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The Role of Swarm Intelligence Systems in Shaping Urban Development Policies

دور أنظمـــة ذكـــــاء الســـرب في صياغـــة ســـياســـات التطويـــــر الحضــــري

Sudaff Mohammed [a] *, Wahda Shukr Al-Hinkawi [a], Nada Abdulmueen Hasan [a]

[a] Department of Architectural Engineering, University of Technology- Iraq, Baghdad, Iraq.

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K E Y W O R D S

Swarm Intelligence (SI), Multi-Agent Systems (MAS), Complex Adaptive Urban Systems (CAS), Urban Development Strategy, Urban Growth, Parametric and Generative Design.

A B S T R A C T

Swarm intelligence is a nature-inspired complex system that draws from the behaviours of social creatures such as ants and birds. This system functions through simple behavioural rules enacted by autonomous, intelligent agents. Existing literature indicates that swarm intelligence possesses a wide range of principles and characteristics derived from the theories of Biomimicry, complex adaptive systems, and parametric and generative design. While the previous studies have intensively addressed the computational aspects of intelligence, a comprehensive conceptual framework is essential for analysing complex urban forms and structures. Therefore, this research develops and applies a conceptual model of swarm intelligence by examining several projects across the following dimensions: growth strategies, mechanisms, and logic; primary and final characteristics; and the types and classifications of the system's agents. The research emphasises the integration of theoretical and practical aspects of swarm intelligence to inform urban growth policies and promote more sustainable urban forms and structures.

الكلمات المفتاحية

ذكاء السرب (SI)، أنظمة متعددة الممثلين (MAS)، الأنظمة الحضرية المعقدة المتكيفة (UCAS)، استراتيجية التنمية الحضرية، النمو الحضري، التصميم البارامتري والتوليدي.

الملخص

ذكاء السرب هو نظام معقد مستوحى من الطبيعة، يعتمد على سلوك الكائنات الاجتماعية مثل النمل والطيور، وغيرها. يعمل ذكاء السرب من خلال قواعد سلوكية بسيطة يطبقها ممثلون يمتازون بكونهم مستقلين وذوي ذكاء ذاتي. من خلال مراجعة الأدبيات السابقة، يتضح أن ذكاء السرب يتسم بمجموعة واسعة من المبادئ والخصائص المستمدة من نظريات متعددة أبرزها نظريات محاكاة الطبيعة، الأنظمة المعقدة المتكيفة، والتصميم البارامتري والتوليدي. وعلى الرغم من أن الدراسات السابقة تناولت الجوانب الحسابية لنظام ذكاء السرب بشكل مكثف، إلا أن هناك حاجة واضحة إلى صياغة إطار مفاهيمي لتحليل الأشكال والهياكل الحضرية المعقدة تبعاً لنموذج ذكاء السرب. بناءً على ذلك، يقوم هذا البحث ببناء وتطبيق نموذج مفاهيمي لذكاء السرب من خلال تحليل مجموعة من المشاريع استنادًا إلى الأبعاد التالية: استراتيجيات وآليات ومنطق النمو، الخصائص الأولية والنهائية للنظام، وأخيراً نوع وتصنيف ممثلي النظام. يقوم البحث بتسليط الضوء على دمج الجوانب النظرية والتطبيقية لذكاء السرب لصياغة سياسات نمو تحقّق أشكال وهياكل حضرية أكثر استدامة.

* Correspondent Author contact: sabaa.mujtaba@stu.edu.iq
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1. Introduction:

Biomimicry theory relies on observing natural creatures as a source of inspiration for creating formations with aesthetic values that align with the traditional standard of beauty by achieving a cohesive balance among the parts of these formations. The emergence of Biomimicry as a theory is attributed to the increasing need for an environmentally sustainable design approach that does not compromise community needs (Faragllah, 2021; Nkandu, 2018). Over the years, nature has developed and tested methods and solutions to many problems that it faces. Consequently, the emergence of nature simulation theory marked a significant shift toward learning from nature rather than merely about it, using nature as a source of ideas to solve various problems through design by proposing alternative solutions to human problems via replicating or simulating models and solutions previously tested through human observation of nature and its systems (Benyus, 2009; Pathak, 2019). Therefore, Biomimicry theory imitates biological or natural technology to create sustainable innovations (Ivani, 2015). Biomimicry is an applied science in architecture and urban design that considers aesthetic aspects and studies the underlying logic to solve functional problems by mimicking the simplest forms of living organisms and extending to the internal logic of entire ecological systems. This supports urban sustainability by developing models inspired by natural systems to address urban challenges (Uchiyama, 2020; Sarwate, 2016). These dynamic systems inspired by nature are considered to be the third generation of Complex Adaptive Systems (CAS) (Dodder R, 2000). They are open, nonlinear systems that sustain themselves through a continuous influx of energy, contributing to their ongoing development and adaptability (Nel, 2009). This makes these systems susceptible to initial conditions, meaning the reasons for their emergence significantly impact the city system and are reflected in its morphology (DE LOTTO, 2018; Wohl, 2018). City development is a spatial process dependent on the system's adaptability, derived from its openness, self-organisation, and complexity. It keeps the urban system in continuous interaction with its environment without the need for reductionism (Shi Y, 2021; Beckage, 2013). Urban systems can be understood and managed by considering them as a network of nonlinear, self-adaptive agents interconnected by laws defining their relationships, with each agent having its independent tendencies or preferences (Huang Hao, 2021; Nel, 2009; Manesh et al., 2011). Swarm intelligence systems, inspired by the collective behaviour of social creatures such as insects and birds, are among these systems (Johnson, 2012). A swarm is a group of individuals that somehow remain together even if they appear to move in random directions. The concept of the swarm is composed of homogeneous individuals, the agents; this definition includes social processes, systems of thoughts, beliefs, behaviours, and everything occupying minds (Johnson, 2012; Carrillo, 2010).

The conceptual model of the swarm assumes that having multiple independent agents is more effective than a single, sophisticated agent, leading to the creation of swarm-based strategies that improve the design of dynamic urban systems by simulating nonlinear behaviours that help nature self-organise (Petrš, 2016; Wiesenhuetter, 2016). The behaviour of the swarm intelligence system is described as robust, scalable, and reliant on the collective behaviour of the decentralised systems. This behaviour is characterised by its simplicity, based on rules applicable by agents to achieve a specific goal within a fixed or dynamic space. Studying this behaviour can develop complex emergent systems resulting from local interactions between agents, producing intelligent behaviour at the group level (Roy, 2014; Zedadra, 2018). Swarm intelligence systems contribute to system reorganisation during extreme uncertainties through ready-made algorithms that can be used in various urban contexts (Ghnemat R, 2010). Swarm intelligence serves as a tool to support the design process by embodying the logic of the urban system (Petrš, 2016; Vehlken, 2019). The adaptability of swarm intelligence systems leads to continuous system upgrades, resulting in the generation of patterns and a higher-level emergent phenomenon from the complex parallel interactions among local agents, requiring them to be programmed as cognitive units rather than simple agents (Hasan, 2022; Ettema, 2005). With mathematical representation, swarm intelligence systems aim to improve design processes at the form, structure, and pattern generation levels. They operate automatically without needing self-awareness, considering parametric and generative design trends. On the one hand, the parametric design considers the urban system as a field rather than a space. This field consists of a set of swarm-like formations governed by force and direction to enhance synergy among the components of the urban environment (SILVA RC, 2010). On the other hand, generative design focuses on solving complex challenges by transforming the behaviour of social creatures into tectonics and then architectural and urban algorithms that produce nonlinear formations with final properties differing from the system's initial properties (Shi Y, 2021). Urban systems can correct their path and return to their initial trajectories, requiring them to be open to all possibilities provided by their environment due to the interaction of many agents and subsystems (Nel, 2009).

Urban systems are complex adaptive systems that have evolved through local and global changes. Such systems can exhibit meaningful behaviour at any moment, a behaviour more remarkable than the sum of its parts, resulting in the distinct behaviour of the urban system. Most studies focus on the mathematical aspect of swarm intelligence and its connection to generative and parametric design approaches as tools for improving urban design and analysing urban formations. However, few studies have addressed the construction of a comprehensive conceptual model encompassing the dimensions of swarm intelligence in urban development to achieve sustainable urban formations that enhance system resilience and adaptability over time. Therefore, this research aims to build a comprehensive conceptual model of swarm intelligence to analyse urban formations, structures, and patterns and test this model by applying it to several practical projects via the following steps:

- Studying the principles of swarm intelligence and how they can be used in urban development policies.
- Managing urban growth considering swarm intelligence.
- Reviewing specialised urban studies to identify the main dimensions of Swarm Intelligence.
- Understanding its relationship with parametric and generative design, investigating the classification of its agents, and determining the rules governing them to build the conceptual model.
- Applying the conceptual model to several practical projects that have successfully employed swarm intelligence to analyse and generate urban formations.

1.1. Principles of Swarm Intelligence:

Two primary levels characterise complex urban systems: the global and local levels, each operating according to its principles (Hasan, 2022). As the system's complexity increases, interactions between the global and local levels become more pronounced. This interaction is facilitated by the two main principles of swarm intelligence: emergence and self-organisation (De Wolf T, 2004). Their interaction leads to the appearance of cohesive collective behaviours that enhance adaptability and resilience, making the behaviour of urban systems more unpredictable (Porqueddu, 2018; Gauthier Picard, 2002). Emergence refers to qualitative changes resulting from the complex properties of the urban system, which are difficult to predict or plan for (Walloth, 2013; Porqueddu, 2018). Thus, the urban system of a city embodies emergence, and like any emergent system, "a city is a pattern in time." Cities maintain their pattern forms over generations and varying conditions, retaining some aspect of their original pattern. Consequently, the urban system represents an ascending system that surpasses the complexity of its parts and can, therefore, be analysed through the principles of swarm intelligence (Johnson, 2012). Complex urban systems exhibit emergent properties, the most important of which is self-organisation, which refers to the system's ability to organise itself without central control (Fromm, 2005). It is a key mechanism for achieving the goals of the urban system through the interaction of many agents following simple local rules to reach holistic solutions (Zambonelli, 2015; Gershenson, 2011). Self-organisation consists of dynamic adaptive mechanisms to maintain the system's structure locally, operating at the level of individuals and the rules governing them (Partanen, 2015; Batty, 2009). Self-organising systems like swarm intelligence have essential characteristics: dynamism, emergent properties, and nonlinear relationships, which lead to divergences, making self-organising systems have multiple stability points (Hasan, 2022).

Therefore, to develop more realistic strategies, it is necessary to integrate heterogeneous agents into a common simulation framework to test the holistic properties of complex urban systems (Lai, 2023). When planning or completing the current urban environment based on actual needs and capabilities, emergence is probable for urban development and growth. While self-organisation and emergence can exist independently, they often interact in complex systems (Buš, 2012; Tom De Wolf, 2004). The principles of swarm intelligence have led to the emergence of coherent phenomena at the global level. Thus, traditional urban systems are less conscious formations and, therefore, align with emergence, starting from a partial level in the system to a phenomenon at the global level, leading to new stable solutions and states based on changing some initial factors and conditions with random fluctuations in agents behaviours (Hasan, 2022). Self-organisation aims to maintain the system's structure without central or external control, enhancing a specific function or property by defining several decisions without being directly imposed on the system's agents. Therefore, the methodology of swarm intelligence at the design and analysis level shifts from designing or analysing a system to designing or analysing the fundamental behaviour of its formation (Leach, 2010; Lai, 2023). Accordingly, the logic of emergence is not a product of individuals but results from shape-generating matrices. Finally, learning from individual behaviours leads to urban policies capable of addressing nonlinearity and self-organisation (S. S. Youssef, 2021). The urban system can be transformed into swarm formations whose compositions change flexibly while the elements remain unchanged, supporting the system's ability to respond better to external emergencies (SILVA RC, 2010).

1.2. Urban Growth Management in Light of Swarm Intelligence:

The principles of swarm intelligence systems contribute to solving numerous complex urban challenges, including urban growth, land use patterns, transportation, and demographic changes (Crooks, 2014). Swarm intelligence views growth as a potential external phenomenon that is not inevitable. It does not grow continuously; when the swarm intelligence system needs to grow, it does so by adding new agents or levels within the urban system (Hasan, 2022). Therefore, analysing growth in the context of swarm intelligence requires a flexible and adaptive system capable of handling the urban system's continuous growth and resulting complexity (Leach, 2010). In highly dynamic urban systems, also known as natural urban systems in some studies, analysing urban growth requires a deep understanding of the morphological characteristics of urban networks (Christopher Alexander, 1978; Shahad Abdulabbas Hammoodi, 2023). This is achieved through principles and mechanisms applicable to complex urban systems exhibiting the properties of swarm intelligence, such as traditional urban systems (Hasan, 2022). Urban systems are not independent entities with defined functions; they act as supporters and expressions of human activities. Thus, the urban system embodies the intersection of various types of networks (Shahad Abdulabbas Hammoodi, 2023; Al-Hinkawi, 2017). Because the urban system has two primary levels—the local and the global—the interaction between these levels requires both local and global principles, taking into account the level of the urban system to be analysed (I. J. Mohammed, 2023). Therefore, building and analysing a swarm intelligence system involves two primary levels: the mobile agents and the interactive network that connects them (Partanen, 2015).

Developing urban policies necessitates attention to managing urban growth, especially in complex urban systems characterised by continuity and multiple possibilities that increase complexity. Consequently, swarm intelligence has been proposed as a concept whose diverse potentials can be leveraged to analyse or generate urban formations with an internal logic and a shared goal. The following section will review several specialised urban studies focusing on specific aspects of swarm intelligence, paving the way for deriving the dimensions of the conceptual model.

2. Review of Previous Studies:

This section reviews several urban studies focusing on aspects of swarm intelligence, as follows:

- **Study by (Leach, 2010) and (DeLanda, 2010) on the Logic of Swarm Intelligence and Urban Systems:**

The urban system has achieved a dynamic, adaptive system consisting of intelligent agents with spatial mobility. The urban system is a site for formation or physical structure that can be interpreted through physical deposits representing the city's physicality. In contrast, the inhabitants are non-material agents who move within the spatial domain of the urban system, viewed as a site for spatial practices. This forms the basic classification of agents within the urban system, considering swarm intelligence. Therefore, the task of design is to predict the future state of the urban system by studying the impulses of human occupation through a scenario-based design method that replaces traditional urban planning with an urban algorithm as a design tool. Thus, swarm intelligence encompasses a broader scope related to social policies. It is a system sensitive to equilibrium and disequilibrium states because it fundamentally operates through strategies triggered by collisions, directly affecting its internal logic and prompting responses to collisions resulting from varying impulses of human occupation within the urban system. Consequently, swarm intelligence is considered a political and social transformation tool, and reducing it to a mere formal strategy undermines its potential.

- **Study by (Bratton, 2010) and (Roche, 2010) on Swarm Intelligence Agents' Behavior:**

The repetitive collective behaviours (routines) of swarm intelligence agents play a fundamental role in modelling computational simulations of large social systems, such as urban systems, which naturally change slowly. At the macro level, the system does not respond to the individual behavioural changes of the agents. However, not all agents can be subjected to a specific collective behaviour on a smaller scale. This highlights the need to represent deviations from collective behaviours, such as responses to crises or emergency behaviours within the system. While swarm intelligence systems are characterised by their non-hierarchical nature, this does not eliminate the differentiation and preferences among agents. Specific agents influence other agents' behaviour, decisions, and choices, showing deviations from the system's collective behaviour or routine. This phenomenon, known as emergence, indicates that the system cannot control the behaviour of all agents at all scales. Emergent systems, such as swarm intelligence, require long periods for emergence to manifest at the macro level. Swarm intelligence develops highly flexible agents whose behaviours are not strictly governed by rules but are based on the agent's beliefs about the environment with which they interact. These agents, known as Belief-Desire-Intention (BDI) agents, operate without rigidly defined rules. They use real-world information about their environment to form specific beliefs, which then inform a set of optional behaviours based on feasibility and desire. They use achievable and desirable options to create goals; ultimately, commitment to these goals forms the intention to act. Through this approach, swarm intelligence creates a balanced system with specific rules that do not negate differentiation among agents but allow each agent to learn and develop internal behaviour models following their role within the system. This contributes to the emergence of new phenomena. Key concepts that prevent the reduction and destruction of swarm intelligence at the representational level include agency, model agency, aggregation varieties, rhythmic processes, and the collective self. Aggregation varieties refer to emergent patterns with a hierarchy produced from the emergent behaviour of agents. These aggregations gather according to specific rhythms to form a final picture, known as swarm topology or collective self. Because complex systems have an ultimate goal, they must possess a means to measure agents' progress toward this goal, referred to as the model agency of the swarm intelligence system.

- **Study by (SILVA, 2010), (Kartal, 2020), and (R. Khalil, 2021): Swarm Intelligence in Parametric and Generative Design:**

Urban design trends related to parametric design and swarm intelligence are interconnected through the ideas of Patrik Schumacher. The parametric design aims to establish a new logic in urban design based on interconnected systems to enhance open and closed spaces, exploring new visual diversity and differentiation mechanisms, thereby eliminating repetition within the urban system. The parametric design assumes that urban centres form a swarm-like structure composed of multiple elements, such as buildings, and that this shift in design philosophy replaces the homogeneous space concept used in modernist architecture with a model that embodies swarm intelligence. In generative design, swarm intelligence utilises the agent concept to generate models, create structures, and improve spatial quality by transforming the social behaviours of animals into mathematical systems and then into architectural tectonics and computational algorithms for use in the design process. Thus, swarm intelligence provides a broad range of potential solutions that meet the design criteria, addressing complex computational challenges with its rapid response to urban obstacles. This is due to the quick interactions between its agents, which lead to final characteristics that differ from the initial properties of the system components. The general logic of parametric urban design is that nothing in the city repeats itself. Therefore, the urban realm possesses direction and power, influenced by systematic morphological modifications that produce strong urban effects, facilitating spatial orientation. These modifications are described as formal codes, which Schumacher refers to as positive drivers, which are procedures or rules that create morphological differentiation by avoiding negative drivers, such as repetitive standardised elements, Platonic forms, straight lines, and right angles, and the use of common design patterns. Consequently, at the analytical level, urban systems should be studied according to local formal codes (derived from the system itself) rather than general abstract codes.

- **Study by (Hasan, 2022) on the Role of Swarm Intelligence Principles in Urban Policies:**

This study highlights that architecture and urban design not only attempt to mimic nature by borrowing natural models but also strive to understand the generative potentials of swarm logic, which results in complex emergent traits in form, structure, organisation, and patterns. Swarm intelligence represents a synergy between artificial and natural conditions, making the system complex and adaptive. Over the past two decades, swarm intelligence has been utilised to model systems based on multiple agents, aiming to equip these agents with the flexibility to react interactively to urban policies rather than simply complying with them. Applying swarm intelligence principles to urban systems leads to a flexible structure that supports the overall system's sustainability by responding rapidly to sudden changes and adapting to the desires and needs of the population. This results in generative systems that vary in form but not in essence. Swarm agents exhibit cohesive behaviour, where interactions between agents are based on simple behavioural criteria and utilise locally shared data, either directly or through the environment, in a decentralised manner, leading to self-organised system behaviour. Growth within a swarm intelligence system occurs through new additions—either by introducing new levels of agents or increasing the number of agents under the same classification.

- **Review of Study by (Ettema, 2005) and (Ghnemat, 2010) on Interactive Networks:**

Swarm intelligence systems are characterised by complexity, multiple centres, and various criteria, which enhance the system's ability to generate emergent phenomena through spatial development and morphological feedback loops. These loops connect the overall emergent behaviour with the interactive network, which acts as the infrastructure linking the system's components, requiring a decentralised modelling approach for both the system components and the interactive network. Classical analytical methods often rely on defining the system behaviour through equations, constraining the simulation to the predefined behavioural pathways generated by these equations. Urban systems, comprising traditional and modern components, deal with various types of feedback. Positive feedback indicates that emergence leads to increased organisation, while negative feedback signifies that emergence has controlling organisational properties, eventually leading to system stabilisation or collapse. Therefore, urban development and management require flexible decision-making processes instead of rigid classical methods. Here, multi-agent systems play a crucial role, using feedback loops to assess system development trends. When programming behavioural rules for swarm intelligence agents, it is preferable to model these agents as cognitive units capable of recognising and interacting with their environment. Each entity in the system is programmed with the same behavioural principles but interacts independently, resulting in an interactive network that self-organises through structural interactions between the system and its components.

3. Developing the Conceptual Model of Swarm Intelligence:

Using swarm intelligence to analyse and generate sustainable urban formations requires examining several aspects, including urban growth management through strategies and mechanisms guided by a clear logic based on the swarm's ability to overcome the obstacles imposed by the conditions and requirements of an urban system. The swarm generally grows as needed, making growth a potential aspect of urban development that can be analysed using this system. Growth occurs through a primary strategy known as addition, which involves adding a new component or level to the swarm intelligence system. This is applied through various mechanisms identified by Craig Reynolds in the Swarming Model. Swarm intelligence possesses several key characteristics, including irreducibility and non-hierarchy, which are fundamental to complex adaptive systems. These characteristics lead to the generation of final system attributes entirely different from the system's initial attributes. To achieve final attributes distinct from the individual system characteristics, emergence and self-organisation ensure the development of local patterns that maintain the overall structure and organisation of the system. This is reflected in the classification and type of swarm intelligence agents. The non-hierarchical nature of swarm intelligence does not imply the absence of a hierarchical order among system agents based on their impact on the behaviour of other agents. Complex adaptive systems demonstrate deviations in the behaviour of some agents from the routine behaviour of the system at the local level, which affects the system's behaviour at the macro level. Therefore, it necessitates a diverse classification of agents into material and non-material types, as well as infrastructure and meta-agents, as illustrated in Figure (1).

After developing the conceptual model for the dimensions of swarm intelligence, this model will be applied to analyse the case studies discussed in the following section.

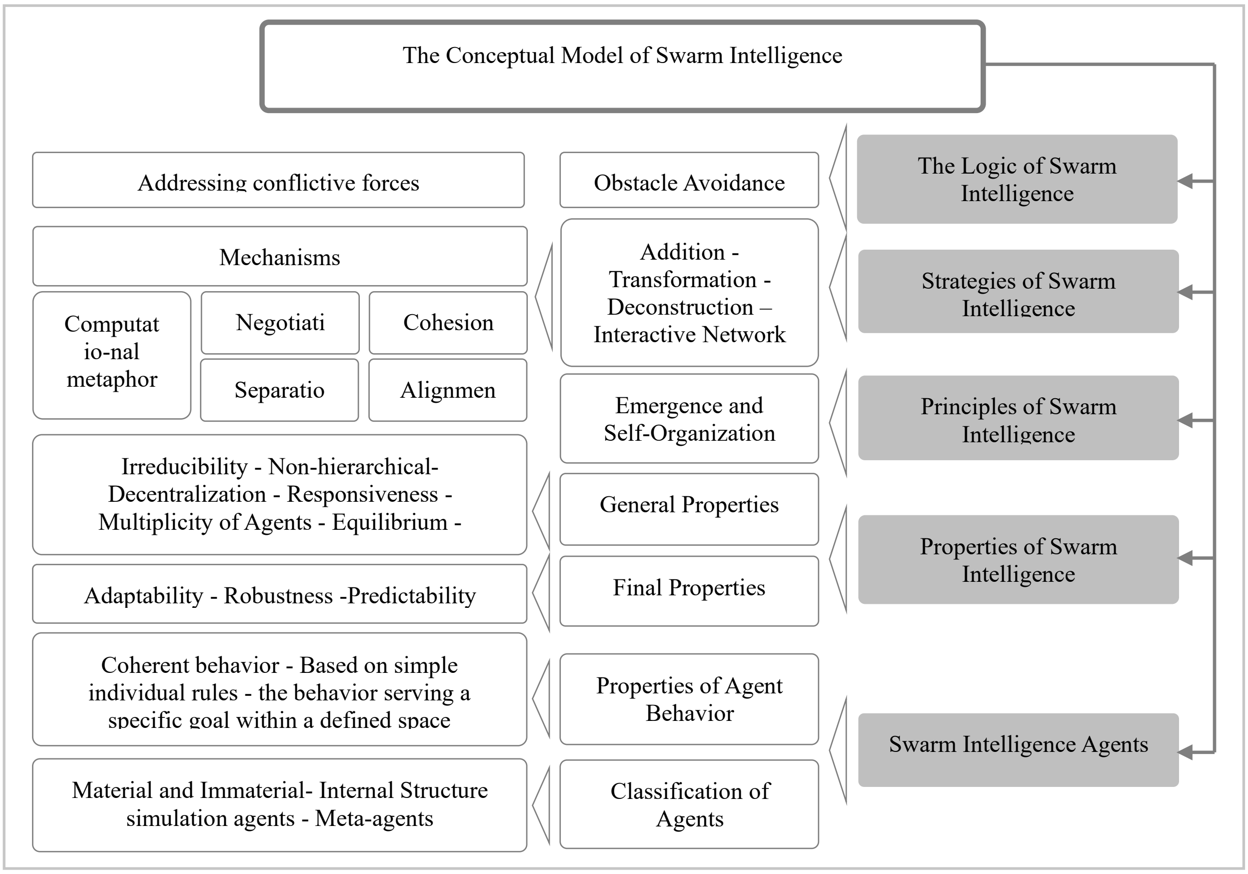

Figure 1: Construction of the Conceptual Model of Swarm Intelligence, the researcher based on previous literature review (Source: Authors).

4. Case Studies Related to Swarm Intelligence:

This section discusses several case studies that use swarm intelligence capabilities within parametric and generative design frameworks. These experiments focus on identifying the obstacles that the system seeks to avoid and the variables used to achieve its goals, as follows:

4.1. Redesign of Melbourne Docklands, Australia / Roland Snooks and Robert Stuart-Smith / 2009:

This project establishes an urban design methodology based on the emergent capabilities of swarm intelligence to redevelop the Melbourne Docklands. Applying swarm logic to urbanisation shifts the approach from traditional master planning to algorithm-based design, transforming urban design from a series of sequential decisions within a limited scale to a synchronised process where multiple partial or local decisions interact to generate a complex urban system. Instead of designing an urban plan that meets a set of criteria, urban imperatives are programmed into self-organised agents. This approach leads to flexible systems that respond to the changing forces of urban development by employing three key swarm intelligence concepts. Decentralisation: The hierarchical sequencing of scales and densities is a traditional urban design requirement. However, the decentralisation inherent in swarm logic flattens the hierarchical structure of urban systems in the design process by portraying all elements of the urban fabric as having agency. This allows them to interact without requiring a sequential hierarchy in design, making the obvious hierarchical density at the macro level an emergent result of the self-organising process of urban fabric elements. Agency: The agency operates through two primary processes within this design: First, using design agents to self-organise urban material (physical structure), and second, encoding intelligence into urban system elements and topologies. Agent Stratification: Agents in swarm intelligence systems are not general but exist within a system of agencies. This divides urban system agents into groups programmed according to their preferences and specific information. In this proposal, there are two groups of agents: the first creates a self-organising program called stigmatic growth, which resembles the collective behaviour of material aggregation in termite colonies. The second group’s behaviour is similar to the self-organising processes of the slime mould, which constructs systems with minimal movement paths akin to the collective organisation in ant bridges. This group is used to create circular infrastructure networks such as transportation networks (functioning as vascular systems). The project aims not to map agents within the urban plan but to create a system capable of generating collective intelligence within self-organising urban structures by exploiting the ability of swarm intelligence systems to create complex, three-dimensional urban structures and networks. It replaces the dominance of master planning with urban algorithms. Thus, swarm intelligence can evolve into a flexible planning tool that is adaptable to the changing needs of the environment and responsive to stimuli, interactions, and unforeseen actions of residents. This design process involves billions of computational steps, creating feedback loops that improve the system and reduce errors, a process Leach describes as the inheritance of operational processes with higher levels of abstraction involving the embedding of design intent into a set of independently self-organising agents to generate emergent urban forms, as illustrated in Figure (2).

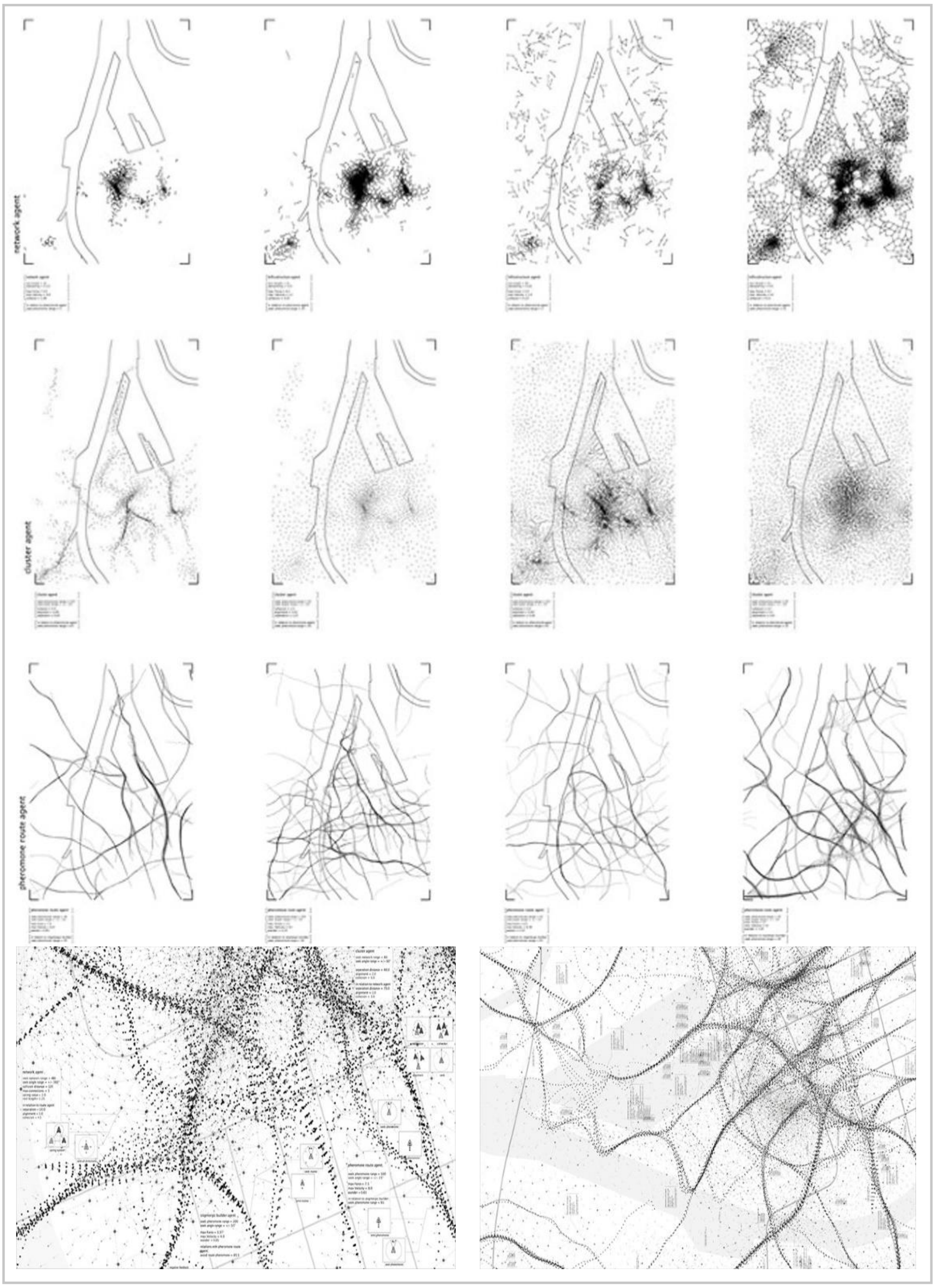

Figure 2: Application of swarm intelligence principles in the Melbourne Docklands redevelopment project, Source: (Snooks, R. & Stuart-Smith, R., 2009).

4.2. Swarm Urbanism Project / Zhaochen Wang / 2011:

This project explores an interactive space between nature and urban life by applying swarm intelligence at multiple levels to create a space that resembles natural landforms. The project's site is in a cold, polar climate that diminishes urban vitality; hence, colours were used to enhance the project's dynamism and attract users. The project's functional program mirrors the diversity of land use in the city, with activities distributed within the project area proportionally to their presence in the city. Spaces and volumes were then generated according to local users' preferences and lifestyles, with half of the design unit's area designated as a shared space integrating nature with functional space using computational algorithms. The vertical layering of the activities, guided by generative algorithms, resulted in various masses with differing heights. The area was covered with a comprehensive structure beneath which the activities were distributed in tectonic forms, varying in usage ratios, area, and height. To enhance the project's interaction with its environment, the external structure was clad with transparent solar panels that change colour with temperature variations and possess reflective properties to better integrate with the surroundings. The project employed two main form generation mechanisms: Variation: The final external shape features differing heights, creating a form resembling natural landforms. This height variation results from the second mechanism. Computational Metaphor: This involves calculating a specific variable for a level within the urban system and then applying it to another level. In this project, land uses in the surrounding area were studied, and the results were applied to the distribution ratios of functions within the project area. Each land use was considered a local agent within the swarm intelligence system. Eventually, the project's interaction with its environment was enhanced by making it responsive to changing climatic conditions. The aspects of swarm intelligence applied in this project are:

- Benefiting from swarm intelligence system properties like interactivity, responsiveness, and sensitivity.
- Utilising computational capabilities to generate algorithms that align with user preferences.
- Creating feedback loop: The project's self-organisation role is unclear, possibly due to a negative feedback loop that guides shape generation procedures. Increased organisation led to a predictable final form, suggesting that achieving this final shape was an inherent intention within the system's agents, as illustrated in Figure (3).

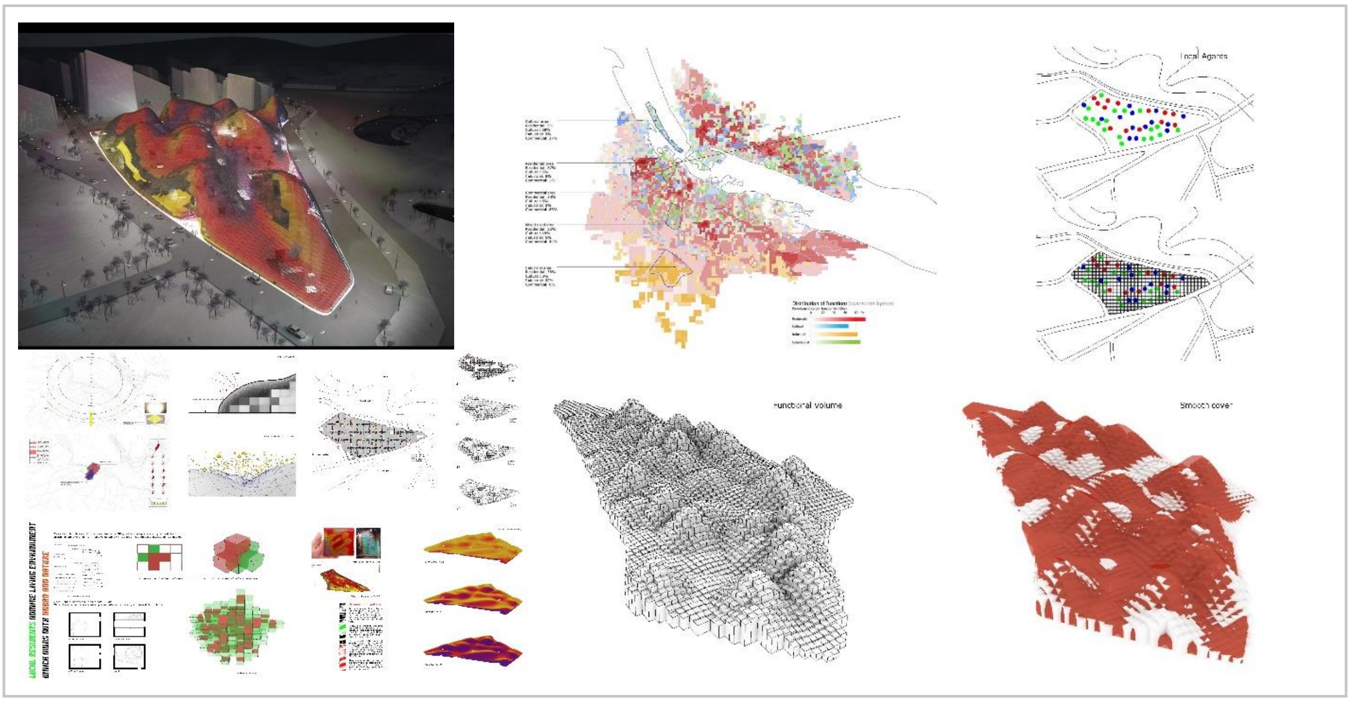

Figure 3: Application of swarm intelligence in the design of the Swarm Urbanism project, Source: (Zhao, 2011).

4.3. Taipei Performing Art Center / Roland Snooks / 2008:

- Targets: Event location, achieving a building pattern and creating a circular movement system between spaces.
- Selected parameters to Address the targets: Area, height, volume, and movement pattern.
- Procedures of Form and Structure Generation: This experiment aims to deconstruct the traditional design criteria related to spatial enclosure to create a performing arts space and a public exhibition area. The process involves a negotiation between the site constraints (obstacles) and the parameters programmed to avoid conflictive relationships with these constraints. The objective is to generate a structure that accommodates a space with specific functional characteristics. To achieve this, swarm intelligence generative potentials were employed to program the requirements of the experiment and transform them into applicable tectonic forms shaped according to the site's outline. A surface encompassing the entire project space was modelled. Intersection points on the surface structure were considered to be agents within a swarm intelligence system, with each agent responsible for generating and defining a segment of the surface area. To establish a network of relationships between the surface points, each group of agents represented a segment of the area. To facilitate the negotiation between the opposing forces in the design (parameters and obstacles), Craig Reynolds' model was used to program agent behaviours through isolation, linear alignment, and cohesion. Figure (4) illustrates the procedures for generating the form and structure using the negotiation capabilities of the swarm intelligence agents.

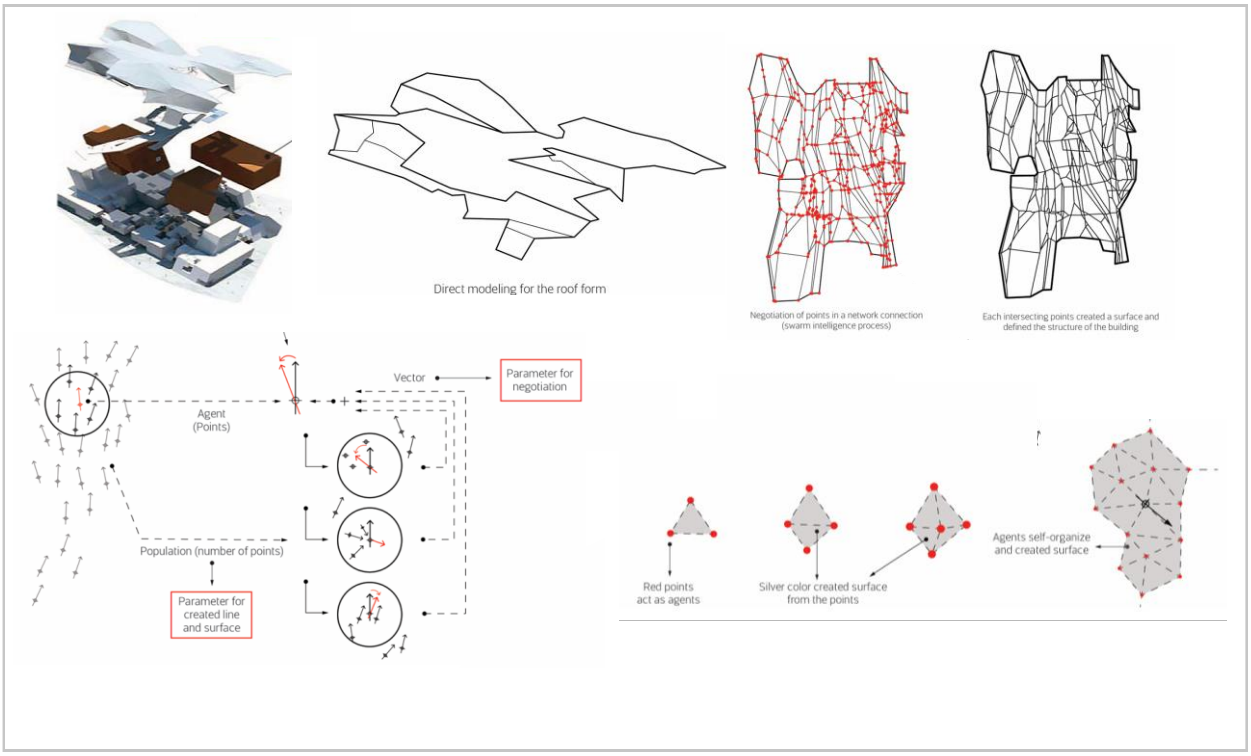

Figure 4: Use of swarm intelligence to generate form and structure for the Taipei Performing Arts Center project, Source: (Azmy, 2016).

4.4. Generating Structural, Spatial, and Ornamental Patterns Using Swarm Intelligence:

- Target: Generating an ornamental facade and an inhabitable space.
- Selected parameters to Address the target: Structure height, floor thickness between levels, floor heights, and number of floors.
- Procedures of Form and Structure Generation: This experiment employs generative design and direct modelling to create the initial structure of the building, followed by the use of swarm intelligence to develop the final ornamental structure. Subsequently, the intersection points of the lines in the generated design can interact non-linearly, creating a networked, inhabitable space through self-

organisation. Hierarchies of nonlinear interaction among local agents in the generated form emerge, varying in complexity and density, as illustrated in Figure (5).

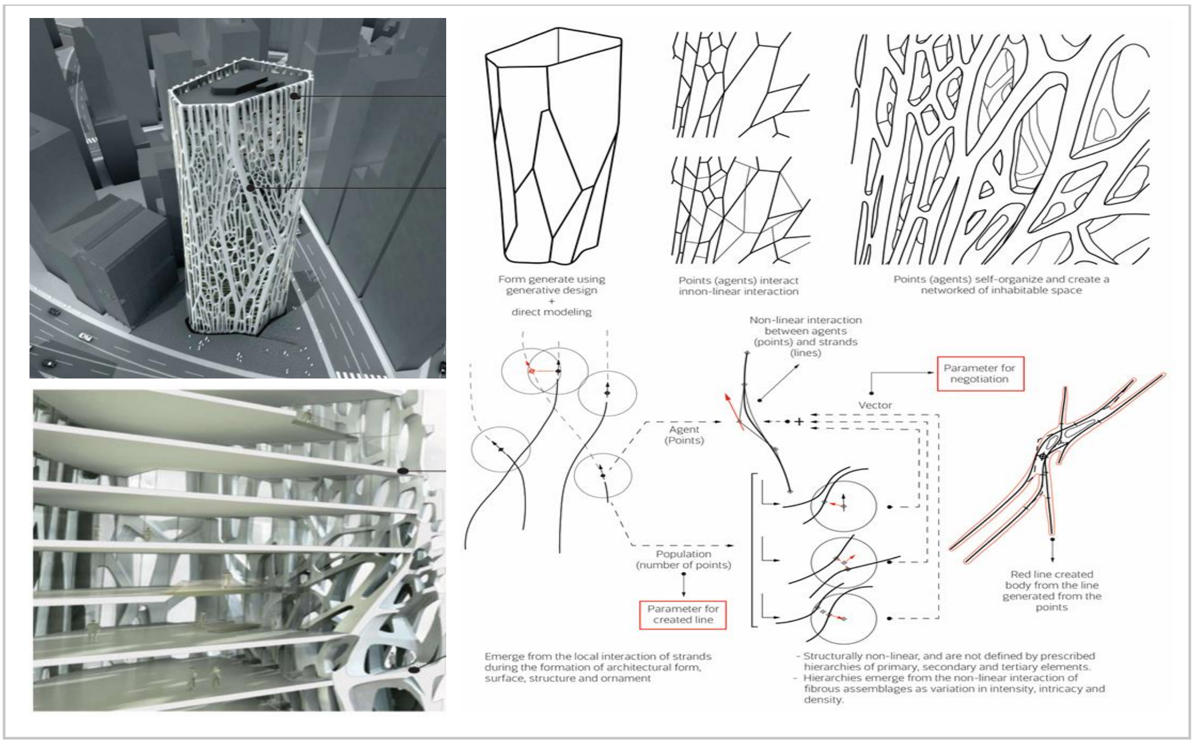

Figure 5: The structure and decorative facade were generated using generative algorithms and swarm intelligence Source: (Azmy, 2016).

4.5. Form Generation Using a Grid Network:

- Target: the objective is to create a facade that maximises sunlight penetration.
- Selected parameters to address the target include grid cell dimensions (width and height), required ratio, distance between points, and steering force.
- Procedures Form and Structure Generation: This experiment involves creating a form using a grid composed of square cells with dimensions that can be adjusted according to the designer's preferences. After partitioning the area into a grid of cells, the centroid of each cell is identified. The cells are then classified into two categories, those representing mass and those representing voids, after which the centroid of each cell is recalculated. The intersection points of the cell edges are designed to function as seek points, programmed to fulfil the intended design objectives. These points, along with the cell centroids, act as agents of swarm intelligence. The next step involves employing Craig Reynolds' model behaviours to move the points, thereby generating a form that aligns with the design intent and targets defined by the grid dimensions and cell properties, as illustrated in Figure (6).
- The conceptual model developed in the previous section will be applied to the projects discussed. This application is detailed in Table (1).

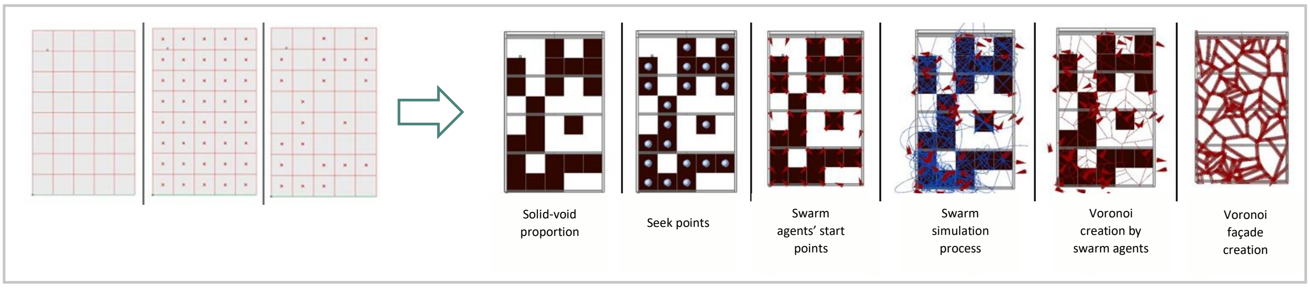

Figure 6: Shape generation using parametric and generative design software, Source: (Agirbas, 2019).

Table 1: Applying the conceptual model of Swarm Intelligence to the case studies, the researcher based on the analysis of previous knowledge (Source: Authors).

Case Studies	Logic and Target of the Case Study	Strategies	Mechanism	Properties	Principles	System's Agent Creation
First Case Study	Generating complex, three-dimensional urban structures and networks	Transformation	Stigmergic growth	Non-hierarchy	Emergence & Self-organization	Abstract virtual representatives
			Pathfinding	Agency		
Second Case Study	Linking nature and urban life by creating a dynamic interactive space	Generating volumes of varying heights	Variation	Dynamism		Virtual representatives based on computational metaphors
			Computational metaphor	Interactivity		
			Reflection	Resilience		
			Differentiation	Responsivity		
				Sensitivity		
Third Case Study	Determining optimal event locations, achieving construction patterns, and creating a circulatory movement system between spaces by controlling area, height, volume, and movement patterns	Deconstruction	Negotiation	Nonlinearity		Intersections of the generated surface
			Cohesion			
			Separation			
			Alignment			
Forth Case Study	Generating an ornamental facade and usable space by controlling height, floor thickness, floor height, and the number of floors	Gradual Generation (Generating the structure using generative algorithms and then generating structural details using the swarm intelligence system)	Generative Algorithms			Intersections of the generated structure
Fifth Case Study	Generating a facade that allows maximum sunlight penetration by controlling the dimensions of the grid cells (width and height), required ratio, spacing between points, and steering force	Interactive Network	Cohesion			Intersections and centroids of the grid cells
			Separation			
			Alignment			

5. Conclusions:

Swarm intelligence refers to nature-inspired systems that are characterised by their robustness and high adaptability to environmental conditions. The study of these natural systems aims to understand emergent urban phenomena—phenomena that are greater than the sum of their parts and arise from intelligent, meaningful, and self-organising collective behaviour. Understanding the potential and contributions of swarm intelligence is essential for formulating effective urban policies that address complex urban challenges, such as managing urban growth in a dynamic environment. The swarm intelligence system seeks to reduce randomness by creating multiple stable dynamics, which can be expressed through a set of direct mathematical relationships that arise from understanding the interactions among swarm intelligence agents. These agents can represent any element or level within the urban system, resulting in a continuous loop of reciprocal assumptions that lead to an ongoing negotiation between the primary components of the urban system: the city and its inhabitants. It suggests the potential for developing urban policies that program agent behaviours to align with policy goals rather than merely complying with them. Thus, swarm intelligence represents a system that integrates mathematical and social aspects within a unified framework.

The conceptual model of swarm intelligence encompasses several key dimensions that warrant examination. It includes an introduction to the theoretical foundation of swarms, elucidating their internal logic and the principles governing swarm intelligence systems, and discussing the behaviour and classification of swarm intelligence agents. Swarm intelligence is characterised by its non-hierarchical and decentralised nature; however, this does not imply the absence of hierarchical classification among agents based on their influence on the behaviour of other agents or their respective levels. Swarm intelligence systems consist of three layers of agents: routine agents, meta-agents, and internal structural simulation agents (BDI agents). Each of these layers has specific objectives within the system to ensure the survival of the urban environment. Swarm intelligence systems facilitate the analysis or prediction of the future state of urban systems by translating the city's behaviour into algorithms based on local data, which considers the unique probabilities associated with each urban system. Subsequently, swarm intelligence transforms these algorithms into architectural tectonics, which represent behavioural rules that generate morphological patterns recognised as emergent behaviour. This emergent behaviour persists over time due to its proven ability to support the system's survival. Thus, the continuous change, transformation, and growth of the urban system represent a negotiation process between generating new possibilities and preserving original pathways (the causes of system emergence). The primary goal of swarm intelligence is to preserve the system by circumventing physical and non-physical urban obstacles through the development of generative mechanisms that lead to the ongoing improvement of urban formations. This results in more sustainable urban configurations that support the system's growth and development over time.

When constructing a comprehensive conceptual model of the dimensions of swarm intelligence, it is essential to recognise that this model is multi-layered. It consists of general strategies, mechanisms for implementing these strategies, and an emphasis on the overarching characteristics and principles that most significantly influence each strategy. Given the limited number of studies addressing the integration of swarm intelligence at both theoretical and practical levels, there is a pressing need to supplement the review of previous urban studies with several case studies. The analysed case studies revealed a diversity of urban challenges and limitations, ranging from large-scale urban projects to smaller initiatives aimed at generating form and structure. It was observed that the application of swarm intelligence necessitates a complex environment with multiple possibilities to pursue the most suitable scenarios or to develop new ones, particularly in the context of Scenario-based design to support urban system balance. Generally, all case studies included two main phases: analytical and generative. Consequently, the elements of the conceptual model of swarm intelligence can be categorised into analytical elements, which focus on analysing the urban system and generative elements, which use local computational analogies to regenerate possibilities that reflect the overall quality of the urban system.

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