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Algorithmic approaches toward information-based urban form

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ABSTRACT

This study explores the potential of using information flow as a spatial generator in urban architecture, through an algorithmic approach that emphasises relational thinking and adaptability in shaping the built environment. Bridging computational design and ecological paradigms, it reframes architecture as a medium for information exchange in the second machine age. The proposed method employs algorithmic processes Cellular Automata and Swarm Intelligence to generate dynamic spatial systems that address the logistical complexities of urban contexts. Applied to real urban sites, the CA-SI workflow reveals aggregation fields, directional gradients, and distributed trajectories that converge into five recurrent network topologies: annular, co-linear, co-vertex, diffused plane, and intersectional plane. These swarm networks prioritise relationships and interactions over isolated forms and foster a self-organising and metabolistic nature of urban networks. The findings indicate that information-driven spatial tendencies interact with and reorganise existing material conditions, which result in a co-constituted physical–digital field understood as multispace. This interplay highlights both the generative potential and interpretive limits of computational abstraction. By integrating modular and scalable components that dynamically respond to spatial and informational demands, the study offers a morphogenetic approach to urban architecture and positions information as a driver of adaptive and interconnected urban ecosystems.

Introduction

Unlike the first machine age, which harnessed energy from chemical bonds to transform the physical world, the second machine age is set to unlock the potential of human creativity through information (Brynjolfsson and McAfee 2014). This study explores the evolving architecture in the second machine age, where information has become the primary resource. Although information may seem abstract, it is physical and has physical implications (Gleick 2011), influencing entropy and requiring effective management to shape the built environment (Menges and Ahlquist 2011). Thus, managing information becomes essential to reduce uncertainty and complexity within architectural systems.

In this era, tools like Building Information Modelling (BIM) and artificial intelligence (AI) are already integrating information into architectural design. These tools allow for environmental analysis, optimisation, and real-time simulations, reflecting how architecture is adapting to information flows (Aksamija 2018; Tchouanguem et al. 2019). However, these tools often remain instrumental rather than generative: information is typically applied to optimise or evaluate predefined forms rather than to generate spatial logics in its own right. This study argues that the presence of information as a physical and systemic entity should be recognised merely as data for representation, but as a medium capable of producing architectural and urban form.

Current urban practice heavily relies on physical resources, but the abundance of information in the second machine age presents new challenges (Brynjolfsson and McAfee 2014). Scarcity, as Goodbun et al. (2014) argue, is a construct shaped by capitalist economics, and the post-capitalism era second machine age positions information as the primary resource (Mason 2015). Ecological perspectives offer a productive model: nature, as a sophisticated information system, demonstrates adaptive, life-cycle-oriented processes that can guide architectural thinking (Lucas, Ballay, and McManus 2012). Ecological design, as Goodbun et al. (2014) suggest, transcends efficiency, fostering dynamic systems that respond to change. Urban and social networks, inspired by ecosystems, embrace change as a constant rather than resisting it through rigid planning.

Allen's (1997) "logistic of context" framework (p. 30) addresses urban complexity by highlighting architecture's top-down approach limitations in organising cities. Modernist approaches often fail to engage with the complex, field-like conditions of cities, proposing that architecture be understood through its morphogenetic processes rather than as fixed types. Architecture must respond to local connections and collective behaviours, as reinforced by the crowd theory (Canetti 1984). In an information-based economy, where data exchange occurs directly, traditional urban forms may no longer suffice (Rubedo 2009). Instead, architecture must adapt to process and respond to abundant information without restrictive control, maintaining its generative potential.

Computational design offers many precedents, such as cellular automata for modelling growth (Li, Packard, and Langton 1990; Batty 2000), swarm intelligence for collective behaviour (Beni 2020; Darabi et al. 2021), and numerous agent-based urban simulations. However, in dealing with information, most studies employ the algorithms descriptively or predictively. They often analyse patterns after they emerge, or use computation to simulate phenomena already understood in urban theory. Only a few works directly examine information as the generative substrate of architectural form, and fewer still connect this inquiry to morphological readings of real sites. Recent studies have begun to move in this direction Moosavi (2017) uses deep learning to extract latent urban typologies and Zhang et al. (2022) employ GANs to simulate morphologies. Yet, these works largely treat information as a representational or statistical abstraction, rather than as an active generative force within specific urban contexts.

Thus, there is a gap in the lack of methods that position information flow as the primary generative mechanism and trace its spatial consequences empirically within a specific urban context. This study responds to this gap by developing an algorithmic workflow that treats information not program or geometry as the driving logic of urban morphogenesis. The study explores how cellular automata and swarm intelligence might jointly articulate relational patterns, spatial aggregations, and network behaviours. The objective is to investigate how these information-driven processes can reveal organisational dynamics within an urban site, and to consider the architectural consequences of treating information as a spatial generator. In particular, the study hypotheses that the algorithmic processes have the capabilities to establish the information-driven mechanisms to produce the urban forms that resonate with Allen's logistic of context, ecological information metabolism, and multispace urbanism.

Methods

This study investigates information as the primary resource in urban environments and develops methods for generating urban architecture within the framework of future urban ecologies (figure 1). Inspired by Davenport (1997) concept of information metabolism and Impagliazzo (1995) dual worlds Heuristica (physical world) and Algorithmica (digital management) the research envisions a speculative future where urban systems prioritise information. These layers reflect distinct complexities of information processing, forming a dynamic, interconnected urban network.

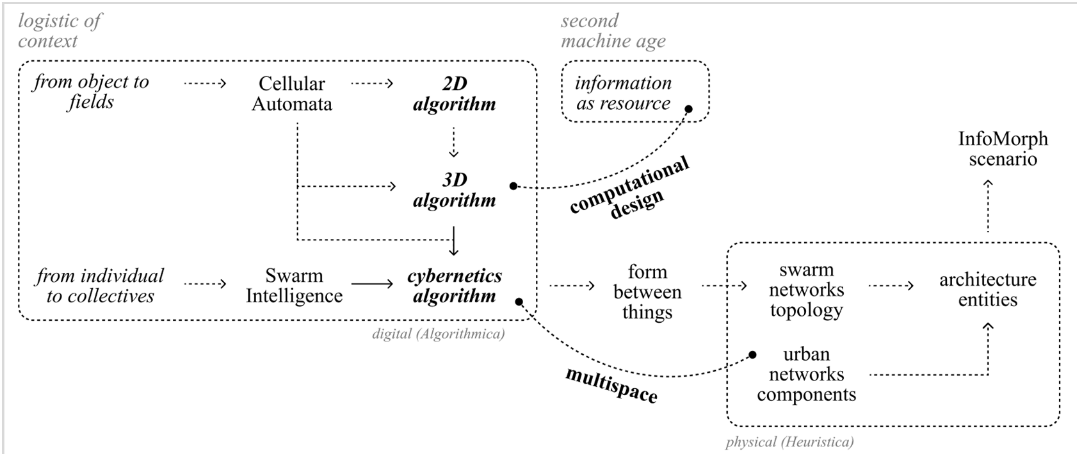

Figure 1. Algorithmic design method framework

Referring to Menges and Ahlquist (2011) of processing information algorithmically and Allen's "logistic of context," the design process was developed in three stages: transitioning from 2D to 3D algorithms, developing cybernetics algorithms, and applying them to a real-world site. The algorithms are implemented in a 1 km² urban area with minimal but relational elements such as building footprint points as the site for testing how informational cues can reorganise urban spatial fields.

The study implements two main algorithmic approaches, Cellular Automata (CA) and Swarm Intelligence (SI). CA translates the spatial elements into a field of local informational relationships. Following established rules (Li, Packard, and Langton 1990; Batty 2000), cells activate or remain inactive depending on neighbour conditions, producing patterns of aggregation, thinning, or stability. SI then interprets the resulting gradients, treating active CA cells as attractors and inactive cells as repellent zones, generating decentralised movement paths and convergence points (Beni 2020; Darabi et al. 2021). Rather than simulating real flows, this CA–SI sequence tests how simple informational cues can drive spatial reorganisation.

The two processes form a recursive loop in which CA establishes the informational structure and SI traces agent responses, echoing the iterative dynamics of information metabolism (Davenport 1997). Outputs are evaluated using spatial and topological indicators such as clustering tendencies, path convergence, and network formation bridging abstract information flows with material urban forms. This method treats computation not as optimisation but as a way to investigate how information itself can generate spatial tendencies within a real urban context, supporting the vision of a self-organising, metabolistic urban ecology.

Results and discussion

This section presents the algorithmic design process based on information. Figure 2 illustrates how the information flows through each step of the process. The following subsections presents each stage of the design, exploring the interplay between data-driven algorithms and architectural outcomes, and highlighting key observations during the process. The discussion focuses not only on how information is transformed and utilised at each stage but also on the broader implications for the construction of urban networks and architectural systems.

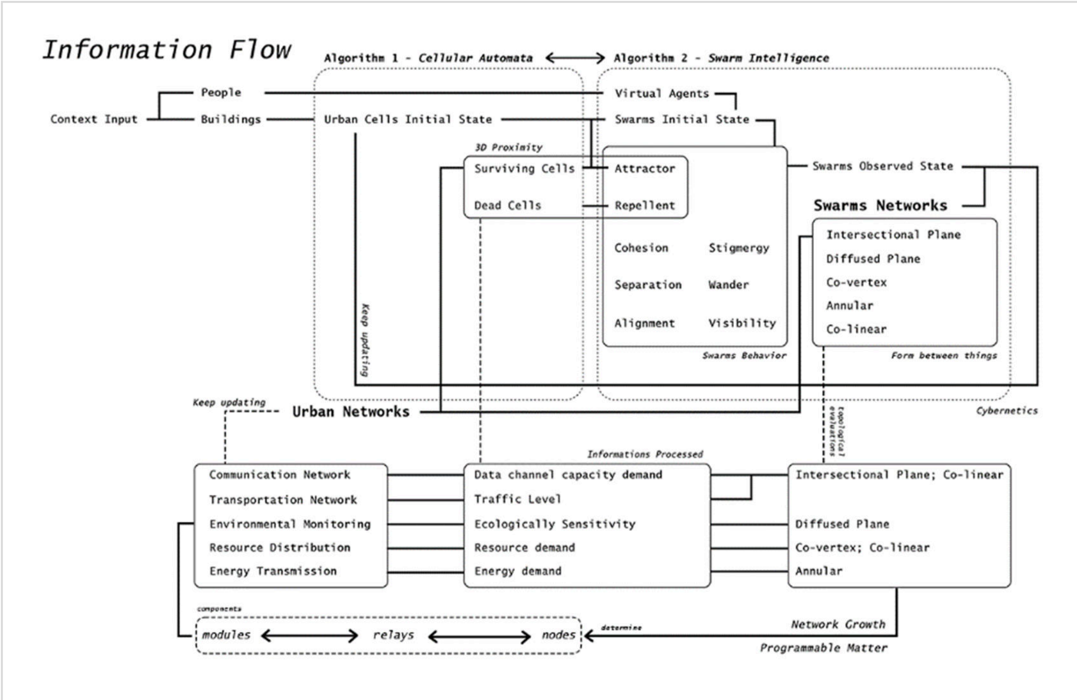

Figure 2. Information flow in design method

Development of algorithm to map proximity and relationships of urban physical objects

Initially, the process begins with the creation of a 2D script that organises objects within a two-dimensional field (figure 2). CA is applied as a computational system where each cell's state evolves based on local interactions and neighbourhood rules. This mechanism reflects survival and reproduction dynamics, making CA a versatile tool for modelling natural processes like biological growth and urban expansion (Li, Packard, and Langton 1990; Batty 2000).

$$IF\ (stat = 0, if\ (nei = 3,1,0), if\ (nei = 2,1, if(nei = 3,1,0)))$$

In mapping the proximity and relationships of urban physical objects a point field, the function serves as the underlying logic to determine the state of a cell based on the number of its neighbours. In simpler terms, the formula is designed to set the cell's state to 1 if it has exactly 2 or 3 neighbours. If it has fewer than 2 or more than 3 neighbours, it remains or reverts to state 0. The state 1 (alive cells) are then stacked to observe the accumulation and distribution tendencies across the field. The resulting 2D patterns (figure 3) establish the foundational relationships that guide further spatial generation.

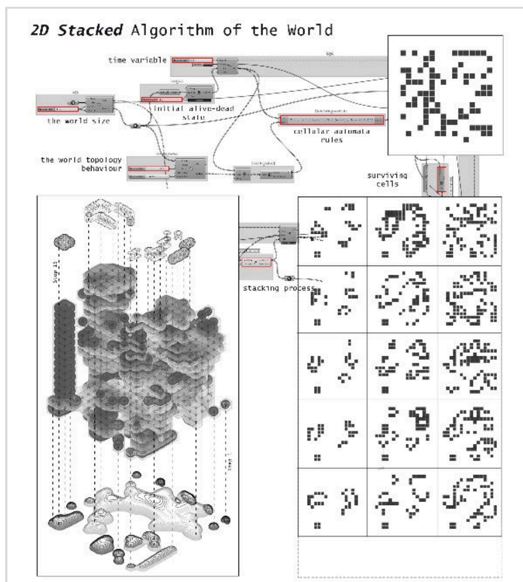

Figure 3. Examples of 2D world building algorithm

These 2D formations are then expanded into a 3D environment (figure 4), allowing for the exploration of volumetric constraints and the development of more complex spatial relationships. This stage sets the ground for the integration of SI algorithms, where agents navigate, cluster, or diverge within a spatial field.

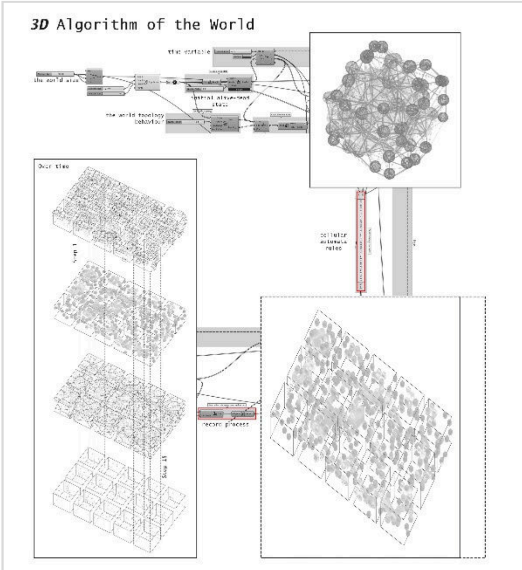

Figure 4. Examples of 3D world building algorithm

Development of cybernetics algorithm to simulate urban environments

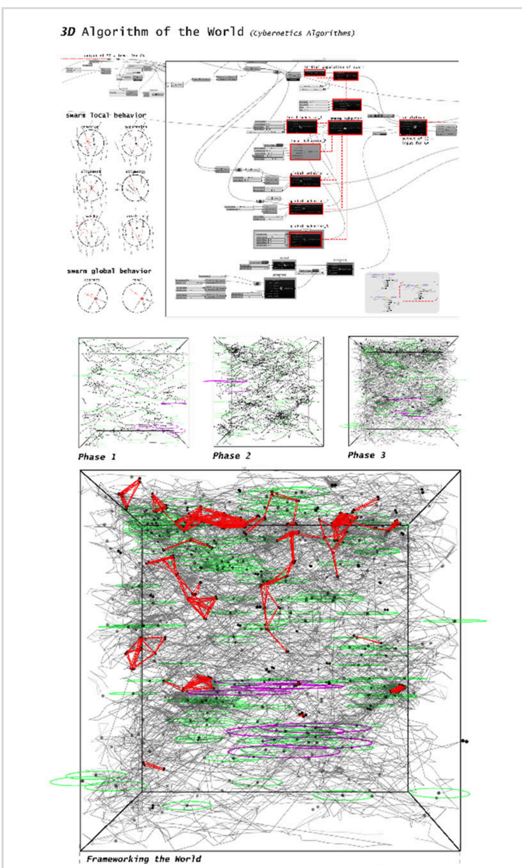

Figure 5. World building cybernetics algorithm

The second stage develops cybernetic algorithms that use a 3D script to model complex urban interactions (figure 5). CA is employed to simulate neighbourhood formation by iterating the states of cells, which represent active and inactive components within a given space. SI, a decentralised approach inspired by natural collectives like ant colonies and bird flocks, applies simple rules and local interactions to generate adaptive collective behaviour (Beni 2020; Darabi et al. 2021). Active cells act as attractors and inactive ones as repellents, enabling Swarm Intelligence to refine spatial organisation and generate emergent, self-organising patterns within the urban environment.

Application of algorithm into an existing urban context

The third stage applies these algorithms to a 1 km² site using building footprints as initial input points, which are evaluated through CA and SI. The algorithms are designed to operate in a loop, where the output of one algorithm serves as the input for the next. This iterative process creates a cybernetic system for managing information within an urban context (figure 6).

Figure 6. Urban context input to the world building algorithm

The resulting swarm networks represent “forms between things” within the urban context, aligning with Allen's (1997) idea that relationships and interactions outweigh isolated forms. Rather than producing static and discrete objects, the networks generate relational fields that adapt dynamically to context, echoing Lima’s (2017) concept of topological space, where relational coherence is prioritised over geometric form.

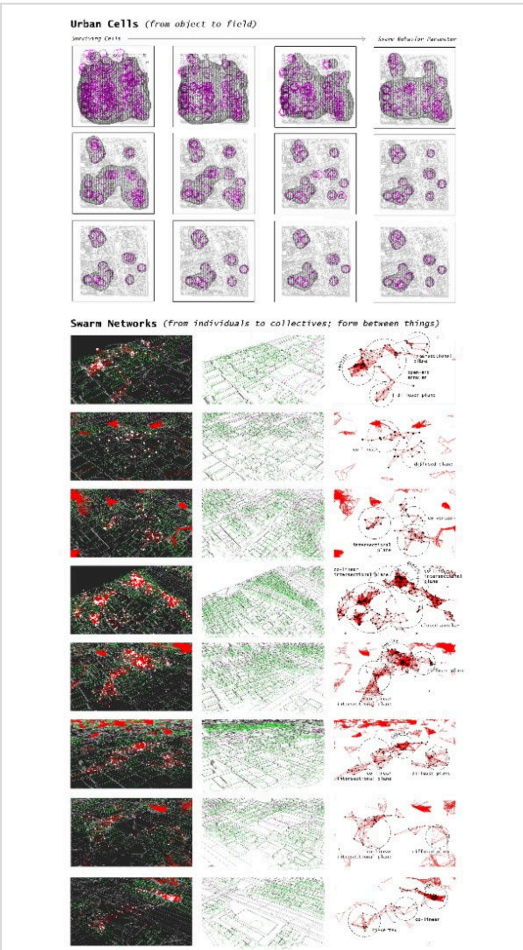

Figure 7. Field condition of the chosen urban site

Figure 7 illustrates how the networks correspond with the site’s field conditions. CA aggregations frequently align with areas of high building density, while SI traces highlight voids, circulation corridors, and edge conditions. These correspondences are not predictive but indicate that informational tendencies can meaningfully interact with urban morphology. Divergences occur where algorithmic outputs conflict with material, social, or regulatory constraints, revealing the limits of information-driven morphogenesis.

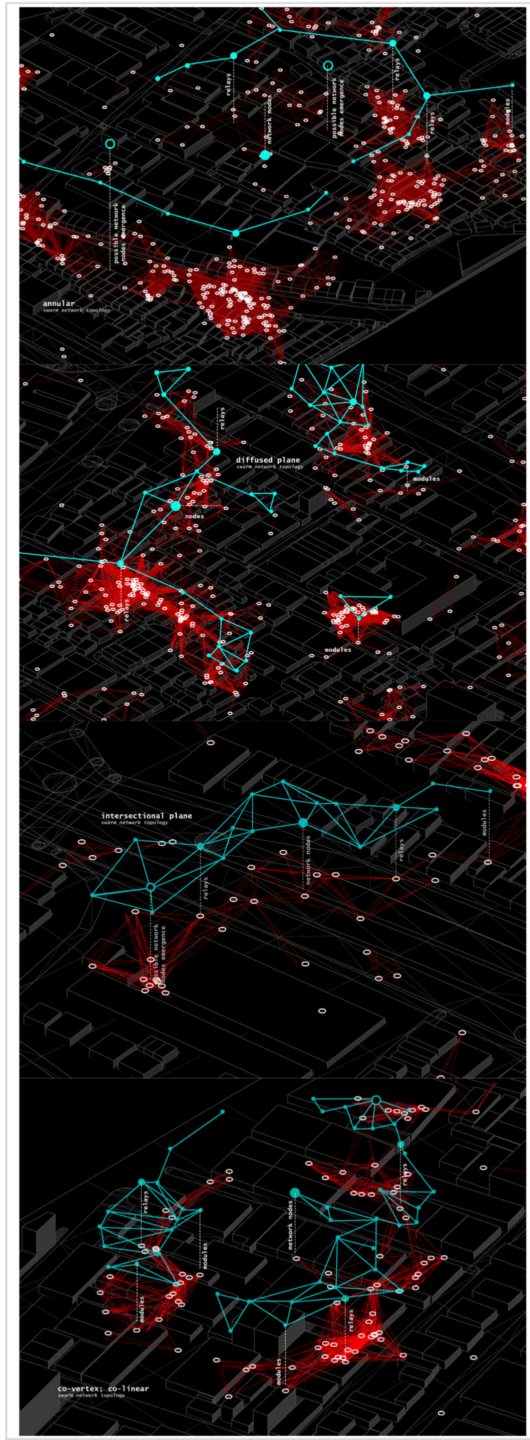

Figure 8. Observed networks from field condition of the chosen urban site (1) annular, (2) diffused plane, (3) intersectional plane, (4) co-vertex; co-linear

Figure 8 introduces five distinct network topologies observed in the site: annular, co-linear, co-vertex, diffused plane, and intersectional plane. The annular topology forms a ring system circulating information; co-linear aligns elements along a single axis for efficient transmission; co-vertex creates star-like arrangements for network coordination; diffused plane extends spatial reach; and intersectional plane functions as a mesh supporting multipath communication and redundancy.

Across these topologies, nodes, relays, and modules operate as hierarchical components. Nodes act as central hubs of activity, relays facilitate the flow of information, and modules function as reconfigurable clusters integrating spatial, informational, and ecological dimensions. Together, they form a responsive, multi-scalar system capable of reorganising across physical and logical domains (Kapruwan et al. 2022; Jalil 2024).

By embedding information flows as the guiding logic for their formation, these networks transform Allen's theoretical framework of field condition into actionable urban strategies. They emphasise responsiveness to fluctuating conditions, enabling cities to evolve dynamically alongside shifting demands. As an infrastructural foundation for contemporary urbanism, these networks embody a self-organising and metabolistic nature, integrating diverse forces such as human activity, technological processes, and environmental flows into a living urban fabric.

Within this framework, resource distribution, communication, energy, environmental monitoring, and transportation networks emerge as functional layers of an adaptive urban network ecology. Resource networks transform static supply chains into fluid, real-time systems with centralised hubs and modular nodes adapting to fluctuating demand. Communication infrastructures form responsive meshes that adjust connectivity across space. Energy networks employ modular and reconfigurable structures, balancing supply and demand autonomously. Environmental monitoring networks translate ecological signals into feedback for adaptive management, while transportation networks optimise routes and capacities through continuously updated topologies.

Overall, the findings indicate that information-driven algorithms do not impose form but reveal relational patterns embedded in the urban context. These topologies are emergent tendencies rather than fixed typologies, illustrating how agents negotiate informational gradients. The resulting networks exemplify architecture as a "field condition" (Allen 1997 p.24), adaptive, relational, and metabolistic. While algorithms uncover latent organisational logics, they also highlight the friction between computational abstraction and the complexities of real urban environments.

Information-based urban network architecture as multispace

The resulting architecture from this algorithmic design approach emphasises hierarchy, modularity, redundancy, and generativity, dynamically responding to the evolving demands of urban systems (Lucas, Ballay, and McManus 2012). Rather than arising from predetermined formal intentions, these qualities emerge from the CA–SI processes, reflecting patterns of iterative information exchange rather than fixed programmatic requirements. Architectural components are designed to transform and adjust autonomously, maintaining efficiency through modular principles (Menges and Ahlquist 2011). This adaptability extends seamlessly into multi-space environments, where urban network components navigate and integrate within the physical city. Drawing on the ideas of Goodbun et al. (2014), voids in the urban fabric become opportunities for architectural entities to emerge and adapt. These components may act as parasites, floating or anchoring into the ground, merging or separating based on urban needs. The plug-in architecture approach ensures that these elements can be easily added or removed, fostering a logistics-driven, autonomous urban system that thrives on flexibility and responsiveness (Allen 1997).

The concept of multispace arises from the integration of physical (Heurestica) and digital realms (Algorithmica), redefining the city as a unified information space where the physical and digital coexist (Hopkins 2023). The computational workflow demonstrates how digital patterns can reorganise physical-relational fields, while those physical conditions influence subsequent algorithmic behaviour (figure 9). Rather than viewing these realms as separate or parallel, the multispace model positions them as interdependent layers, with architecture acting as a medium through which information circulates and spatial relationships recalibrate. Such integration represents a shift toward dynamic urbanism, where the city is defined by its capacity to process and adapt to information flows (Rubedo 2009).

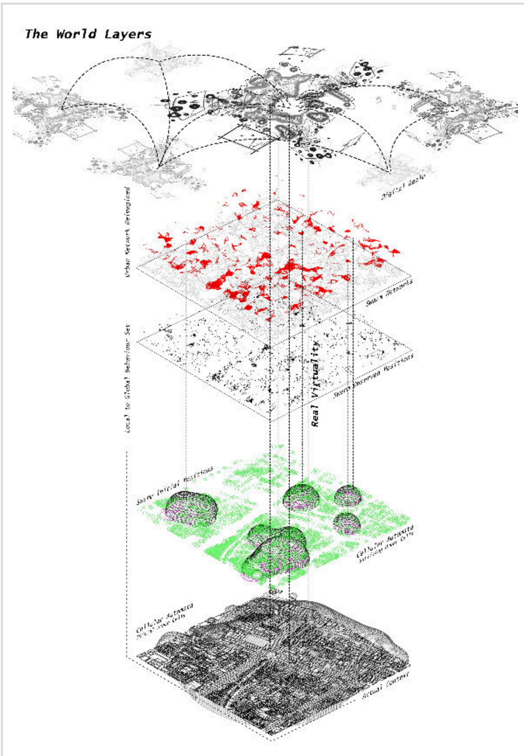

Figure 9. Multispace urban layers based on information

Conclusions

The study developed an information-based urban architectural design method through algorithmic approaches to demonstrate how information can generate spatial tendencies within a real urban context. By applying Cellular Automata (CA) and Swarm Intelligence (SI) to a real urban site, the workflow revealed identifiable patterns aggregation fields, directional gradients, and distributed trajectories that emerge from minimal relational inputs. These patterns give rise to five recurrent network topologies annular, co-linear, co-vertex, diffused plane, and intersectional plane each composed of nodes, relays, and modules. Their presence across the site demonstrates that information-processing mechanisms can uncover latent relational structures without imposing predetermined forms.

By demonstrating how information can act as a generative force in shaping the built environment, this study highlights the increasing significance of algorithmic design in the second machine age, where information assumes primacy in defining spatiality and architectural practices. The development of iterative CA–SI framework contributes to the approaches involving foundational patterns and spatial organisation while simulating collective behaviours that prioritise relationships and adaptive responses over static compositions. The analysis further shows that these emergent CA–SI networks actively interact with and reorganise existing material conditions to generate a co-constituted physical–digital field understood as multispace. These interactions expose points of alignment and divergence between algorithmic tendencies and urban morphology and offer a measure of the method's interpretive capacity. This approach suggests the possibilities for integrating modular and scalable architectural components, as a way to ensure coherence and flexibility within diverse urban systems.

Employing Allen's logistics of context as a guiding principle and leveraging ecological perspectives, this study challenges conventional top-down urban planning methods. Instead, it advocates for a bottom-up, field-based approach that aligns with contemporary urban complexities. Hence, this study highlights the transformative potential of computational design for the current and future urban development. By embracing information as the primary resource, it proposes a paradigm shift toward self-organising, metabolistic systems that address logistical challenges while reimagining cities as integrated, adaptive ecosystems. These insights offer a framework for navigating the complexities of the second machine age, which positions architecture as a dynamic mediator between information flows and the urban built environment.

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Author(s) contribution

Leonardo Dillon contributed to the research concepts preparation, methodologies, investigations, data analysis, visualizations, articles drafting and revisions.

Yandi Andri Yatmo contributed to methodologies, supervision and validation.

Paramita Atmodiwirjo contributed to the research concepts preparation and literature reviews, data analysis, article drafts preparation and validation.

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