building on this perspective, Rauws [76] proposes adaptive planning as an approach that does not abandon planning altogether but reshapes it to strengthen the conditions under which urban transformations can unfold. Adaptive planning prioritizes influencing the "*possibility spaces*" for urban development rather than prescribing outcomes, thus accepting uncertainty as a fundamental operational context rather than treating it as a problem to be eliminated. This implies that planners must increasingly accept uncertainty as a fundamental condition rather than an obstacle to be eliminated. Adaptive planning thus emerges as an essential approach, encouraging decentralized, bottom-up experimentation, iterative learning processes, and pluralistic strategies rather than rigid master plans. Furthermore, knowing how to act under uncertainty requires acknowledging the limitations of prediction and embracing a relational understanding of the built environment. To operationalize complexity theory within planning practice, recent frameworks such as resilience and adaptive

theories have emerged, offering methodologies to assess and enhance the capacities of urban systems to cope with unexpected events.

4.2. Modeling Complex Adaptive Urban Systems

Modeling plays a central role in planning for the built environment. As Soulikias et al. highlighted in their study [77], digital tools became fundamental. Tracing back architecture's embrace of digital technology in the 1960s, the idea was likened to the Industrial Revolution, which likewise sped up production. While the first digital tools mimicked the design process that was originally conceptualized, relying on sheets and pencils, from the 1990s onward, digital tools fundamentally reoriented the design process. Nowadays, contemporary workflows routinely combine performance simulation, evolutionary optimization, and computer-controlled fabrication, generating novel design strategies that evolved from being an aid to documentation into a generative framework that reshapes how architectural problems are conceived and solved [78].

However, the aim is not to propose a state-of-the-art modeling technique for the built environment, but to provide a perspective behind the logic that is currently influencing how the models are conceived. All models of complex adaptive urban systems are necessarily approximations and have clear limits. As previously said, by definition, complex systems exhibit emergent and unpredictable behavior, as well as distributed tacit knowledge, making them difficult to capture in any single formal representation. Even if the simulation models of the built environment are increasingly accurate and dynamic, there are some fundamental aspects to account for. Whether the model is used to propose an optimized solution for climate change, or a digital replica to aid the analyses behind the design phase, computational thinking renders a complex design problem into disconnected smaller parts; disregarding the evolution of the planning paradigms that advocate for holistic perspectives accounting for the different dimensions that characterize urban systems [77].

From this perspective, a recent work by Moroni [79] regarding digital twins [80] for cities is noteworthy. Moroni argues that digital twins and similar models can be useful for urban problems that are "*simple*" (systems characterized by a very small set of components linked through equally few, transparent relationships [79]) or '*complicated*' (systems that contain a larger number of interdependent parts, yet they remain oriented toward an overarching purpose that can be stated unambiguously or arranged hierarchically [79]). However, digital twins face "*structural limitations*" in complex contexts. In particular, emergent phenomena and "*dispersed knowledge*" in cities cannot be fully centralized or encoded in a model. This means that models will inevitably simplify or omit many dynamics. This logic reconnects with what is proposed in Figure 2; the more the complexity increases, the more planners need to deal with deep uncertainty and rely on models that are not a single snapshot of a preferred state. This means that a model may fix a particular configuration, freezing out the very emergent or temporal processes that may be crucial to a city's evolution. Even dynamic digital twins, which aim to update in real time, typically focus on quantifiable physical processes and may overlook the evolving social "place" of a city. For instance, Qanazi et al. [81] observe that current urban digital twins focus largely on the physical aspects of "spaces" and tend to overlook the interwoven social dimensions, introducing a transformative concept for integrating social dimensions into urban digital twins. However, they highlight a fundamental gap concerning the temporal reach of social-behavior forecasts. Existing models rarely retain explanatory or predictive power beyond a modest horizon of a few days, sharply constraining the strategic usefulness of those tools for medium- and long-term planning. On the same stream of thought, Hazbei and Cucuzzella [82] note that while physical and environmental factors are often easily

included, the "cultural, historical, social, economic, and political" context is often left out because it is difficult to quantify.

Batty's recent reassessment of digital-twin practice reaches a similar conclusion [83]. While acknowledging that advances in big data and GPU-level computation have largely overcome the sparse data and limited computational power that have hindered the earliest digital-twin implementations, Batty stresses that problems of theory remain and urban systems remain plagued by intrinsic unpredictability. Consequently, he argues that the very notion of a single, all-encompassing twin must give way to "*an ecology or federation of twins. . .[where] no single twin can be considered as best*".

Furthermore, both architectural and urban planning models leave very little room for uncertainty; when uncertainty is addressed at all, it is typically reduced to parameter or data error [84–86].

In planning domains that demand long-term foresight, such as water-resource management, climate adaptation, and regional mobility, planners increasingly turn to Decision Making Under Deep Uncertainty (DMDU) frameworks [87]. Within these frameworks, models are re-purposed from point-forecasting devices into exploratory engines: they map diverse sets of assumptions to their corresponding outcomes and *stress-test* candidate strategies over thousands of plausible futures. Approaches such as Robust Decision Making [88] view planning as an iterative cycle in which strategies are repeatedly exposed to large ensembles of scenarios, vulnerabilities are diagnosed, and designs are revised until they perform satisfactorily across the widest feasible uncertainty set. Because the exercise makes the conditions of failure and success explicit, it allows decision-makers to select robust rather than optimal strategies and build in monitoring triggers for subsequent adaptation. In this way, models become facilitators of deliberation and learning, rendering deep uncertainty both visible and manageable instead of relying on a single best estimate or limited scenarios describing the best or the worst outcomes given the assumptions made. However, the form and purpose of any model depend heavily on its underlying assumptions and paradigm. Models developed under DMDU approaches are built to stress-test policies across a wide scenario space, whereas models arising from architectural or urban planning paradigms often reflect a fixed design agenda or quantifiable performance criteria.

In complex adaptive urban systems, a model's principal merit is not a long-range prediction but the disciplined exploration of what-ifs. For a complex system such as the built environment, any single representation, however data-rich, can capture only a fraction of the dispersed knowledge and emergent dynamics that shape cities. Treating models as provisional heuristics, planners can expose vulnerabilities, chart the bounds of plausibility, and stress-test strategies across wide scenario sets, a practice already formalized within DMDU methods. Yet exploration alone is insufficient; analytic insights must be embedded in governance arrangements that keep plans revisable. Batty's call for an "ecology of twins" and Moroni's warning about structural limits converge on the same prescription: combine multiple partial models with monitor-and-adjust procedures that privilege robustness over optimization. The next three subsections examine how the paradigms of resilience (what), adaptive planning (how), and regenerative design (why) operationalize this shift from prediction to adaptive stewardship.

4.3. Resilience Planning

The term *resilience* first appeared in a technical sense in Francis Bacon's writings of the early 17th century [89]. Since then, and especially after its formalization in ecology and systems theory, it has become central to urban research. Holling's landmark paper (1973) [90] defined ecological resilience as a system's ability to absorb disturbance, reorganize, and continue performing its essential functions. The IPCC later broadened the

idea, describing resilience as "*the ability of a social, ecological, or socio-ecological system and its components to anticipate, reduce, accommodate, or recover from the effects of a hazardous event or trend in a timely and efficient manner*" [91]. In the urban field, this definition is often cited because it stresses not only speedy recovery (damage resistance) but also risk anticipation and proactive adjustment.

Urban resilience thinking has evolved through several stages and interpretations [92–95]. Early applications in engineering and disaster management focused on engineering resilience, essentially measuring how quickly a system could rebound to its prior state after a disturbance. The emphasis was on robustness and rapid recovery; for example, how soon critical services can be restored after an earthquake.

In the 2000s, the dialogue expanded to ecological resilience, which recognizes multiple possible stable states and the potential for systems to undergo nonlinear transformations [96,97]. This perspective redirected attention toward thresholds and tipping points [88]. On that basis, scholars advanced the concept of social–ecological resilience, which interweaves human and natural subsystems. The resulting framework highlights adaptive cycles, self-organization, and learning, and shows that urban resilience relies as much on social networks, governance, and shared knowledge as on physical infrastructure. A comparative synthesis of engineering and ecological resilience is provided in Table 2.

Table 2. Synthesis of engineering and ecological resilience from [98–102].

Dimension	Engineering Resilience	Ecological Resilience
Definition of resilience	System's ability to resist disturbance and rapidly return to a pre-disturbance equilibrium or desired function. Emphasizes constancy, predictability, and "bounce-back" of the system.	Capacity of a system to absorb disturbances and reorganize while retaining core functions and structure. Emphasizes persistence and adaptability: the magnitude of disturbance tolerated before shifting to an alternate regime.
System assumptions	Assumes operation near a single stable equilibrium with linear responses; variability is minimized and disturbances are treated as small perturbations around a known steady state.	Assumes complex nonlinear dynamics with multiple potential equilibria and feedbacks. Systems are inherently dynamic and uncertain with interactions across scales.
Recovery or transformation model	Emphasizes rapid recovery to the original state. Resilience is measured by the time or rate of return to baseline performance. Strategies focus on robustness and redundancy so the system "bounces back" to its previous configuration.	Emphasizes adaptation and reorganization. The system may transform into a new configuration after disturbance. Resilience is the capacity to absorb disturbance and reorganize under change so as to retain core identity and function.
Preferred system state	Prefers a single optimal or designed state (steady equilibrium) where efficiency and performance are maximized. Departures from this state are considered failures to be corrected to restore the system.	Does not assume one preferred state; multiple viable states are recognized. Focus is on maintaining key functions and diversity of options across regimes. Systems may cycle through successional stages.
Treatment of thresholds and nonlinearity	Generally assumes linear behavior and does not emphasize critical thresholds; analysis operates within a known stability domain around equilibrium.	Explicitly recognizes nonlinear dynamics and threshold effects. Resilience is defined by the distance to critical thresholds (the maximum perturbation absorbed before a regime shift). Crossing a threshold leads to a qualitatively different state.
Measurement criteria	Quantified by engineering performance metrics (time-to-recover, reliability, redundancy, etc.).	Quantified by system-level indicators: resistance to perturbation, distance to threshold, and adaptive capacity. Requires defining "resilience of what to what".

As emerges from the synthesis, two powerful metaphors dominate debates on urban resilience. The first—bouncing back—emphasizes rapid recovery to a previous, presumed-desirable state. The second—bouncing forward—treats disturbance as an opening for innovation and transformation (Figure 2).

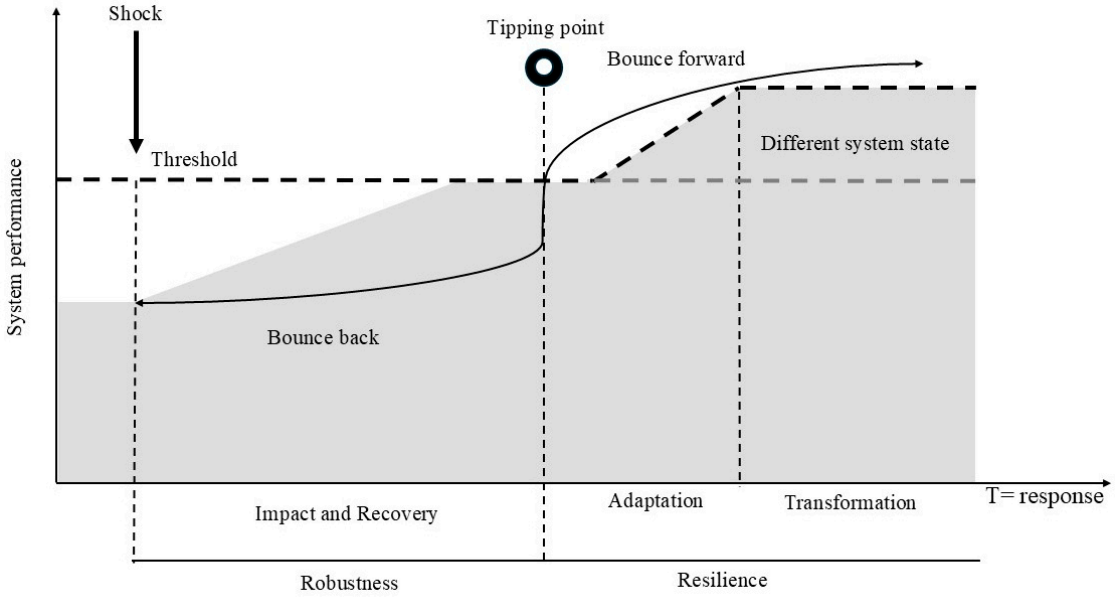

Figure 2. Resilience trajectory. A disturbance lowers system performance; robustness restores the baseline (bounce-back). At the tipping point, adaptive and then transformational resilience propel a bounce-forward to a higher, new system state. The gray area represents the system's state. Author's interpretation from [103].

As Chelleri and Baravikova observe, contemporary urban resilience scholars increasingly lean toward the latter, weaving sustainability concerns into disaster risk practices and urban planning [104]. Yet the literature shows that definitions still oscillate between persistence, incremental change, and radical transformation; many treat all three as valid pathways, while others privilege only one. The very plasticity that allows resilience to operate as a "*boundary object*", bridging engineering, ecology, and governance, also fuels criticism that the term has become semantically overloaded and risks policy vagueness.

Walker [105] states that true resilience is not about returning unchanged, but about adapting, reorganizing, and learning so that future shocks are less damaging. This is where confusion with robustness arises.

In systems theory, robustness describes the designed ability to remain within performance bounds despite uncertainty, what engineers call fail-safe design [106]. According to Walker, resilience, by contrast, assumes that some thresholds will be exceeded; the goal is to fail safely by redirecting, absorbing, or transforming when needed. Anderies et al., therefore, cast robustness as a property of designed subsystems and resilience as an emergent, system-level capacity to navigate change [107].

Furthermore, scientists caution that resilience is not automatically benign [105]. Long-lived poverty traps, authoritarian regimes, or carbon-intensive economies can be extremely resilient by engineering standards, yet profoundly undesirable, or even the self-adaptation, if not guided, is not necessarily good or reduces vulnerability [23].

Quantifying resilience remains methodologically demanding. Indexes proliferate, but no single metric spans persistence, adaptability, and transformability across ecological, social, and technical layers [101]. If resilience is to avoid the fate of an empty buzzword, it should be clear whose resilience is enhanced, to what risks, over what timescale, and at whose expense [108].

Against this backdrop, recent built-environment research frames resilience less as an endpoint and more as an ongoing negotiation between anticipation, absorption, recovery, and transformation. Design principles that emerge consistently include the following:

- Redundancy and Modularity: Systems benefit from redundancy, allowing for overlapping functions that ensure continuity even as certain components fail. Modularity enhances this by preventing cascading failures across interconnected systems [107].
- Flexibility: Adaptability requires flexible infrastructures that can accommodate diverse future uses, thereby reducing vulnerability to unforeseen risks [23].
- Robust Feedback Mechanisms: Real-time monitoring and responsive feedback loops allow systems to adjust rapidly and effectively under stress or disturbance, which is crucial for adaptive management [109].
- Distributed Governance and Participation: Decision-making processes that involve stakeholders across different scales help to ensure that resilience strategies reflect local needs and equitable resource distribution [108].
- Temporal and Spatial Scalability: Considering multiple temporal and spatial scales is essential, as resilience strategies effective at one scale can inadvertently compromise resilience at another. Planning must integrate immediate reactive capacities with long-term anticipatory measures [110].
- Cultural and Institutional Capacities: Recognizing and enhancing cultural and institutional knowledge is vital. Historical adaptation strategies and institutional memory often provide insights crucial for contemporary resilience planning [23].

Therefore, resilience in the built environment is increasingly viewed as a continuous adaptive cycle, involving iterative learning and adjustment. It is a negotiated balance, accommodating social, ecological, and technical dimensions, and consistently realigning design practices to anticipate change, rather than merely respond to it [111].

These principles resonate strongly with adaptive planning logic. Where adaptive planning offers iterative pathways, signposts, and real-option triggers, resilience thinking supplies a normative compass: keep system identity negotiable, preserve choice for future generations, and accept transformation when existing regimes undermine long-term viability. Robustness and resilience are thus complementary rather than competing goals. The planner's task is to decide where robustness (hard protection, redundancy) justifies its cost and where flexibility (managed retreat, socio-technical experimentation) better serves uncertain futures.

While resilience outlines what cities must achieve, adaptive planning explains how to do this when futures are unknowable.

4.4. Adaptive Planning

Adaptive planning has consolidated over the past years into the principal procedural response for cities conceived as complex adaptive systems operating under deep uncertainty. This planning paradigm does not belong to a single school of thought but has been shaped by multiple intellectual lineages that have converged in recent decades. Three major streams can be identified: adaptive management, adaptation pathways, and real options planning [21]. Adaptive management was one of the earliest influences, originating in ecological management in the 1970s [112] and later informing environmental planning [113]. Its core idea is "*learning by doing*" [114]: policies and plans are treated as experiments so that each intervention yields empirical information on the system's response. Rather than delaying action until certainty is achieved, adaptive management posits that uncertainty can only be reduced by intervention; consequently, actions ought to be designed to probe the system and reveal its dynamics. Over time, this lineage has brought into planning the notion of iterative, cyclical planning (plan–act–monitor–adjust) and highlighted the importance of

institutional learning and flexible governance. Case studies in urban water governance and climate adaptation planning show that this approach can convert uncertainty from a liability into a learning opportunity for future change [115].

Parallel to the development of adaptive management, a second lineage emerged from the policy analysis and engineering communities to tackle deep uncertainty in long-term planning [116].

The Pathways scholarship, under the umbrella of Decision-Making Under Deep Uncertainty (DMDU) [117], has produced methodologies such as Adaptive Policymaking [118] and Dynamic Adaptive Policy Pathways (DAPP) [119]. Building on early methods such as Dewar's assumption-based planning [120], which introduced the idea of identifying "signposts" [121] and devising contingency plans for when assumptions prove inadequate, DAPP formalized a stepwise approach to designing plans that can change over time. Planners applying this approach establish monitoring indicators and tipping points [122] that signal when the current strategy is likely to fail or when an opportunity for beneficial change arises. This condition-based planning ensures that actions are taken when needed rather than simply as scheduled, making flexibility operational, as plans adjust or evolve as new information emerges, or the system's behavior deviates from expectations.

Alongside flexibility lies the pursuit of robustness. Rather than optimizing for one forecast, an adaptive plan aims to remain viable under a wide range of scenarios A core technique in this regard is adaptive pathways mapping: planners chart a set of possible pathways (sequences of decisions) into the future, each path remaining viable up until an adaptation tipping point is reached, at which point a switch to an alternate path is created. These adaptation pathways, pioneered in climate adaptation planning, explicitly encode future decision points and alternatives, allowing a plan to branch into different courses depending on how uncertainties unfold.

By identifying tipping points (akin to signposts or trigger conditions) in advance, this approach makes flexibility concrete. In sum, adaptive planning replaces the static timelines of traditional plans with dynamic "if-then" decisions. It is forward-looking in considering many plausible futures, but also reactive in a controlled way, rather than ad-hoc improvisation (Figure 3). Nevertheless, even though this approach has been proven successful in many fields that require planning for the future, its application in the built environment remains in its infancy [123–125].

Real Options Analysis (ROA) [126] carries the ideas of financial options into project appraisal. Rather than treating an infrastructure scheme as a single, once-and-for-all commitment, ROA views each key decision as an option that can be taken, postponed, expanded, or abandoned as conditions unfold.

In practice, ROA augments a standard cost-benefit calculation by running many simulated futures and applying decision rules that trigger the option only when specified thresholds are reached. The premium required to embed such flexibility is then compared with a rigid baseline to judge whether the option pays off. Within the built environment, this logic underpins methods such as engineering options analysis and the broader flexibility-in-design approach, which test alternative layouts or phasing strategies across a range of probabilistic scenarios. As highlighted in [21], more recent research blends ROA with adaptive pathway planning [127]; Bayesian learning or stochastic dynamic programming updates probabilities over time, helping decide when to reinforce current flood defenses or when to shift to strategies such as managed retreat.

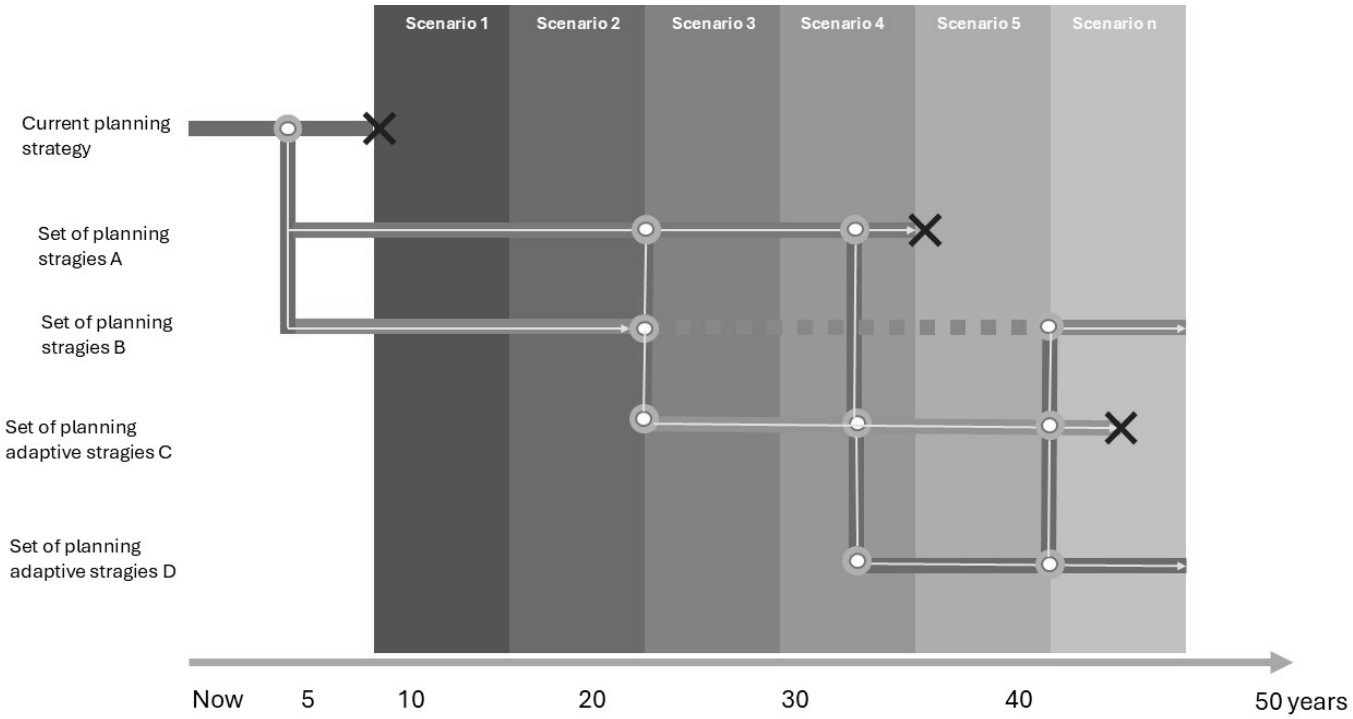

Figure 3. Illustrative Adaptive Pathways map. The horizontal axis shows a 50-year planning horizon divided into *n* exploratory scenarios (shaded bands). Solid lines depict candidate strategies; circles mark transfer points where a shift to an alternative strategy is feasible at low cost; crosses mark adaptation end-points, i.e., years in which a strategy no longer meets performance objectives in the given scenario. Current strategy reaches its endpoint after ≈ 8 years. Two robust follow-up options are available: Strategy A (upper branch) and Strategy B (middle branch). A remains viable in all scenarios except 3–5 and fails at year ≈ 35. B is viable across the whole time frame unless scenarios 3–5 materialize. If planners adopt A first, they can wait and see: when new information reveals whether scenarios 3–5 are developing, they may stay on A or shift laterally to B. Both A and B connect to an opportunity pathway C, which offers additional benefits but expires at year ≈ 45. Beyond that tipping point, a final adaptive option D provides robustness through to the end of the 50-year horizon.

Across these approaches, a common conceptual core is fixed. Planning now aims to keep multiple futures viable; decisions are explicitly provisional and will be revisited once monitored variables breach an agreed tipping point. Monitoring is therefore not an afterthought but a constitutive moment in the planning cycle, turning each step into a hypothesis test that refines both model and practice. In this conception, planning pivots from engineering fixed forms to facilitating knowledge flows and negotiating when thresholds for change are crossed. De Roo captures this shift by describing adaptive planning as "*acting in moments of uncertainty*", a situated, reflexive practice that couples stepwise experimentation with failure-driven learning to preserve the negotiability of urban trajectories [26].

Although adaptive planning offers structured methodologies to deal with uncertainty, it largely operates within formal planning processes and institutional frameworks.

However, as emphasized by recent studies [128], the capacity of urban systems to transform does not stem solely from intentional interventions but also from the spontaneous, decentralized initiatives of multiple urban actors.

These bottom-up dynamics, such as market shifts, community initiatives, social-media mobilization, and informal transformations, reflect what Cozzolino and Moroni define as self-adaptation [129]: endogenous processes of change that arise independently of formal plans yet remain conditioned by the surrounding institutional and property frameworks.

However, it is important to note that a city's propensity for self-adaptive transformation is not invariably beneficial; under certain conditions, it may produce maladaptive outcomes [130], for example, the expansion of informal settlements in vulnerable areas [131].

Adaptation shares conceptual roots with resilience and regenerative design, recognizing that systems must not merely resist disturbances but continuously adapt and evolve. A resilient urban system can change course when conditions demand, which is precisely what adaptive planning is designed to enable. Indeed, adaptive planning may be interpreted as strategic planning for resilience: it strives to avoid brittle solutions and instead favors approaches that can bend or bounce back, relying on robust measures, or moving forward by adjusting to novel conditions. The following subsection develops these connections in greater detail.

4.5. Regenerative Design: Catalyzing Net-Positive Change in the Built Environment

Regenerative design has emerged in recent decades as a paradigm that moves beyond conventional sustainability to actively catalyze net-positive outcomes in the built environment. Its conceptual roots can be traced back to ecological design pioneers such as Lyle [132], who proposed that buildings and cities could be developed in ways that regenerate degraded ecosystems rather than merely reducing harm [133]. Building on these foundations, a growing cohort of theorists in the 2000s began articulating the need to shift from sustainability to regeneration [22,48,134] in response to mounting evidence that incremental "*less bad*" approaches were insufficient to halt environmental decline and social inequities. In effect, this call for regeneration represented a paradigm shift, a move towards an ecological, systems-based mode of thinking that explicitly aimed for the positive evolution of socio-ecological systems rather than mere maintenance [24,135].

Sustainability practices often focused on minimizing negative impacts and meeting prescribed performance checklists and were seen as limited in the face of escalating ecological crises. Therefore, authors such as McDonough and Braungart [136] argued that being less bad is not good enough, calling for a more transformative eco-effective design approach that makes positive contributions to ecosystems and communities. Likewise, Birkeland [137] advanced a model of positive development, wherein new projects leave ecological and social conditions better than before rather than simply less damaged. Regenerative design arose from this critique, reframing the goal from sustaining the status quo to fundamentally improving it. Rather than simply slowing the rate of harm, regenerative projects aim to restore and even enhance ecological health, increase natural and social capital, and generate conditions in which human and natural systems can thrive together [138]. In other words, the ambition is to leave a place better than it was before development, an aspiration often summarized as a net-positive impact on the environment. This orientation underscores the normative distinctiveness of regenerative design, which deliberately frames development as an opportunity to improve socio-ecological health, rather than one that merely reduces damage [139]. In practice, this net-positive lens translates into tangible performance goals for regenerative projects. For example, Lyle's work [133] demonstrated that human settlements can be designed with circular resource flows so that a development produces more energy or water than it consumes, actively giving back to natural systems rather than merely drawing from them. Similarly, Robinson and Cole [140] conceptualize regenerative sustainability as a "net-positive" approach, positioning projects as contributors that accrue ecological and social value. Furthermore, regenerative design also prioritizes the recovery of ecological functions beyond pre-development baselines. Du Plessis [138] emphasizes active engagement with the living world to restore ecosystem health in tandem with development. Equally, the paradigm seeks to enhance social capital and community well-being; Mang and Reed [141] stress that regeneration requires cultivat-

ing a co-evolutionary relationship between people and place, which involves strengthening community networks, knowledge exchange, and long-term stewardship capacities. In a nutshell, regenerative initiatives create positive feedback loops whereby human actions continuously replenish and strengthen the ecosystems and communities they are part of, generating new potential for life and well-being [139].

In practical terms, adopting an ecological worldview means aligning human development activities with the fundamental processes of nature and acknowledging continuous change and uncertainty as normal conditions [142]. Such a worldview departs from the Cartesian separation of humans and nature, aligning instead with a holistic understanding of the Earth as a co-evolving web of life, essentially a systems view of life that highlights the profound interdependence between human and ecological processes [135].

In the built environment context, regenerative design translates this worldview into a set of practical principles and approaches. First, it emphasizes that people, their settlements, and their artifacts are part of ecosystems, deeply embedded in a particular place's ecology and culture rather than standing apart from "nature". Second, design interventions are conceived not as one-time technical fixes, but as catalysts for ongoing ecological and social vitality. A regenerative project is expected to contribute positively to the functioning and evolution of local ecosystems, for example, by enhancing biodiversity, restoring natural water cycles, improving soil health, or strengthening community cohesion, thereby enabling the self-healing processes of nature and society to flourish. Third, regenerative design is inherently place-based and context-specific [138,140].

This contrasts with conventional sustainable design, which often applies generic best practices; regenerative practice instead starts by listening to a place and its inhabitants to uncover what unique potential could be realized there. Finally, regenerative design is understood as an ongoing, participatory process rather than a finite product [138]. Development and design are viewed as continuous, reflective processes that actively involve stakeholders in co-design and long-term stewardship. The role of the designer or planner thus shifts from being an expert who delivers a static solution to being a facilitator of collaboration and a guardian of the project's core vision over time [141]. This process-oriented ethos acknowledges that achieving regenerative outcomes requires learning and adaptation well beyond the completion of construction, building capacity in the community to carry the work forward.

This redefinition of practice is grounded in a new epistemology: rather than presuming that planners can predict and control complex urban dynamics, regenerative design treats knowledge as provisional, evolving, and co-created through active engagement with place and community [24].

Regenerative design's relationship to concepts such as resilience and adaptive planning is one of both complementarity and progression. The regenerative design focuses on using disturbances or changes as opportunities to bounce forward, to transform systems into new configurations that are healthier and more beneficial than before.

In this way, regeneration adds a normative, aspirational dimension to the descriptive framework of resilience. The two paradigms in some aspects overlap (since a regenerative system must also be resilient to persist), but regeneration explicitly pursues qualitative improvement and evolution of the system, not merely the maintenance of function. Put simply, resilience offers a descriptive account of how systems respond to disturbance, whereas regeneration provides a normative agenda for how they should respond; that is, by actively improving ecological and social conditions through change [139]. As du Plessis observes [24], the real promise of resilience thinking lies in understanding that the collapse of a rigid system can "*release potential and opportunity*" for reorganization, to shape that reorganization toward a better outcome. In practical terms, this means that

regenerative planning continually asks what new, more sustainable trajectory can emerge from any change. This underscores an alignment with the principles of adaptive planning derived from complexity theory. Adaptive planning and management frameworks in urbanism advocate iterative, flexible strategies that can adjust as conditions change or new information arises. Regenerative development fully embraces this adaptive, systems-oriented practice, viewing each project as a hypothesis in a complex adaptive system that must be monitored and adjusted over time.

As Mang and Reed argue, the ultimate aim is "*the continual evolution of culture in relationship to the evolution of life*" [141]. Achieving such co-evolution requires rethinking success: not as reaching a static end-state, but as initiating a trajectory of ongoing, mutual adaptation between a development and its environment. Put differently, regenerative design seeks to cultivate a "*co-evolving mutualism*", a mutually beneficial integration of human and natural systems that grows stronger over time [141].

The emergence and evolution of regenerative design thus represent a significant broadening of ambition for what the built environment can contribute. It builds upon the foundations laid by sustainability, yet it challenges practitioners to go further and conceive development as a process that can actively seize the opportunities arising, going beyond "*less bad*".

In this light, regenerative design asks practitioners to cultivate the systems-thinking skills that complexity science makes possible, the ecological imagination that frames humans as participants, and the willingness to view every project as an experiment in reciprocal flourishing. While the field is still refining its tools, these premises offer a coherent scaffold for moving from "*doing less harm*" to designing places that actively heal and enrich the larger living community they inhabit.

5. Discussion

This article provides a conceptual synthesis addressing the key epistemological and methodological shifts necessary to plan and design built environments under deep uncertainty and complexity. By critically revisiting the trajectory from modernist determinism through sustainability paradigms, this study has highlighted fundamental tensions between traditional planning approaches and contemporary urban challenges. Explicitly framed through a complexity lens, it proposes a structured functional frame consisting of resilience (what), adaptive planning (how), and regenerative design (why).

The preceding narrative framed the core ideas that underlie and still influence architectural and urban planning, rooted in deterministic and mechanistic methodologies. Such methods, characterized by predict-and-control logic, presumed stable, predictable urban dynamics that could be managed through centralized interventions. Despite considerable criticism, deterministic legacies persist in contemporary practices, hindering planners' ability to respond adequately to evolving and uncertain conditions. The sustainability paradigm initially emerged as a counter-response, promoting a holistic, integrative vision, and became the first boundary concept to unite environmental, social, and economic agendas within a single planning mandate. However, regardless of its intentions, sustainability frequently reverted to efficiency-led, checklist incrementalism that pursues "*less bad*" scores but rarely tests systemic change. Consequently, sustainability often struggles to accommodate the inherent nonlinearity, emergent phenomena, and deep uncertainty that characterize complex urban systems.

Complexity theory provides a robust epistemological foundation for this reframing, highlighting that urban systems are inherently nonlinear and dynamic. In such systems, small disturbances can trigger cascading impacts, and future conditions are intrinsically unpredictable. Traditional predictive planning models, therefore, inevitably encounter

limitations when confronted with unforeseen events outside the static assumptions made. These limitations are also mirrored in digital tools and modeling, as both Moroni's and Batty's critiques underline that single, all-encompassing digital twins are insufficient for comprehensively capturing urban complexity.

Digital tools, therefore, should serve primarily as decision-support instruments whose insights are continuously supplemented by qualitative, place-based knowledge.

The famous quote by Box, "*All models are wrong, but some are useful*", captures the essence of the issue. Models are not supposed to be treated as omniscient crystal balls, but they should be "*fit for their purpose*" [143]. Occasionally, using a model as a snapshot of reality is justified, depending on the scope and timeframe considered. When analytical dimensions widen and temporal horizons lengthen, new complexities and uncertainties emerge from subsystem interactions. Ignoring these interactions can do more harm than good.

The transformation in modeling practice reflects a broader methodological shift necessitated by complexity and uncertainty. Traditional deterministic methods prioritize efficiency and optimization based on singular predictions. Contemporary approaches, conversely, focus on robustness, adaptability, and flexibility. This shift requires planners to embrace new techniques. In turn, planning becomes an ongoing cycle of monitoring, learning, and adaptation rather than a linear implementation of predetermined outcomes.

By framing explicitly the built environment in a complexity lens, the narrative built for resilience, adaptive planning, and regenerative design can conceptually aid in responding to sustainability's conceptual gaps. Resilience planning defines the essential socio-technical functions and structures that require safeguarding (what). However, resilience alone remains conceptually and operationally ambiguous without complementary paradigms that clarify methodologies and normative orientations. Adaptive planning fills this methodological gap by operationalizing the resilience concept (how). Explicitly designed to function under conditions of deep uncertainty, adaptive planning employs iterative strategies, dynamic adaptive pathways, and real options, planning to maintain robustness across multiple plausible futures. The approach treats uncertainty not as a temporary anomaly but as a permanent condition. Thus, adaptive planning transforms traditional linear planning into a flexible, iterative practice, systematically integrating continuous monitoring and adaptive responses.

Hence, planners transition from passive implementers of static plans into active navigators, strategically responding to unfolding uncertainties and maintaining adaptive capacity. Regenerative design addresses the normative dimension of planning and "why" planning should aim beyond harm reduction toward actively cultivating socio-ecological improvements. Regenerative design explicitly promotes net-positive outcomes by enhancing ecological health, fostering social equity, and creating conditions for long-term systemic vitality. Its place-based, participatory orientation ensures that planning and design practices align closely with local contexts and community aspirations, positioning urban development as a catalyst for ecological restoration and social renewal. Thus, regenerative design provides planners with an ethically grounded aspiration that directs resilience and adaptive interventions toward meaningful transformative change. Integrating these paradigms through the explicit what–how–why alignment could significantly enhance the practical implementation of a climate-proof planning paradigm. Rather than focusing solely on the semantics and conceptual definitions, planners and decision-makers would benefit from an operational and structured approach that delineates resilience as the targeted systemic capacities (what), adaptive planning as the strategic methodological process (how), and regenerative design as the normative and aspirational direction (why). Such alignment promotes clarity and consistency in planning decisions and interventions, enhancing the

ability to navigate complexity proactively. Moreover, embedding resilience, adaptability, and regeneration into urban planning and design frameworks provides a systematic way of accounting for uncertainty, embedding continuous learning, and leveraging complexity for beneficial outcomes.

However, turning regenerative, resilient, and adaptive ideals into concrete projects means equipping planners with new skills. DMDU methods and tools provide a practicable bridge from theory to implementation. Robust Decision Making, Dynamic Adaptive Policy Pathways treat strategy as a sequence of reversible steps, informed by continuous monitoring and are ready to pivot when signposts signal that the world is veering from expectations [119]. The same approach that prepares for negative tipping points can be harnessed to seize positive windows of transformation, which is exactly the stance advocated by regenerative thinkers [139].

Reframing complexity as a creative source rather than an obstacle, planners transition into strategic facilitators guiding cities beyond incremental sustainability towards genuinely transformative trajectories. This shift positions urban and architectural planning not as pursuits of definitive solutions but as adaptive practices adept at navigating contemporary challenges.

6. Conclusions and Future Outlooks

This paper offers a theory synthesis that groups three long-standing but often diffuse paradigms into a functional sequence: resilience clarifies what socio-technical capacities urban systems must retain or recover; adaptive planning describes how those capacities can be steered under deep uncertainty; and regenerative design articulates why planning should move beyond harm reduction toward net-positive socio-ecological outcomes, enabling the possibility of embracing change as a positive catalyst and not something to be necessarily avoided. The analysis purposely privileged narrative coherence over exhaustive coverage, and remained conceptual rather than empirical. These choices make the framework clear, but they also delimit its current applicability.

In addition to the conceptual–empirical distinction already acknowledged, further limitations emerge from the interdisciplinary nature of the synthesis itself. The paradigms explored stem from different disciplinary traditions and are shaped by diverse ontologies, normative commitments, and methodological perspectives. While this study sought to integrate them without collapsing their specificity, it is important to recognize that synthesizing across such domains may entail epistemological tensions. Concepts mobilized across fields can acquire divergent meanings, and any attempt to frame them within a shared heuristic, such as the proposed what–how–why scaffold, risks foregrounding commonalities over contradictions. This does not diminish the heuristic value of the framework, but rather calls for its contextual use and empirical testing.

Future endeavors will be dedicated to translating into practice what has been conceptualized in theory. First, the scaffold must be operationalized through explicit decision heuristics, monitoring indicators, and stepwise implementation guides. Second, its robustness must be tested across contrasting planning contexts to evaluate transferability and identify where local adaptation is essential. Comparative case studies and mixed-method evaluations will be central to this task. Third, a learning architecture is needed: iterative, case-based collaborations in which planners, designers, and researchers jointly refine the framework and document path-dependent obstacles.

The necessity of collaborations also concerns digital tools. Techniques associated with Decision Making under Deep Uncertainty, should become a common grammar for planners who aim to design a resilient and climate-proof built environment.

Professional capacity building is essential. Planners and designers need competencies in complexity thinking, scenario discovery, and participatory co-production if the proposed "what–how–why" sequence is to inform routine practice rather than remain an academic construct.

Finally, the what–how–why framing is intentionally conceptualized to confront the planning paradigm's applicative limitations. Rather than assuming coherence across resilience, adaptive planning, and regenerative design, the theoretical scaffold acknowledges their epistemological and normative tensions. The heuristic format is a methodological response to these tensions, aiming to render actionable planning practice under deep uncertainty. In this sense, the conceptual contribution lies not in resolving such tensions but in offering a tool that helps planners navigate them critically and reflectively. In sum, this study provides a clarified conceptual grammar for linking resilience, adaptive planning, and regeneration, addressing the highlighted gaps constitutes the next step toward switching from theory to practice.

Funding: This research was funded by Next Generation EU under the scheme "Young Researcher Seal of Excellence", grant number: B83C24003310005.

Conflicts of Interest: The author declares no conflicts of interest.

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