Spatial Flexibility in Architecture: An Approach to Integrating Intelligent Swarm Robots for User-Centric Autonomous Architectural Layouts

BT Graduation Studio
Master Thesis

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“The measure of intelligence is the ability to change”-Einstein

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Dedication

I would like to dedicate this thesis to my brothers and sisters in Iran who fight everyday for the freedom of our country despite the brutal oppression of the current regime and to those who have lost their lives on this way, those who are still in prison and anyone who is holding the torch of life in Iran burning. I hope one day I look at this page and smile that our country is finally free.

01

Abstract

This thesis investigates the integration of intelligent swarm robots as wall systems in the creation of automated architectural layouts tailored to user preferences, with a specific emphasis on ensuring spatial flexibility. The research seeks to address the challenges associated with accommodating swarm robots to create flexible architectural layouts while harnessing the adaptability and collective intelligence of swarm robotics. The study aims to contribute to the evolving field of user-centric architecture by exploring novel ways in which swarm robots can dynamically shape and customize spatial configurations to enhance comfort, user participation, and satisfaction. The research methodology involves the development of a framework that combines principles of swarm intelligence, user-centric design, and flexible architecture. By leveraging swarm algorithms and self-organizing strategies, the swarm robots will be configured to respond to users' preferences and needs and the evolving nature architectural space.

Key Words: Swarm Robotics, Autonomous Architectural Layouts, Responsive Architecture,User Centric, Swarm Intelligence Algorithms, Spatial Flexibility

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I

Introduction

A. Background

1. Overview of Responsive & Adaptable Architecture

According to Gero and Radford (1988), design consists of three initial phases which are shown in Figure 1. These phases form a cycle that helps designers find the optimal solutions. When we talk about design evolution and design synthesis, we define a search for optimal design solutions that are adaptable to different design languages.

Adaptability in architecture is characterized by the inherent capability to adjust, modify, and respond to various factors while enabling the configuration and

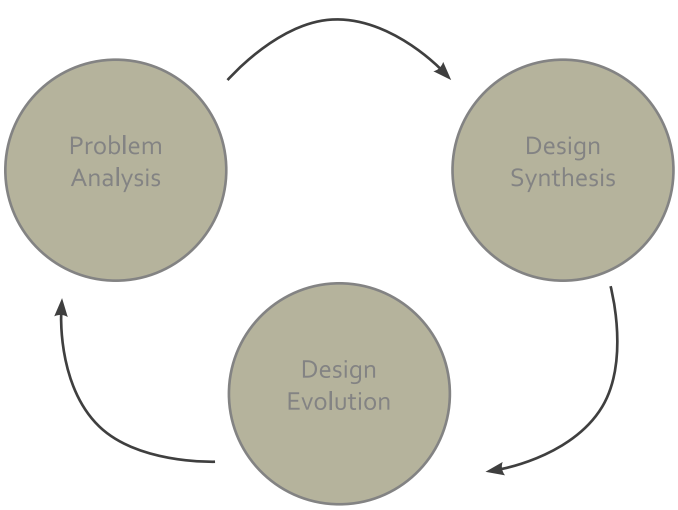


Figure 1. Three initial phases of design. Replicated from Design by Optimization, in Architecture, Building, and Construction. Radford, Gero (1988).

facilitating changes in spatial, functional, and technological components (Schmidt III and Austin, 2016). This occurs without causing significant disruptions to a building, its ongoing activities, and the external environment. Through cultivating opportunities for diverse uses, adaptable architecture recognizes that buildings are not static objects, and must remain useful and thus unfinished, to accommodate the transient nature of user needs, the context they are built in, climate, and technological advancements. Hence, design choices that determine the scale of building adaptability can enhance or deteriorate building performance and durability (Kooi,2022).

Adaptability in architecture is closely related to the notion of flexibility. The distinction between the two is further expanded on in section B.2. Robert Kronenburg (2007), acknowledges that the term "flexible architecture" denotes architecture that responds to change. According to Kronenburg, architecture is complete when it is occupied and utilized by humans, and flexibility might be better defined as transformable, kinetic, and movable architecture that addresses occupants' preferences. Since this study aims to use swarm robots for spatial configuration, the term and concept of flexibility will be the focus of this research.

The evolution of architectural design has been based on contextual, social, and cultural transformations that brought about different occupant identities and needs at different times(Estaji, H., 2017). The emphasis on interactive, responsive, and intelligent architecture came from new advancements in computer science and construction technology which converted architecture from a static to a dynamic state (Corbusier, 1923).

In 1958, in the Mobile Architecture Manifesto, Friedman asked "Why should architects decide for the people who live in their buildings? Later that year, he proposed 'spatial town planning,' in which residents would have flexible structures that allowed them to adapt their areas as needed. In 1961, Cedric Price (1961) introduced 'Fun Palace' with the aim that a building or space be constantly generated or regenerated. From then on, flexibility as a new social notion based on the application of new technologies and involving the occupants in constructing a space has been developed (Kendall, 2004).

Price's visionary project; which will be elaborated on in in section B.2.1, highlights the importance of user-centered design and flexibility in architecture. As we confront modern challenges, like rapid urbanization and climate change, the principles that Fun Palace uses can offer valuable insights into creating dynamic, responsive, and inclusive environments that can accommodate changes well without disruption. These environments are not only functional and aesthetically pleasing but also sustainable, resilient, and conducive to human well-being (Zeng et al., 2022).

It was however, Nicholas Negroponte who published several books and articles, such as "The Architecture Machine" (1970), "The Soft Architecture Machine" (1975), and "The Semantics of Architecture Machines" (1970), which represented early efforts to conceptualize and realize responsive architecture. In these works, Negroponte argued that integrating computing technology into buildings and spaces naturally leads to the development of responsive architecture (Liu, 2016). Although, this thesis will mainly use the term ''spatial flexibility'', it is without doubt that the process and product of it, inherently will be developed by using many principles that are similar between flexible and responsive/comupterized architecture.

2. Significance of User-Centric Design in Architecture

According to the Interaction Design Foundation, the term User Centric Design or UCD was coined by computer scientists in the 1970s and is defined as " an iterative design process in which designers focus on the users and their needs in each phase of the design process. In UCD, design teams involve users throughout

Table 1. Comparison of four approaches suggested by Saffer (Replicated from Chammas, 2015)

Approach	Overview	User	Designer
Activity Centred Design	Focus on tasks and activities that need to be fulfilled	Activities Practitioners	Tools creator for the actions
System Design	Focus on system components	Set of system goals	Ensure that all parts of the system are in place
Genius Design	Ability and gift of designer used to make products	Validation Source	Inspiration Source
User-Centred Design	Focus on the needs and user goals	Lead interface design	Reflects the needs and user goals

the design process via a variety of research and design techniques, to create highly usable and accessible products for them"(IxDF, 2016).

According to Saffer (2010), there are four main approaches in the development of successful interactive design products, which include: activity-centered design, System Design, Genius Design, and User-Centred as shown in Table 1. He suggests the best approach would be a mix of more than one, but also explains that the most popular one is the User-Centred Design approach since user participation is crucial in all stages of design.

The user-centric approach in architecture is a profound understanding that architecture is not merely the construction of edifices but the crafting of environments that resonate well with the human experience (Alexander, C. et al., 1977). Based on the concepts of phenomenology in architecture, it fosters the well-being and a sense of belonging in users, by creating an environment where users not only exist but also thrive. In other words, user-centric design offers a solution to the problems and complexities that rapid urbanization and social changes pose. It helps individuals associate actively with their surroundings and have a sustained evolving relationship with architecture, which in turn influences their perception of the world and themselves.

B. Problem Statement

1. Challenges of Spatial Inflexibility

Inflexible architectural layouts impose numerous constraints on space utilization. The nature of many architectural layouts due to using heavy fixed wall systems fails to align with the dynamic requirements of users and the evolving circumstances of an architectural space. In essence, as the needs evolve, and the spatial utilization changes, these layouts usually become inefficient (Askar et al., 2021). When the users often are not involved in the design process, these layouts create spaces that do not respond to the user preferences, behaviors, or needs (De Paris & Lopes, 2018).

Another issue the inflexibility of architectural layouts creates is that they cannot integrate new technological advancements. With the rise of the Internet of Things (IoT) and smart building technologies, layout inflexibility makes automation, energy efficiency, and improved user experience, difficult, which then leads to outdated structures, high vacancy, and refurbishment or renovation costs (Manewa, A.,2016). Changing these layouts can be more expensive than designing flexible layouts from the beginning. Inflexible layouts also are not usually optimized for sustainability and can not be easily upgraded with proper up-to-date building systems like HVAC, MEP, and communication systems (Slaughter, E.S. 2001).

Nonetheless, for a space to fulfill specific requirements and needs, it must be equipped with appropriate building systems. The RIBA Plan of Work (2020) defines building systems as: 'The constituent parts of a building, including, but not limited to, structural systems, mechanical and electrical systems, façade, ceiling, floors and wall systems' (Royal Institute of British Architects, 2020). In his article "Last Apple", Koolhaas discusses the relationship between space and building systems and emphasizes the significant role of building systems in attaining spatial flexibility. Achieving flexibility involves integrating building technology with spatial design and while advanced building systems play a crucial role in facilitating flexible spaces, it is essential not to compromise spatial quality. The effective organization of spaces, coupled with advanced technology, can create a flexible and high-quality environment. (Koolhaas, 1995).

After all, since the focus of this study will be on wall systems, it will explore the customization of architectural layouts that can cater to various functions and preferences, based on new concepts of such systems. In the context of work or educational spaces, for instance, it will explore how flexible layouts can create dynamic and collaborative environments leading to better performance and wellbeing of the occupants.

2. Role of Intelligent Swarm Robots in Adaptive Design

Swarm robots can offer innovative solutions to the problem of flexibility in architectural layouts. This study will try to test this hypothesis that if swarm robots are used as intelligent building blocks they could potentially create flexible spaces which match the user preferences. Inspired by natural swarm behavior, these robots can dynamically adjust their configuration and spatial arrangement, allowing for the creation of spaces that can cater to various functions and activities. They can also instantly respond to the changes in the environment and user requirements as they operate in real time.
Moreover, their collective behavior is a powerful asset. Swarm robots can work collaboratively, sharing information and coordinating actions to achieve a common goal. This collective intelligence can be harnessed to optimize the spatial arrangement efficiently based on user preferences and environmental factors.This eases the process of customization and assembly which allows for the creation of personalized spaces and maximizing the utilization of available space for quality experiences. Above all, Swarm robots can allow for scalability in design with their adjustable configuration and modularity and thus, offer versatile solutions for a range of architectural applications.

C. Objectives of the Thesis

1. Utilizing Swarm Robotics for Spatial Flexiblity

The primary objective of this thesis is to explore and demonstrate the potential of using swarm robotics in the realm of flexibility in spatial layout design. This research endeavors to bridge the innovative intersection of robotics and architecture by taking the first attempt at implementing swarm robotics into the creation of flexible architecture layouts. It aims to do so, by enhancing the user experience and engagement with built environments. By employing swarm robotics, characterized by de-centralized intelligence and collaborative behaviors, this thesis seeks to redefine the traditional paradigms of architectural design. The focus lies in creating adaptive, flexible wall system modules that respond dynamically to user needs and preferences, ultimately contributing to a more personalized and interactive architectural experience. Through simulation environments, this thesis hopes to establish a well-defined case for the integration of swarm robotics as a transformative tool in shaping the future of architecture that is deeply attuned to the diverse and evolving nature of human life and also our world.

D. Research Questions

This research aims to answer the following questions:

1- What are the key design parameters to achieve spatial flexibility in architectural layout design?

2- What are the most optimal strategies and technological frameworks to efficiently integrate swarm robotics into architectural workflows, which allows for the creation of autonomous layouts that continuously respond to user preferences and evolving spatial requirements?

3- What are the necessary steps to prototype a sample scenario of a robotic swarm configuring a flexible architectural layout?

II

Literature Review

A. Responsive Architecture

Similar to human behaviors, smart environments exhibit certain patterns of responding to specific conditions. In contemporary architecture, with the advancement of technology, the built environment has seen a paradigm shift that redefines the boundaries of conventional design, construction, and human interaction and is defined as 'responsive architecture'; a dynamic field that tries to develop a symbiotic relationship between the built environment and its inhabitants. The term is often associated with adaptive architecture or intelligent and smart environments.

Responsive architecture is a term coined by Nicholas Negroponte in the 1960s when cybernetics was applied to architecture to solve spatial problems. In his theory of "architecture machines," he describes that advances in AI and computerized elements can help buildings intelligently understand occupants' activities and then respond to their needs. Consequently, architecture can change its environment internally and externally (Lee et al., 2021). As Negroponte (1975) states, responsive architecture is defined as an environment that has computationally integrated responsiveness. Responsive architecture is capable of altering its configuration in reaction to changing circumstances. According to Negroponte, it is therefore an artificial entity that responds to data and information collected through various sensors. This response can be manifested through change and movement in physical form or adaptations in services such as lighting, heating, and ventilation. In modern terms, responsive architecture takes advantage of advanced technologies of AI, robotics & machine Intelligence, and kinetic & responsive systems (Rajan, K.; Saffiotti, A., 2017).

Responsive environments where often diverse computerized systems are operated, are made of large sets of digital products that are made feasible through the help of IoT, Big Data, cloud computing, or information communication technology known as ICT. Thus, responsive architecture introduces two large digital ecosystem models of interactive behavior and collective behavior termed IBs and CBs respectively (Lee, et al., 2021).

In the context of responsive architecture, IBs refer to the changes and responsive actions that a structure or environment exhibits in response to its interactions with the users or external conditions. It involves the transformation of physical form or alteration of services, which entails a continuous interaction between the user and the environment.

On the other hand, CBs refer to coordinated responses or adaptations, made by a structure or environment based on collective interactions, either among its users or due to shared external stimuli. Since CBs mostly execute and run IBs, IBs can be translated as "product" while CBs are defined as a "process " (Lee, et al., 2014). In any of the two, collecting and sensing information is what activates the context-driven changes. Figure 2 shows the spatial and informational hierarchy between smart environments and architectural behaviors in a digital ecology (Lee, et al., 2021).

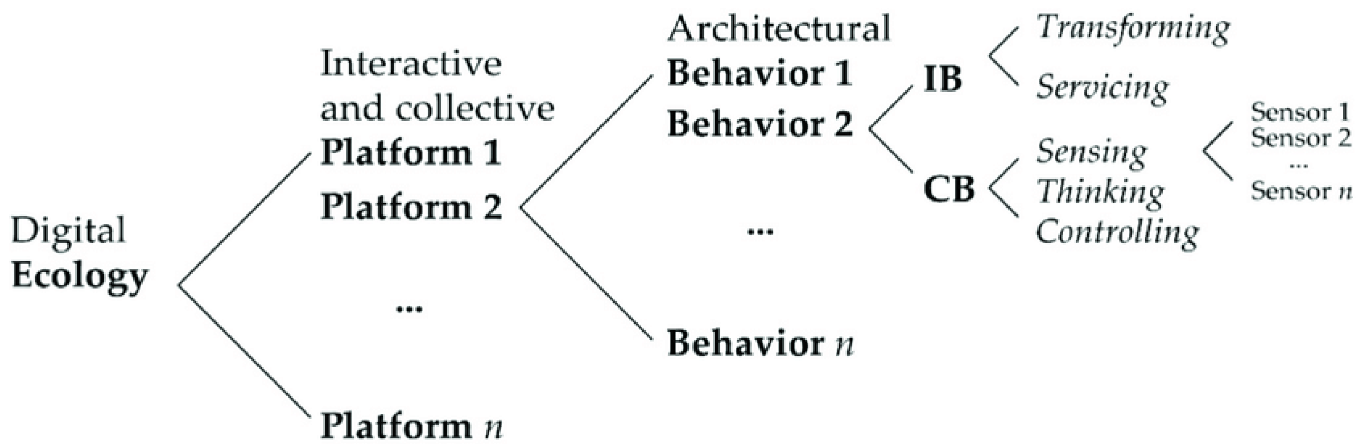


Figure 2. showing "spatial and informational hierarchy between sensing behaviors, architectural behaviors (IBs and CBs) and smart environments (interactive and collective platforms) in the digital ecosystem." Understanding sensing behaviors helps with constructing smart environment. Diagram retrieved from Characterizing Smart Environments as Interactive and Collective Platforms: A Review of the Key Behaviors of Responsive Architecture by Lee et.al (2021)

Meyboom et al (2011) delve into Interactive Behaviors (IBs) in architecture and explore recent developments, such as interactive kinetic media facades using Delta robot kinematics and adaptive solar facades such as Jean Nouvel's responsive screens in Institut du Monde Arabe in Paris shown in Figures 3-5. IBs and such responsive facades are a popular topic of contemporary architecture (Mayboom, A., et al., 2011).

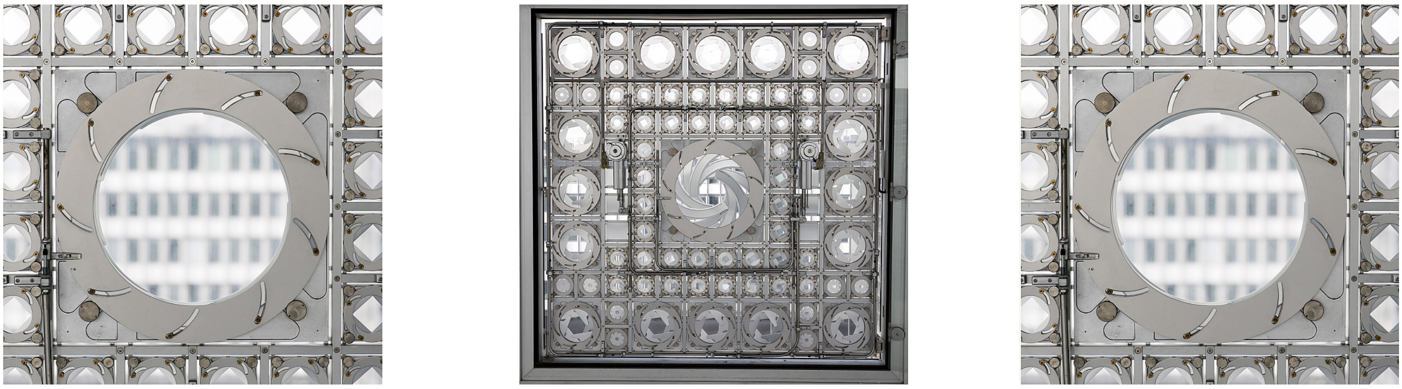


Figure 3 -5. Showing the dynamic facade of Institut du Monde Arabe in Paris by Jean Nouvel. The system uses hundreds of light-sensitive diaphragms to control the amount of light that is allowed to enter the building. The lens opens and closes in steps and forms different geometric patterns which modify the interior spaces along with the exterior. In recent years many similar strategies have been used in building facades. Retrieved from https://www.imarabe.org/fr/architecture

The CBs of responsive architecture correspond with the IBs of the system. Energy and comfort-related indicators like temperature and humidity optimizations, glare probability, sun tracking for daylight harvesting, light levels, and illumination uniformity, noise threshold, the external view can be identified and managed through a network of integrated micro-sensors that engage users actively and passively and introduces the concept of interactive intelligence.

Furthermore, the way collective behaviors (CBs) of responsive architecture are automated and controlled decides the performance of the building. These include control strategies (open-loop or closed-loop systems, single- or multi-variable systems), controlling technologies (self-sensing and self-actuating technology), and controlling algorithms (Al-Masrani, S.M.; Al-Obaidi, K.M.,2019). The systems, after receiving feedback, in turn, interpret sensor signals derived from user interactions and translate them into commands for actuation. Subsequently, actuators generate responses within smart environments.

To better understand context-driven changes, according to Mitchel (2004), in line with Negroponte's concept of responsive architecture and the evolution of space, we need to also understand whether architecture is more about "particularization" than "generalization". Particularization in this sense, is using computing technologies for individual responses and solutions while generalization is over-simplification for the sake of rapid developments. In Negroponte's concept of responsive architecture, particularization will be reframed as computation and materialization (Lee, et al., 2021).

In responsive architecture, materialization has a particular significance and to achieve architectural robustness and ideal performance, optimization of materials is a necessity. Since the early works on responsive architecture, the realization of flexible components typically has been manifested through soft surfaces, like the inflatable plastic artworks of Eventstructure Research Group (ERG) in the 1960s, shown in Figures 6 and 7. The fragility of such materials has always put limitations on their application in larger scales of responsive architecture. Examples of biomimetic and kinetic architectural projects show the search for the materialization of responsive architecture for larger-scale projects still goes on. Therefore, emerging architectural technologies, often seek to enable non-linear interactions with real-time sensory data that is collected and fed into the building's intelligent central system to understand human and environmental needs to appropriate architectural responses within changeable or smart building components (Hosseini, S.M., et al., 2019). Such reflexive behaviors change the built environment from a series of static objects into a dynamic/ interactive"smart" system (Kroner, W.M. 1997). The result would be a "machine" that is not mechanistic as Oungrinis (2014) defines whose components can be mechanical, biological, or robotic (Ramzy, 2011).

Figure 6 & 7. showing the inflatable plastic artworks of ERG, 1969, Amsterdam. Retrieved from https://anambitiousprojectcollapsing.com/aapc//jxnpmqvp3ot7c5iemf4cpohykwpmn2

1. Reactive Vs Proactive Architecture

Meriam Webster dictionary defines the adjectives reactive and proactive as follows:
Reactive: 1. : of, relating to, or marked by reaction or reactance. 2. a.: readily responsive to a stimulus.
Proactive: acting in anticipation of future problems, needs, or changes.

In architecture, both terms are categorized under the term 'responsive'. The traditional design approaches are mostly reactive as they tackle the users' immediate needs. However, with the advent of AI and the fast pace of it, architects are now noticing the need for a more proactive approach that caters to users' needs even before they arise. This avant-garde approach tries to foresee problems to avoid crises or major failures. Proactive design involves anticipatory and context-driven solutions to create personalized experiences. However, the complexity of predicting future issues poses a wide range of limitations on the development of proactive design. Hence, this thesis will try to focus on the reactive aspect of responsive architectural design.

B.Autonomous Architectural Layouts

1. Inflexible Approaches and Limitations

Inflexible or non-adaptive architectural layouts might be considered less than ideal for several reasons, which are mentioned below. However, this study will only focus on aspects of inflexibility for diverse uses, lack of user-centric design, and resilience to change.

Inefficiency in resource utilization: Lack of flexibility to adapt to changing conditions can lead to inefficient use of resources like energy, space, and material (Gosling, J. et al, 2013).

Limited energy efficiency: These layouts often do not incorporate energy-efficient technologies or use passive strategies to take advantage of natural lighting and ventilation and thus, avoid overheating and increased energy consumption (Rabeneck, A.,2021).

Poor indoor environmental quality: Inflexible layouts do not usually optimize air quality or thermal and acoustic comfort which leads to unhealthy indoor environments.

Inflexibility for diverse uses: Space utilization in inflexible layouts can not easily accommodate changes over time. Dynamic modification to support diverse functions within the same space is not feasible in traditional layouts (Rabeneck, A.,2021).

Lack of user participatory design: Lack of user participation in space formation can often lead to user dissatisfaction (Askar et al., 2021).

Resilience to change: Non-adaptive layouts struggle to offer solutions to the continually evolving changes in technology, demographics, and environmental conditions (Pelsmakers et al. 2020).

Sustainability consideration: Sustainable features like rain harvesting, renewable energy systems, and green spaces are usually overlooked in traditional non-adaptive layouts which leads to a large ecological footprint. (Kendall, S.; Ando, M.,2005).

Technological integration: Non-adaptive layouts can not integrate smart technologies seamlessly to enhance efficiency and connectivity (Slaughter, E.S.,2001).

Consequently, inflexible architectural layouts, often designed with fixed, predefined functions for each space, face inherent constraints in accommodating versatility and adaptability. The emphasis on compartmentalized spaces for distinct functions, implies a lack of flexibility in conventional designs, limiting their ability to dynamically respond to evolving user needs or accommodate diverse activities within a singular environment (Hertzberger, 1991). This highlights the necessity for a paradigm shift towards more adaptive architectural approaches that can better address the multifaceted and evolving requirements of users. or non-adaptive architectural layouts might be considered less than ideal for several reasons, which are mentioned below. However, this study will only focus on aspects of inflexibility for diverse uses , lack of user-centric design, and resilience to change.

2. Flexibility Vs Functionality in Architecture: What it is and its Types

Our history as human beings is woven with flexibility. We are a flexible race. We can move, create tools, modify and enhance them, and function in various environments. Our survival as a species depended on our ability to move and adapt. Our nomadic lifestyle and then our sedentary way of living had to be adapted to the many changes in our physical circumstances, needs, and environment. In today's world, our life is once again dependent on the flexibility of our built environment. The success of architecture is dependent on its flexibility.

We spend the majority of our lives within or moving between buildings. We typically perceive buildings as solid and long-lasting entities that shape the places we reside in, educate, or work. We expect our buildings to last for many years, but despite this longevity, buildings undergo transformations – some are demolished while others experience extensions or renovations, to accommodate new requirements, adapt to new climate conditions, or incorporate new building systems. The extent to which buildings adjust to new changes is defined as flexibility. Many architects have aimed at creating flexibility by providing systems and technologies that try to predict the future functions and uses of a building. Although some cases have been successful, the majority of them have failed because their anticipation of the future was not accurate.

The incorporation of ‚flexibility' into the design allowed architects the illusion of projecting their control over the building into the future, beyond the period of their actual responsibility for it (Forty, 2010). Richard Rogers said:

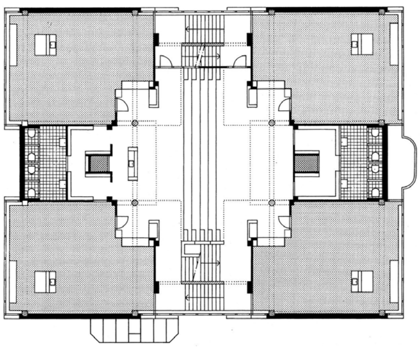
> The impact of accelerating change on the physical form of the city is radical. ... and it is now commonplace to anticipate that a building will outlive the purpose for which it is built in a matter of a few years. Modern life can no longer be defined in the long term and consequently cannot be contained within a static order of symbolic buildings and spaces. ... Buildings no longer symbolize a static hierarchical order; instead, they have become flexible containers for use by a dynamic society (Rogers, 1998).

The term "flexibility" has played a significant role since the 1950s in contemporary architecture, by introducing novel aspects of time and the unknown into architecture as an alternative to the dominant Functionalism (Forty, 2000). Furthermore, the concept of spatial flexibility is increasingly recognized, as it aligns with sustainability and mobility, which are pivotal issues in today's architectural discourse.

On a surface level, flexibility implies immediate relation to movement and adaptability. There exists a straightforward association of flexibility with progress, suggesting that something capable of movement breaks free from traditional constraints, and something subject to change remains perpetually new. Flexibility offers a convenient solution to the prevalent architectural need to be associated with modernity, although most modern flexible projects were one-off experiments based on parts that move or the concept of kit-of-parts. However, to categorize some of the strategies used to achieve flexibility in modern projects we can include adapt, move, transform, and interact.

Young(2013) states that to achieve architectural flexibility in modern times, the most used approach has been what she calls "overprovision first, division later", which has yielded inflexible buildings due to insufficient building systems or irresponsible planning.

Nonetheless, Banerjee & Goel (2023) believes flexibility is not just a design process. It is a cognitive process regarding change that is heavily influenced by the prevailing circumstances. It can not be achieved by a certain plan flow, form, or building systems that ease the multifunctionality of spaces, but by arranging the space so that the user can select space in between spaces. The courtyard of



Figures 8 - 10. Montessori school courtyard in Amsterdam is a space used for different purposes based on user preference. Retrieved from https://www.archdaily.com/915993/montessori-school-de-scholekster-heren-5-architects?ad_medium=gallery

the Montessori school in Amsterdam is a good example of a flexible space as seen in Figures 8-10. Some scholars make a distinction between the two terms 'flexible' and 'adaptable'. Usually, the term "flexible" is used for physical changes, and "adaptable" refers to non-physical changes. Steven Groák (1992) characterizes adaptability as "capable of different social uses" and flexibility as "capable of different physical arrangements". Designing rooms in a way to serve different functions, primarily through a spatial organization or circulation brings in the concept of 'polyvalency', a term used to denote using a space for diverse uses without applying physical alterations. On the contrary, according to Groák, flexibility means modifying the physical structure of a building and pertains to both internal and external alterations and temporary and permanent changes. Examples include sliding and folding walls, or furniture, merging, dividing, or extending rooms. In other words, adaptability revolves around use and function whereas flexibility revolves around form and technique.
It therefore should be noted that it is crucial to acknowledge that flexibility has two distinct faces based on functional demands; one involves accommodating multiple functions whereas the other one criticizes the deterministic nature of functionalism (Kim, 2013)

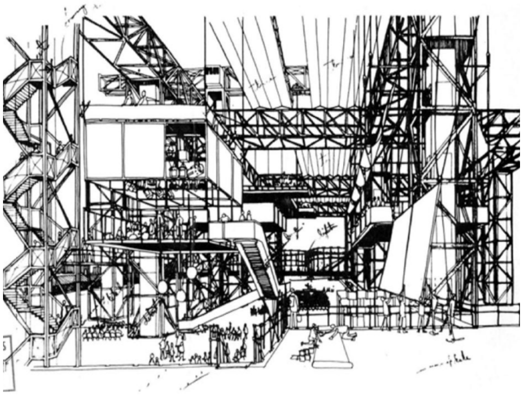
Kronenburg (2002), suggests that flexible architecture has many advantages; it can be used for a longer period, it can serve its individual, cultural, and social functions better, can engage users and their experiences, can incorporate new technology quicker, and is more economical.

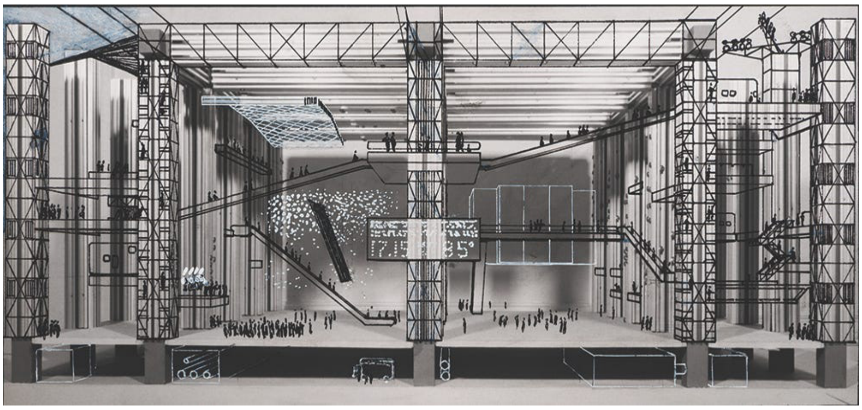
2. 1.Multifunctionality vs Polyvalence

There are a lot of architectural precedents that show multifunctional flexibility. Multifunctional flexibility entails actual alterations in spatial characteristics, such as size, lighting, and acoustic conditions, or the replacement of the space itself. This physical transformation of space allows it to be highly adaptable to users' needs while meeting specified environmental requirements. However, in the usual construction process, after the building design is finalized, it takes one or two years for construction, and the building is typically occupied for at least twenty to thirty years. Therefore, to determine multifunctionality by the anticipating functions that are designated during the design stage, certain uses of the space are predetermined, which is premature given the building's lifespan. This presents the paradox of multifunctionality, as highlighted by various architects, including Henri Lefebvre, who believed the excessive determining of functionalism in the context of flexibility can remove "the possibility of multifunctionality" (Lefevre, 1991).

Cedric Price's Fun Palace is a good example of multi-functionalism as a means of architectural flexibility. Originally it was a proposal for a new performance venue required by by Joan Littlewood's vision for a radical theater scene. It aimed to create a theatrical space free from conventional architectural constraints. Price, who had a keen interest in technology, envisioned "an infinitely flexible, multiprogrammed, twenty-four-hour entertainment center that integrates communication technologies and industrial building components to create a machine capable of adjusting to users' needs" (Goldhagen and Legault, 2000). While initially, it was a prototype for a new performance venue, Fun Palace evolved to be more inclusive by becoming an architectural pioneer designed to provide a non-physical experience by exploring new technology. Price opted for an approach devoid of any formalism to faithfully represent technology. The Fun Palace was conceived with a distinctly multi-functional form, relying on physically moving, changing machinery and IT. Figures 11 & 12 show the Fun Palace.

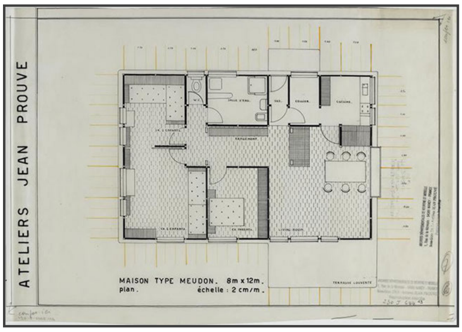
Fun Palace was a successful project since it initiated with an anti-architectural approach, based on fostering the interaction between the space and occupants (performers & audience), while it rejected determining conventional architectural features. However, some scholars like George Baird criticized the project for its reduction of architecture into a machine for life-conditioning by achieving flexibility through technology, which made it impractical for everyday use (Goldhagen and Legault, 2000). In contrast, other projects achieved flexibility through modular layouts and changing units.

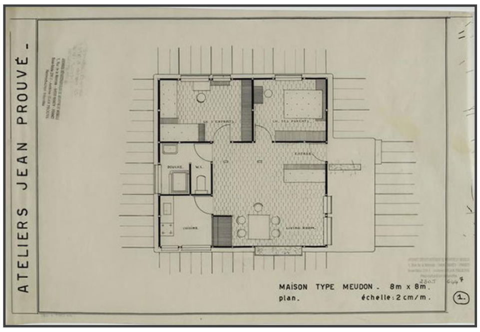




Figures 11,12. Fun Palace by Cedric Price was a project made of a permanent structure but modular units that formed different spatial organizations for theatre performances. Retrieved from https://moooarch.com/fun-palace/# https://medium.com/@likaiqi96 cedric-price-the-fun-palace-57e83cce8c7b   and

Jean Prouvé's Meudon House (1938), was a house designed with 1m modules made from interchangeable panels. The light weight of the panels and their modularity allowed for quick assembly in a day. The occupants could select the material of the panels and, the type of exterior wall (window, solid, door, etc), and the interior space. Prouvé also developed a system called S.I.R.H., an industrialized system with eight basic components. The system opened the way for future architectural flexibility. Figures 13-15 below show the Meudon House modular plan and penalization of them.





Figures 13-15 showing the modular plans and panelization of the Meudon House. Retrieved from https://blog.modernistestates.com/post/176656977805/journal-stay-in-a-jean-prouv%C3%A9-house-in-meudon

In "The Production of Space", Lefebvre (1991) states that in an architectural layout, every function demands a specifically defined space, which inherently constrains the potential for multifunctionality within a given space. This concept aligns with Hertzberger who cautioned direct allocation of specific functions to a space leads to fragmentation rather than spatial unity. He argued that flexibility lies in the "polyvalence of a space." (Hertzberger, 1991). The difference between multi-functionality and polyvalence is seen in Figure 16.

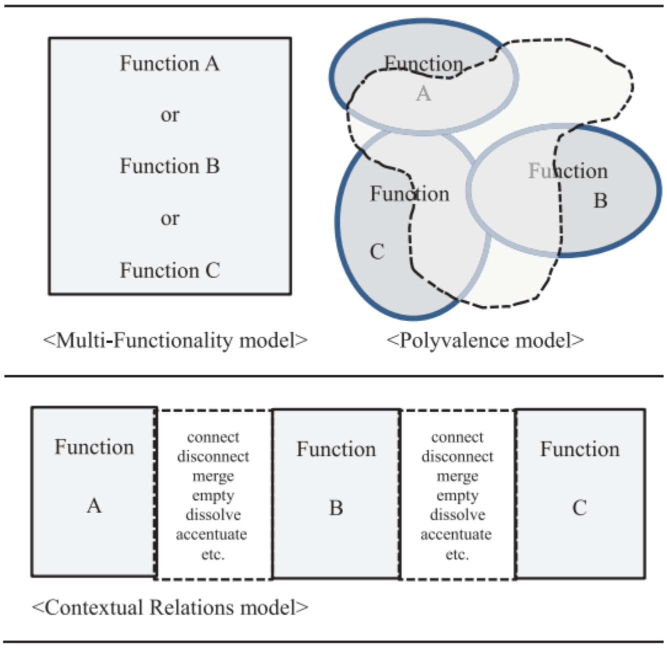
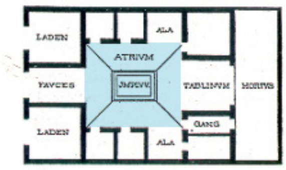


Figure 16. Architectural flexibility and its types. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

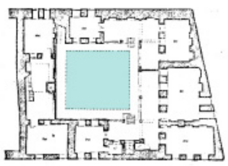
Aldo Rossi was also another architect that along with Herzberger advocated adaptability in arhcitecture. However, he appreciated the adaptability of traditional urban forms and believed they exhibit greater resilience and flexibility compared to modern empiricist architecture. He criticized modern architecture for its "naïve functionalism." Both Herzberger and Rossi emphasized flexibility is derived from archetypical forms, categorizing them as follows:

1-Centripetal type

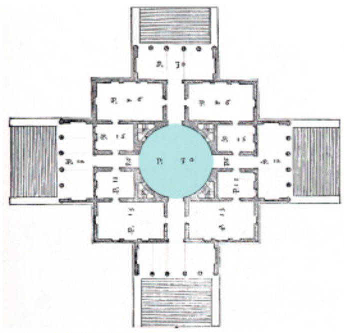
In "Flexibility/Adaptability" Rabeneck et. al. (1974) showcased that numerous housing typologies are designed to function as adaptable spaces. The various types they depicted typically feature a central space without a predefined function, serving as a flexible area for countless centuries. However, there is often a restriction on the range of activities feasible in this space, making it more suitable for private residences than for public spaces. Figure 17 shows some examples of this type.



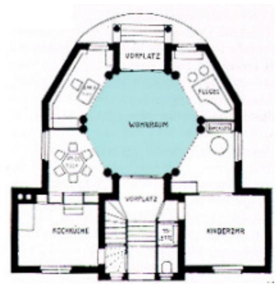
Plan of Domus



Classic Mesopotamian courtyard house in Iraq

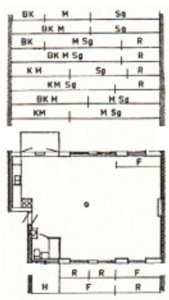


Palladio's Villa Capra



Peter Behrens, Summer Villa

Adolf Loos, Kuhner Villa, 1931

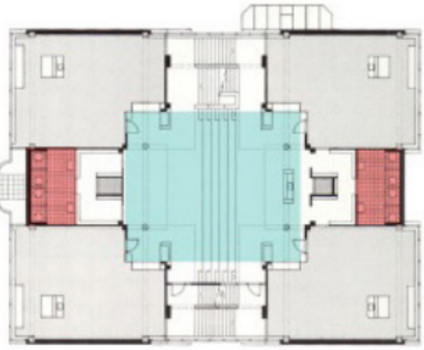


Järnbrott housing, T&A WilliamOlsson, 1954

Figure 17. Centripetal architetcural layout type. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

2-Condensed/Released Type

Hertzberger (1991), who was concerned with the social impact of architecture, expressed disapproval incorporating of artificial elements in contemporary architectural trends. He defined a flexible space as one that is polyvalent, signifying a permanent form capable of accommodating diverse interpretations without undergoing fundamental changes. In his projects, he highlighted the importance of "leaving space" for various interpretations, deeming it as crucial as the act of "making space." He strategically placed functional areas (condensed spaces), allocated to activities like washing, bathing, and stairways, to maximize the availability of free space in his designs. **Figures 18 & 19** show examples of this plan type .



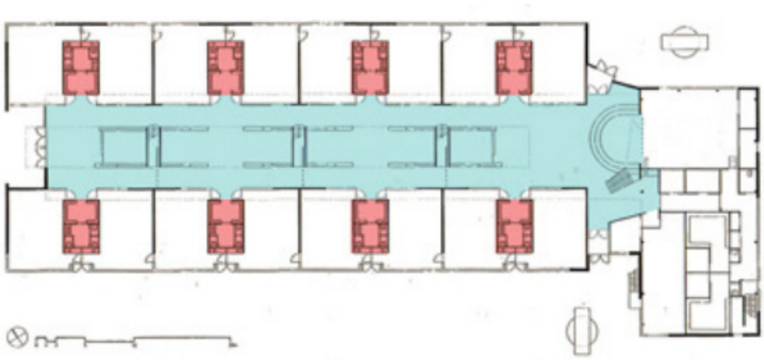
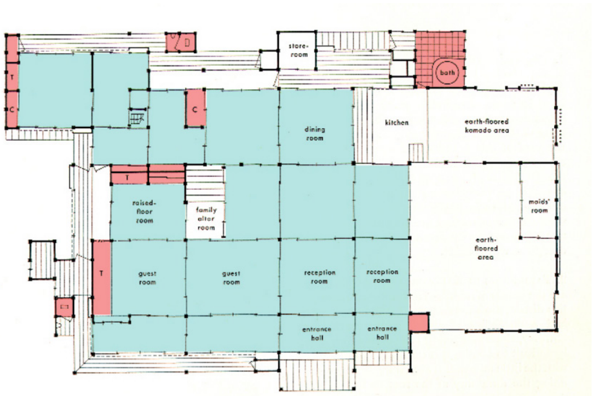


Figure 18. Left :Montessori school at Amsterdam (Left), Hertzberger 1991, 143
Figure 19. Right: De Polygoon Primary school (Right), Hertzberger 2002, 117
Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

3-Non-hierarchical type

Another type of polyvalence can be seen in Japanese traditional houses like Nagatomi House, where there is no spatial hierarchy. Each room enjoys the same quality as a space and the circulation differs per room layout. The flexibility in this type of architecture is a result of spatial relationships. Similar features can be seen in SANAA's projects. In the Stadstheater project, the rectangular plan which is divided into smaller rectangles, has no spatial hierarchy. The layout then, consists of distinct geometrical patterns that match with user scenarios. While elongated rooms might be used for circulation, they are not specifically designed to be used. F Figures 20 & 21 show examples of non hierachical layouts.



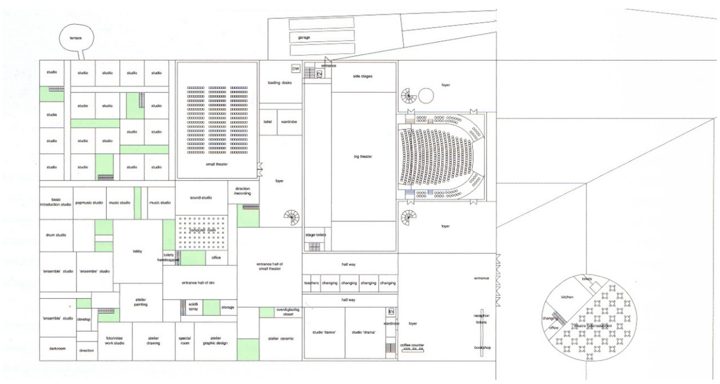


Figure 20. Left :A plan of Nagatomi House in Hyogo, Japan
Figure 21. Right: Kazuyo Sejima, a plan of Stadstheater project,
Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

2. 2. Strategies to Achieve Flexibility

1- Operational Elements

Using operational elements is the most commonly used strategy in achieving flexibility. It is attained by using sliding doors, windows, wall partitions, or moving elements that allow for space modification. Examples of such strategies are Fun Palace, Schroder House, and Suitcase House Hotel. Figure 22 diagrammatically illustrates how this strategy can work in a sample plan view.

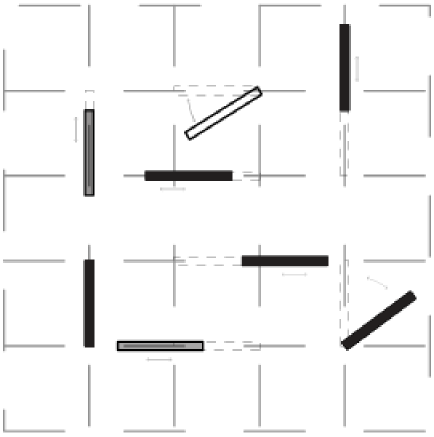


Figure 22. Operational elements like sliding walls, partitions, doors, and windows create spatial flexibility. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

Gary Chang's innovative 'Suitcase House Hotel' is a realization of his lifelong dedication to adaptable spaces. Informed by his extensive experiences in the dynamic environment of Hong Kong, Chang explores the fluid potential of living spaces and multifunctional design. The project challenges traditional notions of a house by ingeniously transforming its functionalities through discreet, pneumatically assisted floor panels. These dynamic spaces effortlessly shift into various configurations, serving as a music chamber, library, study, lounge, glazed-floor meditation area, or a fully-equipped sauna. The versatile surfaces and planes within the structure eliminate the need for fixed furniture, creating an open-plan interior capable of comfortably accommodating up to 14 people. Expansive sliding partitions offer stunning views of the Great Wall, while full-height folding glass doors enhance the overall spatial experience. Beyond its functionality, the outer facade of the building embraces the concept of 'customizable stratification' through vertical wood cladding screens, enveloping the cantilevered steel structure. Figures 23-26 show Suitcase Hotel.

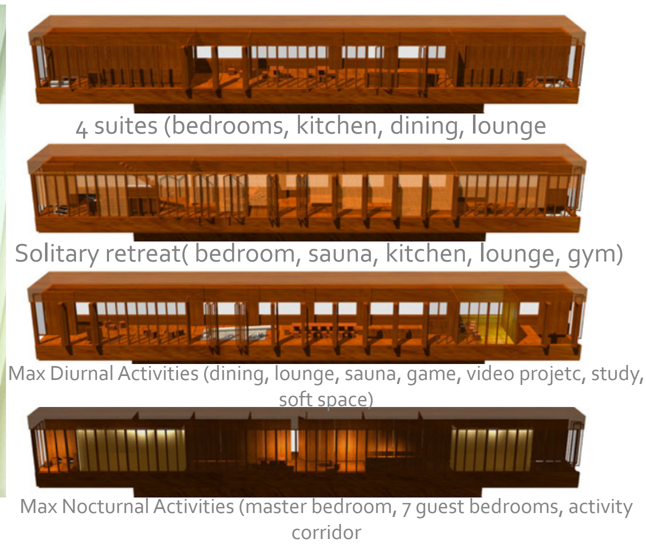


Figure 23 & 24. Suitcase Hotel/ Hong Kong is a successful example where operational elements have created fspatial flexibility. Retrieved from https://www.designboom.com/architecture/suitcase-house-by-gary-chang-hides-program-beneath-ground/

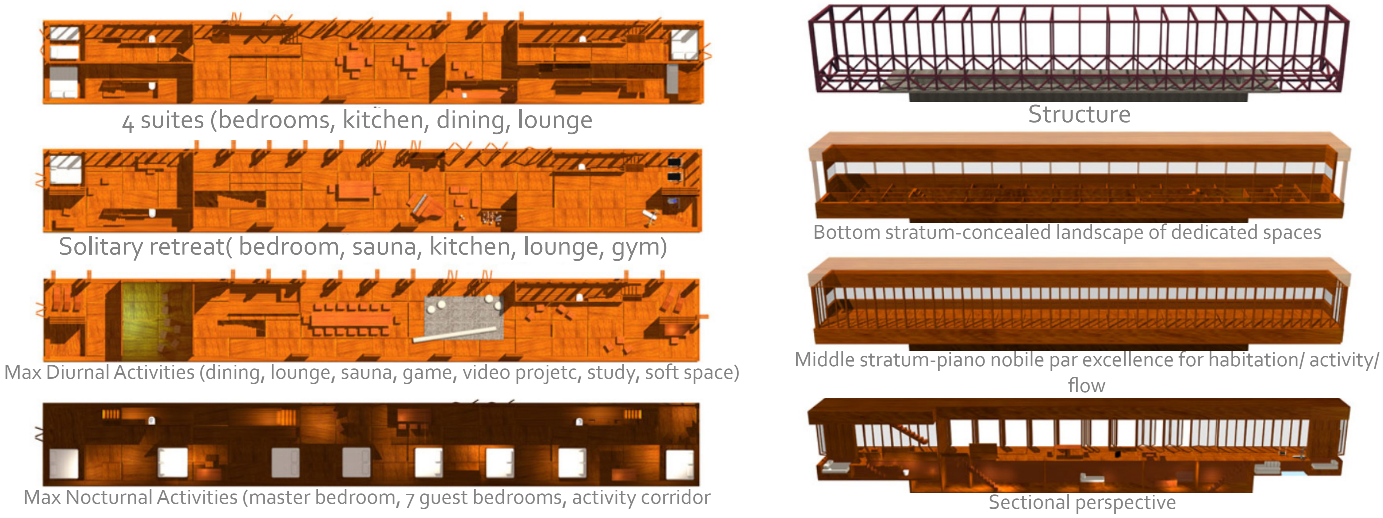


Figure 25 & 26. Suitcase Hotel/ Hong Kong is a successful example where operational elements have created fspatial flexibility. Retrieved from https://www.designboom.com/architecture/suitcase-house-by-gary-chang-hides-program-beneath-ground/

Another example of this strategy as mentioned, is Schroder House, designed by designed by Gerrit Rietveld in 1923, which achieves layout flexibility through a thoughtful integration of movable elements, transformable spaces, and a design philosophy that prioritizes adaptability. The ability to reconfigure the layout according to changing needs reflects the modernist ideals of functionality and user-centric design that were central to Rietveld's architectural vision. Through moving the sliding doors and wall partitions, the spaces can all become one large space or private rooms as the user pleases. Figures 27-29 show Schroder house's operational elements.

Figure 27-29. Schroder House/ Utrecht is one of the early examples in the modern movement that used custom-designed operational elements to create a flexible layout which met the occupants's needs and preferences. Retrieved from https://www.pinterest.com/pin/458100593345249314/ and https://www.theadventuresofpandabear.com/de-stijl-architecture-rietveld-schroder-house-utrecht-netherlands/

.2-Modular Systems

This kind of flexibility is achieved by interchangeable units and parcelization and based on designer and user's modification. A basic sample of a modular architectural plan is shown in Figure 30, and an example of parcelized units can be seen in Figure 31.

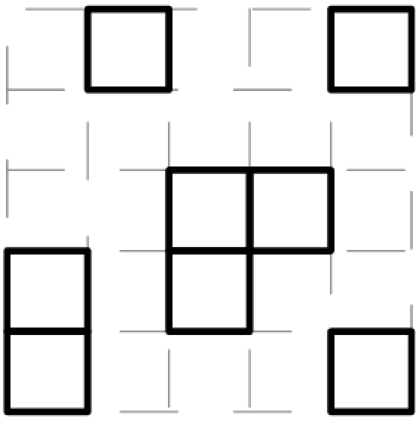


Figure 30. Modular and parcelized spatial organization in architectural plans help with achieving spatial flexibility. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

Espace Construit Adaptable in France, exemplifies the modular systems strategy in architeural layout planning. It is organized into designated 'parcels,' each comprising living units such as bathrooms, kitchens, storage, and furniture. Residents have the flexibility to personalize their floor plan by selecting elements from a catalog, enabling them to customize the space based on considerations like family size or budget.

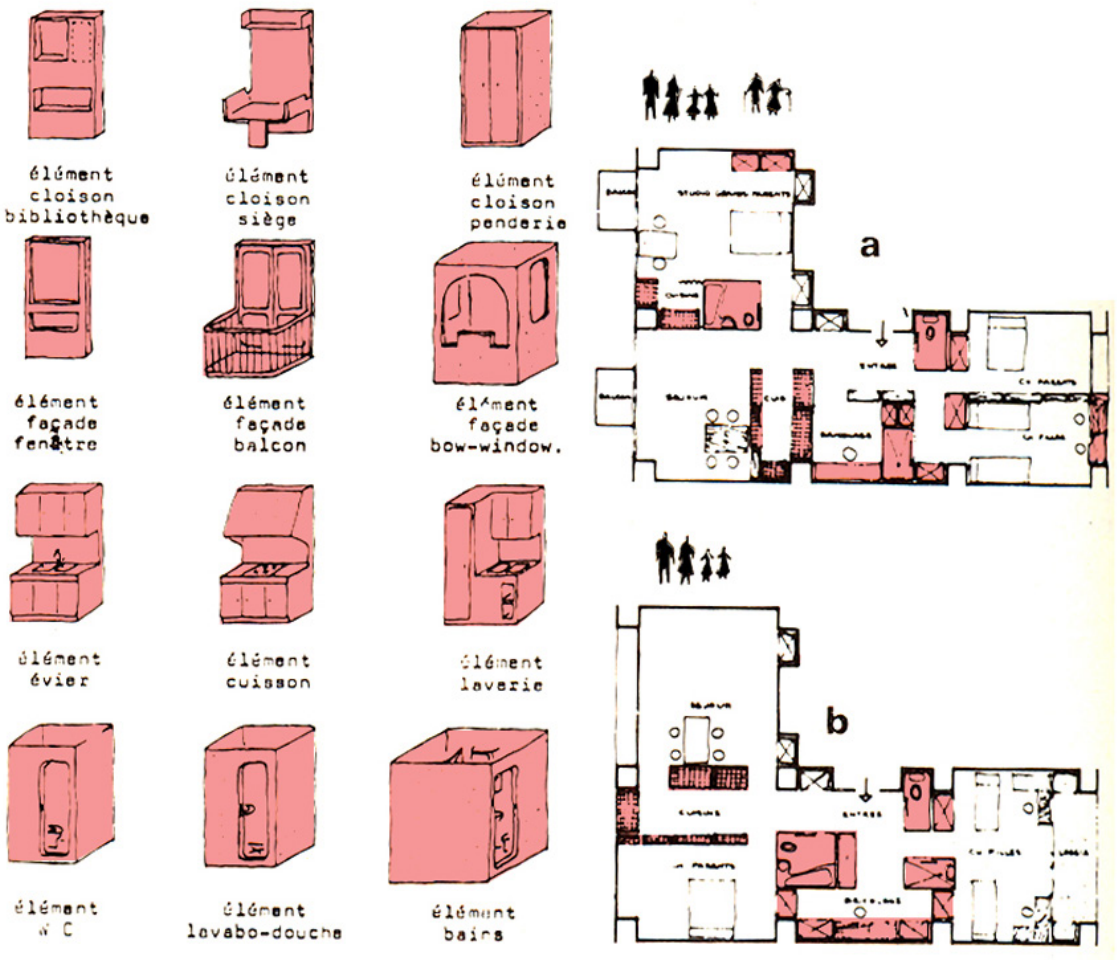


Figure 31. Modular and parcelized elements help with achieving spatial flexibility. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

3-Arrangement of Spaces

In this strategy, flexibility is achieved by zoning, where functional systems are compact and users have permission to use the remaining space the way they like to. This way users can adapt the designer's initial design.

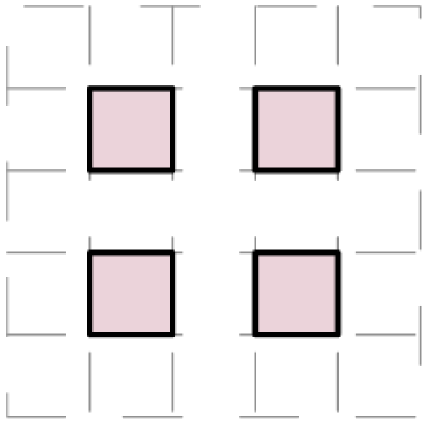


Figure 32. Zoning to create compact functional systems in architectural plans helps to free spaces which users can use the way they like to, and thus have spatial flexibility. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

De Polygoon Primary school by Herman Hertzerberger in Almere as shown in Figure 33, uses the zoning method to pack a series of rooms together based on various functions, to create more free space that can be used flexibly by the users.

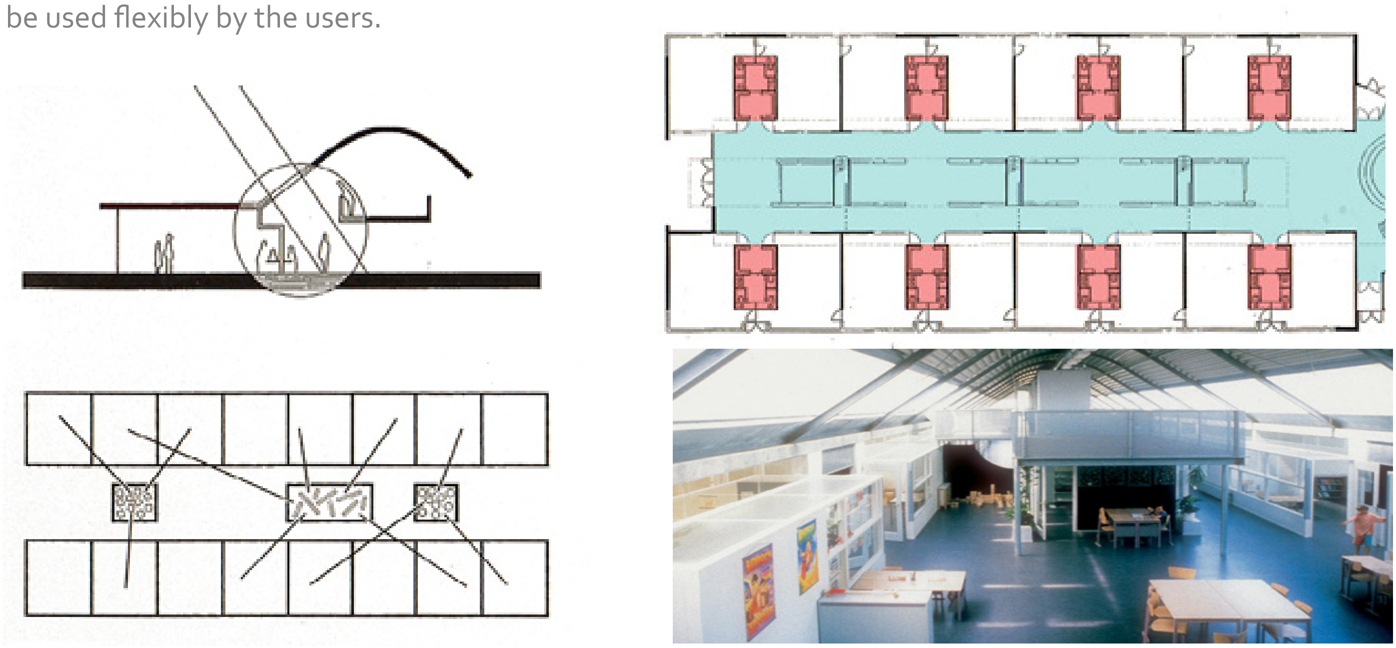
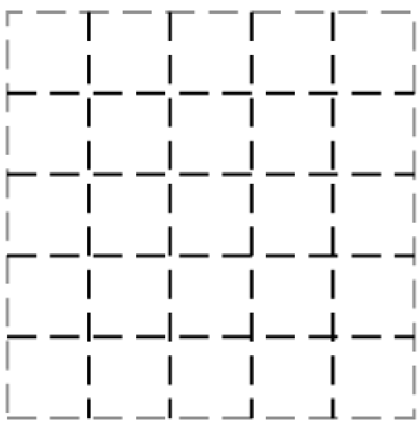


Figure 33-35.De Polygoon Primary school by Herman Hertzerberger/ Almere has zones based on functions. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition and https://oris.hr/en/oris-magazine/overview-of-articles/[148]think-about-architecture-before-making-it,2207.html



4-Erasing Programs

In this strategy, flexibility is achieved through non-hierarchical spaces. The plan is shaped into geometrical patterns that match the user's preferences.

Figure 34. By erasing programs from an architectural plan, there will be enough free space to use based on user preferences and contextual needs. Retrieved from https://www.researchgate.net/publication/264177780_On_Flexibility_in_Architecture_Focused_on_the_Contradiction_in_Designing_Flexible_Space_and_Its_Design_Proposition

2.3.Flexibility in Building Layers and their Rate of Change

As Estaji (2017) suggests, humans adapt to their physical environment through three layers. The initial layer is the body's skin, which regulates temperature changes by adjusting blood vessel diameter. The second layer involves clothing, where individuals can add or remove garments to manage variations in heat and cold. The ultimate defense against environmental fluctuations is architecture. Most buildings exhibit some degree of flexibility, such as opening windows during hot days (passive action), activating heaters in cold weather (active action), or adjusting thermal comfort using a smart system (as shown in Table 2 below).

Various levels of adaptability contribute to a diverse range of definitions and approaches found in the literature. The Adaptable Futures Research Group, led by Robert Schmidt (2010) defines four main characteristics of adaptability. Based on these criteria, they proposed a definition: 'the ability of a building to effectively accommodate the changing demands of its context, thereby maximizing value throughout its lifespan'.

Table 2.Building Layers and Longevity

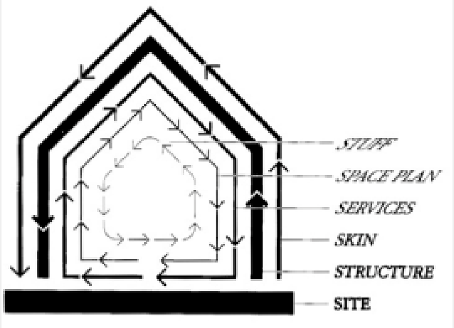
Shearing Layers (different rate of change)	Layer	Description	Longevity
	Site	Geographic setting, urban location	Eternal
	Structure	Foundations and load bearing elements	30 to 300 years
	Skin	Exterior surfaces (Facades)	20 years
	Services	Wiring, plumbing, HVAC systems and ...	7 to 15 years
	Space Plan	The interior layout	3 years
	Stuff	Furniture, kitchen	Daily to monthly

Table 3. Levels of Adaptation in Order of Complexity Based on Lelieveld, et al.

Level	**Description**
flexible	"This level of adaptability needs the direct control of the user, which means that the building elements do not have the ability to change themselves."
Active	"An active building component will give a set reaction on a specific change "
Dynamic	"Dynamic architecture has the possibility to give different output on a certain input."
Interactive	"The building component is able to have a two-way conversation with the users and/or its environment."
Intelligent	"The building can take its own conclusions for certain situation."
Smart	"Smart architectural components have the ability of self-initiative. The system is self-learning and would be able to design itself."

Diagrams retrieved from Estaji, H. (2017). A review of Flexibility and Adaptability in Housing design. ResearchGate. https://doi.org/10.14621/tna.20170204

Table 4. Characteristics of Adaptability based on Robert Schmidt, et al

Characteristics	Definition (samples)	
Capacity for change	change the size or use of spaces	
	change its capacity, function, or performance	
	less frequent, more dramatic changes	
	subsequent alteration	
	modified alteration	
Ability to remain "fit" for purpose	reduced in mismatches between the building and its users	
Value	maximizing its productive use	
	to fit both the context of a system's use and its stakeholders' desires	
	minimum cost	
Time	speed of change	quick transformations
		respond readily
	through life changes	future changes
		in the long term
		extension of use

Diagrams retrieved from Estaji, H. (2017). A review of Flexibility and Adaptability in Housing design. ResearchGate. https://doi.org/10.14621/tna.20170204

Figure 36, shows the disctinction between the main terms discussed in this section.The three notions of adaptability, flexibility, and responsiveness in architecture are based on different criteria for change. However, responsive architecture remains a category under both notions of flexibility and adaptability, depending on whether a responsive bahvior changes the physical form or functions.

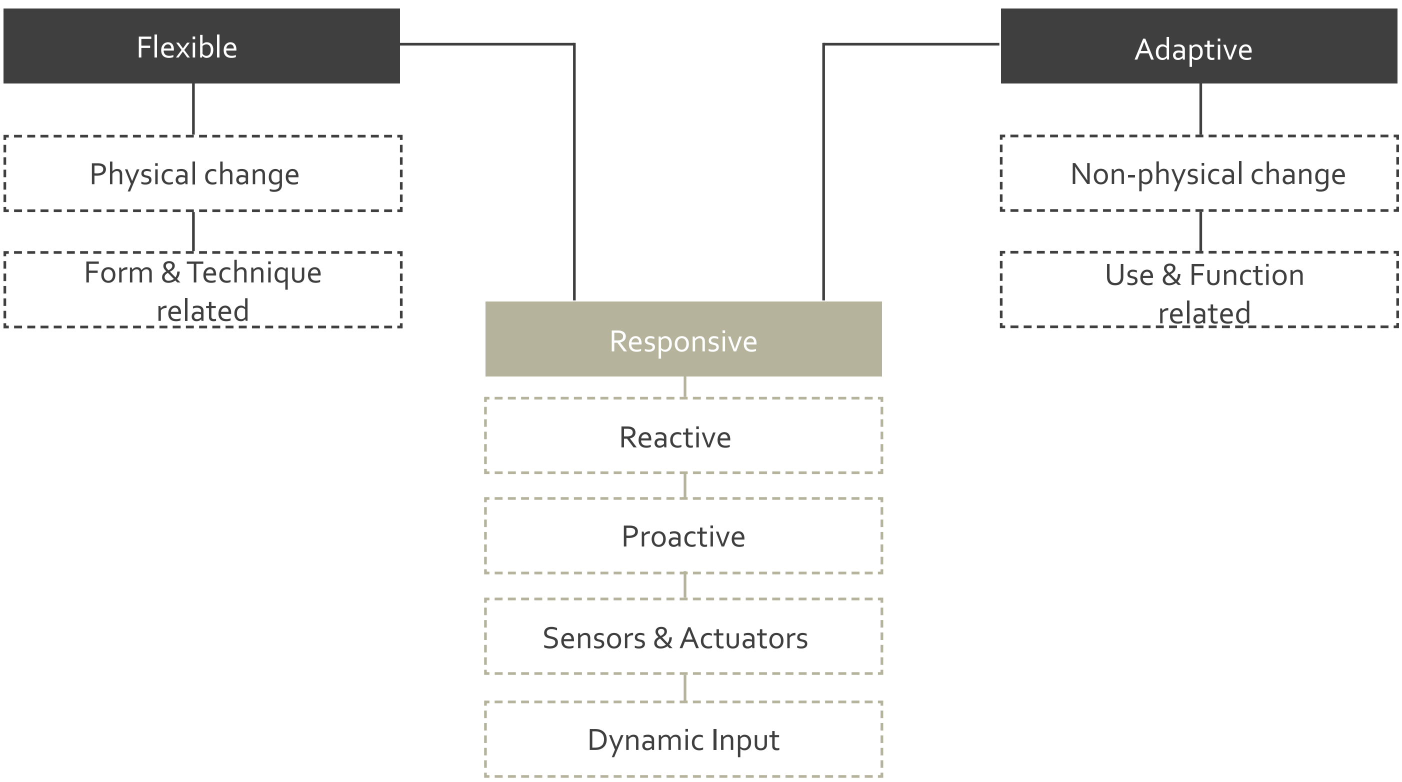


Figure 36. Relationship between flexible, adaptive, and responsive architecture.

1. Phenomenology in Architecture

Walter Gropius (1962) once said: The key to a successful rebuilding of our environment -which is the architect's great task-will be our determination to let the human element be the dominant factor."

Phenomenology, as a philosophical discipline, was defined by Edmund Husserl in the 20th century and emphasizes the study of consciousness and the structures of experience. In architecture, phenomenology refers to an approach that focuses on the direct, subjective experience of architecture from the perspective of those who inhabit or experience the built environment. This opens a dialogue between architecture and neurophenomenology which focuses on the human body as an architectural subject and on the fact that architectural intervention is primarily concerned about how we experience space, as Bollnow (1963) states, "The space as it is manifested in concrete human life." The architectural field has recently embraced the phenomenological approach, a methodology that not only interprets but also actively shapes the relationship between individuals and their environment. An earlier attempt at humanistic architecture was semiology; exploring what the built form means (Bognar, 1985).

According to Steven Holl (1996), phenomenology is the study of the fundamental nature of architecture. Through the interconnection of form, space, and light, architecture can enhance the daily life experience of users with phenomena that arise from different contexts, materiality, and functions. Architecture is initiated by an idea but then turns into a practical entity with elements such as structure, materials, space, color, light, and shadow coming together in the construction of architecture. Pallasmaa puts the body at the center of a spatial experience and says:

> "I confront the city with
> my body, my legs measure the length of the arcade
> and the width of the square; my gaze unconsciously
> projects my body onto the facade of the cathedral,
> where it roams over the moldings and contours sensing
> the size of recesses and projections, my body weight
> meets the mass of the cathedral door, and my hand
> grasps the door pull as I enter the dark void behind me. I
> experience myself in the city, and the city exists
> through my embodied experience. The city and my
> body supplement and define each other. I dwell in the
> City and the city dwells in me."

Through the ongoing cooperation among our senses, we can have a stronger sense of reality. Architecture acts as a medium between our external world and ourselves and broadens our existential experience by offering and facilitating our understanding of the world. It materializes the progression of seasons, the trajectory of the sun, and the unfolding of daily hours. The way architecture offers such experiences affects our cognition under what is called the phenomenon of neural plasticity or "the ability of the brain to alter its neural connections in response to environmental conditions" (Mallgrave, 2013, p. 12), suggesting that architecture and design affect the brain, and as a result of human behavior (Eberhard, 2009).

Hence, with the junction of neurosciences, psychology, and architecture, the correlation between the architectural environment and the well-being of individuals, in both physical and mental aspects, is consistently gaining importance. This suggests that the quality of everyday architectural experiences and the characteristics of the built environment significantly influence the overall health and wellness of people and creating architectural settings that positively contribute to the well-being of individuals is important. Phenomenology in architecture, therefore, revolves around the human experience and how the existential aspects and time, materiality, tectonics, architectural details, and aesthetics help an individual with sensory, emotional, and imaginative explorations and connections with one's surroundings. This approach strives to produce architecture that goes beyond functionality, resonating with profound meaning, addressing human needs effectively, and eliciting emotional and sensory responses.
The relationship between perception, cognition, and our environment in shown in Figure 37.

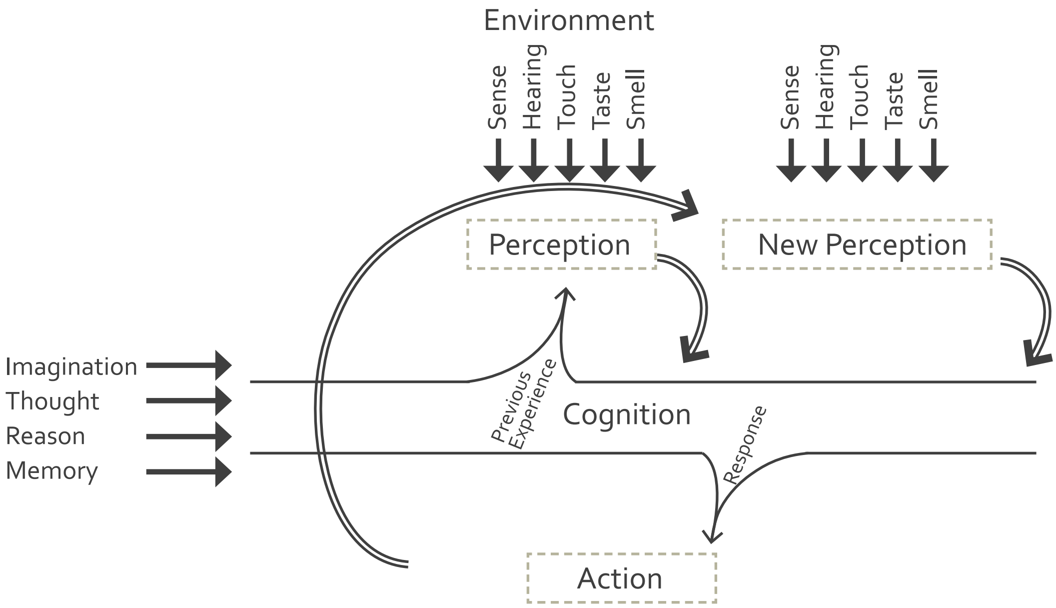


Figure 37. The relationship between perception and cognition. Replicated fromPHENOMENOLOGY IN ARCHITECTURE: Defining experiential parameters by Erik Bakker

2. Understanding and Analyzing Diverse User Preferences

Architects Colomina, B. & Wigley, M., (2018) believe the start of the user-centered design was DaVinci's Vitruvian Man, which triggered a series of architecture & designs formed around humanism. However, it was with Norman & Draper (1986), that the term user-centered design was coined. It is defined as a system that focuses on user needs to promote productivity and performance and minimize errors (Noyes, J., & Baber, C. (1999). The following diagram in Figure 38 shows user centered design.

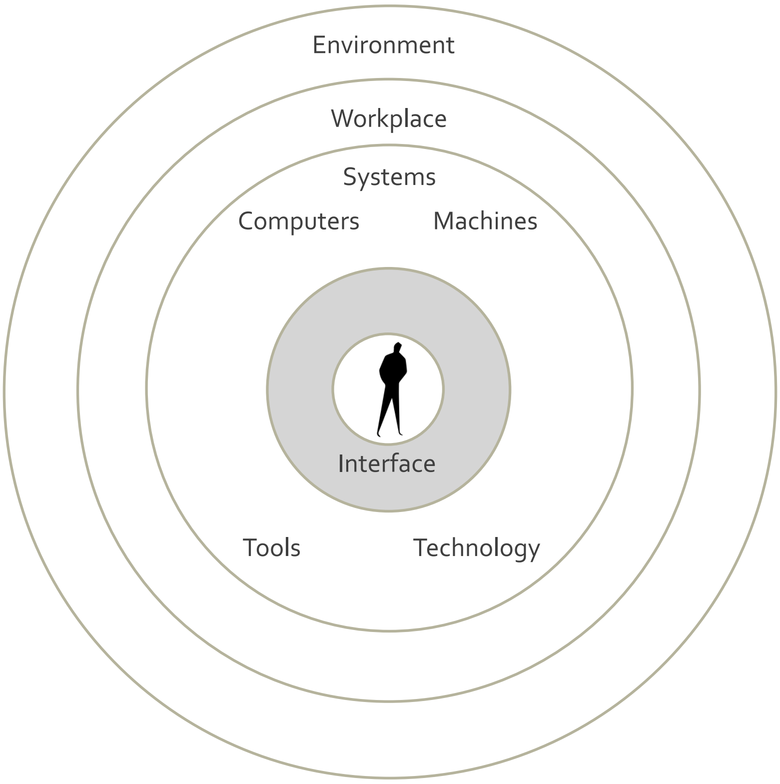


Figure 38. User-centered design, replicated from User-Centred Design of Systems by Noyes, J., & Baber, C.,(1999)

User-centered design is based on the concept of need-finding, which tries to find out what users need or prefer. The presence of a "genuine need" can be a criterion for the success or failure of any design project (Faste, 1987). McKim, R.H. (1972), defines need-finding as a"qualitative research approach to studying people to identify their unmet needs" to "help designers get closer to their end users."

Sanders (1992), divided need expression into four aspects: observable, explicit, tacit, and latent.
Observable needs are seen through research observations.
Explicit needs are expressed by users verbally.
Tacit needs cannot be expressed verbally, though are known to the user.
Latent needs are inexpressible, unknown, and subconscious

Lai, J., et al., (2010)., divided the need-finding methods into what is shown in the following table:
After the needs and preferences of users are identified, the design process begins which is then implemented

Table 5. User Needfinding Methods

Interviews	Talking with a user using a set of prepared questions
Surveys	Giving a questionnaire to a large number of people to gather data quickly
Wants and needs analysis	Brainstorming with a group of users to distill wants versus needs
Card sorting	Having the user sort cards with attributes of product in order to develop mental model
Group task analysis	Working with a group of users to analyze the use of the product
Focus groups	Meeting with a group of potential users to discuss concerns with the product or concept
Field studies	Observing users "in the wild" as they use the product in the real environment
User feedback testing	Bringing prototypes of various fidelities to the user to elicit feedback
Bug list	Enumerating challenges a user group faces in their daily activities; not a software bug

Digarm showing user needfinding methods, replicated from A study of the role of user-centered design methods in design team projects. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, by Lai, J., Honda, T., & Yang, M. C. (2010).

and evaluated. This process as defined by The Interaction Design Foundation(2024) is divided into the following steps as shown in Figure 39:

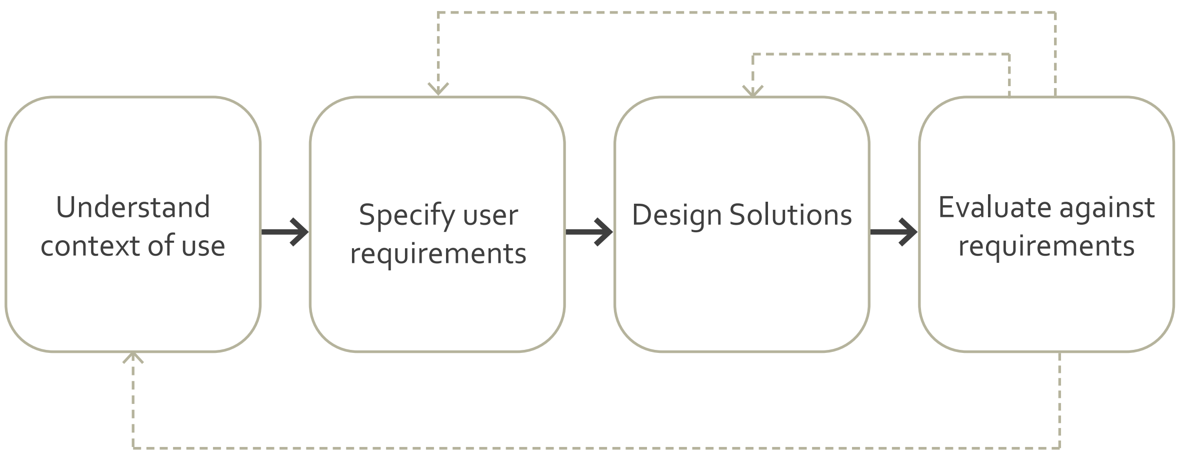


Figure 39. The steps in user-centric design process. Replicated from What is User Centered Design (UCD)? (2024, January 17). . https://www.interaction-design.org/literature/topics/user-centered-design

D.Swarm Robotics

1. Background

Inspired by systematic interaction and collaboration of social species of insects and animals, swarm robotics, represents an alternative strategy for collaboration of often large groups of relatively uncomplicated robots. According to Shahzad et.al. (2023), swarm robots are differentiated from multi-agent robots, by particular criteria that include the presence of a minimum of three agents (although many other definitions require a larger group size than this) and the sharing of relative information, including altitude, position, and velocity, among all agents. Each agent is expected to demonstrate intelligence and be able to consistently follow a predefined set of interaction rules throughout the entire network. Furthermore, the system's stability should not be affected if an agent leaves fails, or disconnects from the swarm.

Swarm Robotics

Three characteristics for a system to be qualified as sa swarm of robots

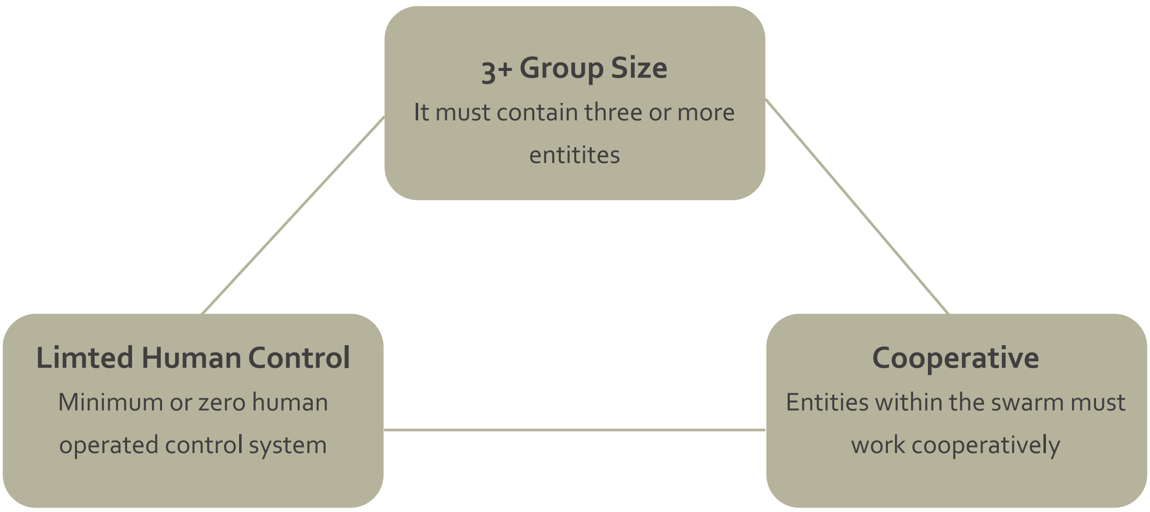


Figure 40. Rreplicated from A review of swarm robotics in a NutShell. Drones by Shahzad, M. et.al . (2023). https://doi.org/10.3390/drones7040269

Shahzad.M. et.al.(2023), shows the difference between a multi-agent system and a swarm robot system as seen in Figure 41.

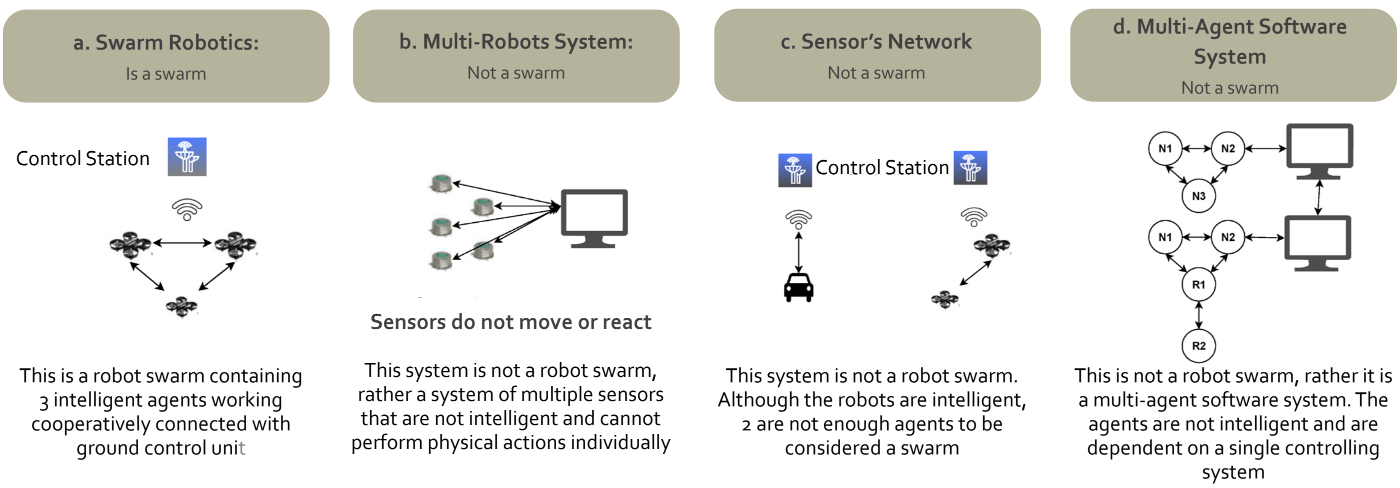


Figure 41. Comparison of Multi-agent Systems and Robot Swarm. (a) depicts swarm robotics system, while (b–d) show non-swarm systems. Diagram replicated from What is a robot swarm: A definition for swarming robotics (2019) . Arnold, R. et. al.

Iocchi, L., et al., (2001) describes autonomous systems as collaborative and defines few basic features for swarm robots as shown in Figure 42:

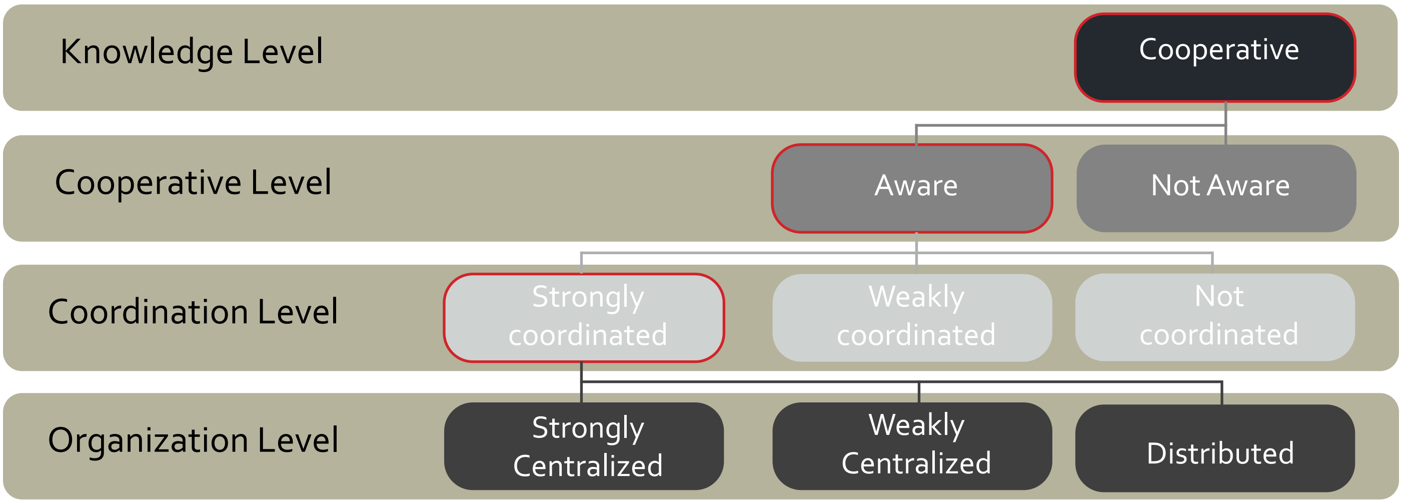


Figure 42. Diagram showing characteristics of swarm robots highlighted in boxes with red edges. "The ability of robots to define their work, the coordination, and management style as a result of cooperation are the characteristic features of swarm robotics." Digaram and defintion retrived from Usage of evolutionary algorithms in swarm robotics and design problems by Türkler, L.,et al., (2022).

The approach that swarm robotics uses is usually defined by three main attributes essential for multi-robot systems: robustness, flexibility, and scalability (ŞahïN,2005).

Robustness, in this context, quantifies the system's capacity to sustain functionality even in case of partial failures or unpredictable circumstances. We can see a high degree of robustness, in social insects or animals as their self-organized systems continue to operate effectively despite significant losses in system members or considerable alterations in their environment.

Flexibility, on the other hand, characterizes the system's ability to adapt to new, diverse, or evolving environmental requirements. While flexibility and robustness can exhibit conflicting definitions, the distinction lies at the problem level. A flexible system must be capable of transitioning to an appropriate behavior when faced with a change in the problem. Biological systems demonstrate this level of flexibility, seamlessly adjusting their behaviors to solve diverse problems. For instance, ants showcase remarkable flexibility, employing the same foundational self-organized mechanism to address foraging, prey retrieval, and chain formation challenges.

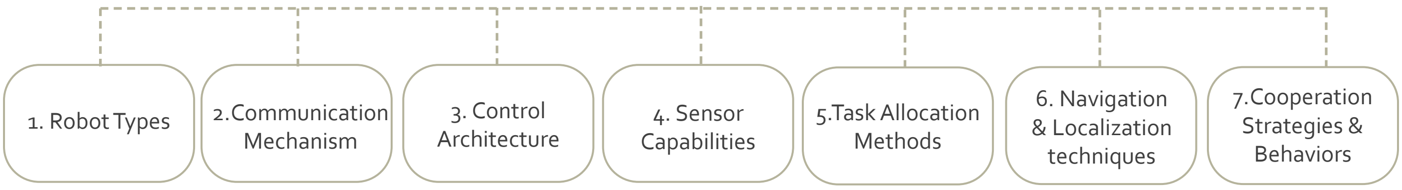
Scalability refers to the system's capacity to expand a self-organized mechanism to accommodate varying numbers of individuals without significantly compromising performance. While there is an acceptable performance range within which the swarm operates, it is preferred to have an expansive range.

A swarm of robots typically comprises a collective of identical or similar members acting asynchronously. Each individual possesses distinct yet limited capabilities compared to the entire group and cannot achieve swarm objectives independently and intricate collective behaviors can emerge without group members needing a comprehensive understanding of the swarm dynamics. Despite the apparent simplicity of individual behaviors, the collective behaviors and structures of swarms exhibit surprising complexity. Members lack a holistic awareness of the swarm's overall state and the entities within the swarm generally exhibit limited individual capabilities. Communication among members is confined to local interactions. We can see such behavior in a flock of birds, where birds collaboratively navigate vast distances to a specific destination while each bird remains focused solely on its local neighbors.

Therefore, decentralization which is a very important factor in swarm robots is closely related to another vital aspect of self-organization. Self-organization in swarms is based on four principles namely, positive feedback, negative feedback, randomness, and multiple interactions. In the case of ants' behavior, when one ant discovers a potential food source, it returns to the colony, marking the path with pheromones. Others who detect these pheromones follow the trail, return to the colony, and reinforce the path with new pheromones. Over time, these pheromone traces diminish, but shorter trails, undergo less evaporation, and therefore, tend to be traversed more frequently than longer ones (Dias et.al., 2021).

2.Taxonomy of Swarm Robots

Creating a taxonomy in swarm robotics helps to better understand the diversity within the field, compare different approaches, and develop a comprehensive knowledge base for future advancements. It provides a structured framework for discussing and analyzing the myriad elements that contribute to the functionality and effectiveness of the robot system. The taxonomy of swarm robots may encompass various dimensions, including:



1. Different robot types within a swarm, such as ground-based robots, aerial drones, or underwater robots.

2. Communication mechanisms among swarm members, such as direct local interactions, indirect communication through the environment, or wireless communication.

3. Control architecture like centralized, decentralized, or distributed control.

4. Sensor capabilities and types of sensors used by swarm robots, such as cameras, proximity sensors, or environmental sensors.

5. Task allocation methods like division of labor or task-switching strategies.

6. Navigation and localization techniques like GPS, odometry, or local sensing.

7. Cooperation strategies and behaviors like aggregation, dispersion, foraging, exploration, and collective decision-making.

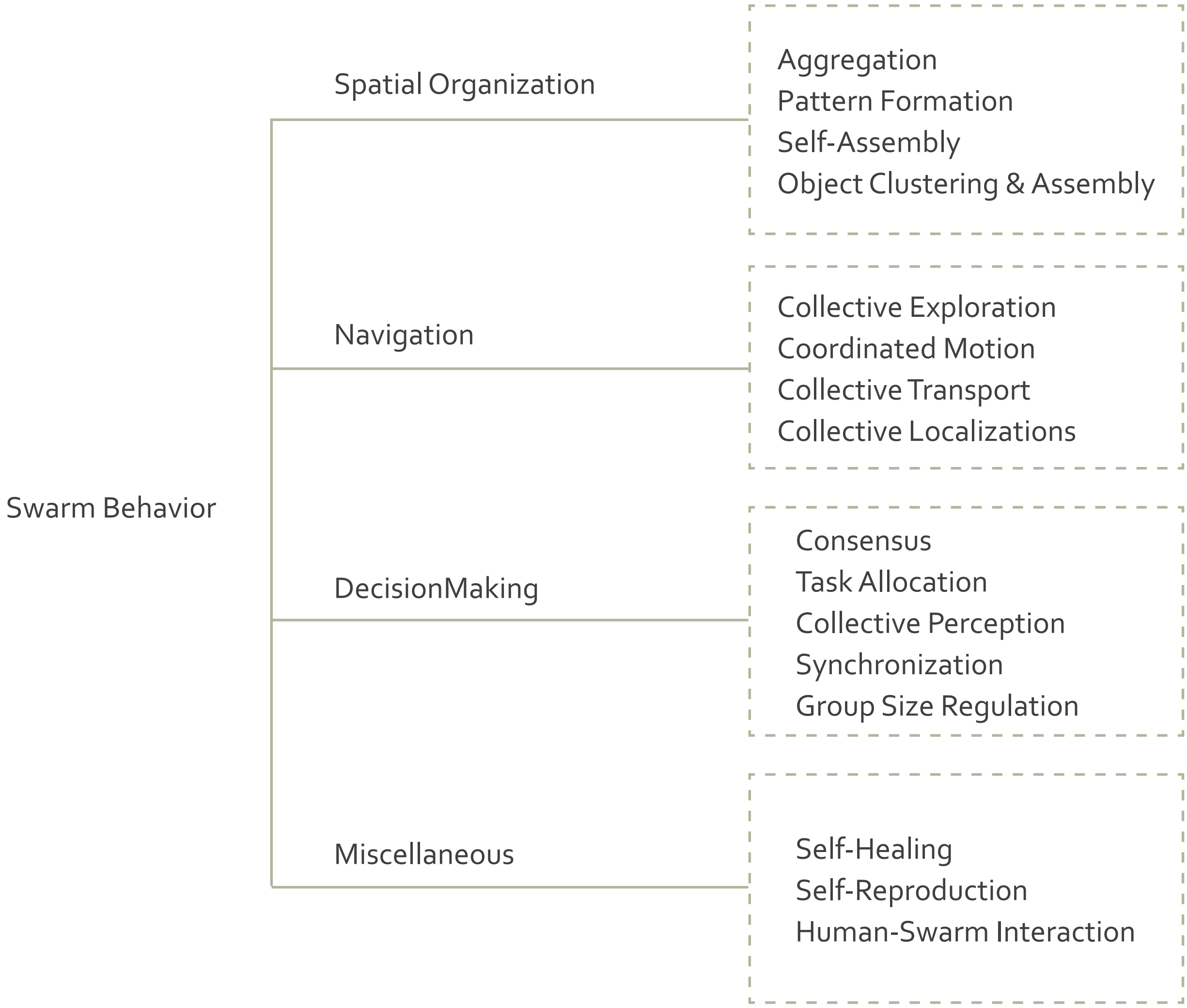


Figure 43. Taxonomy of swarm behaviors from Brambilla et al. (2013). Updated diagram replicated from Schranz et.al (2020)

Schranz et.al. (2020), defines each of the swarm behavior categories as follows:

Spatial Organization

These behaviors allow for the coordinated movement of swarm robots within the environment, to spatial organization of themselves or objects.

- Aggregation: This behavior directs individual robots to gather in a defined region of the environment, to get close to other members for efurther interaction
- Pattern Formation: This behavior arranges the robot swarm into specific shapes. A notable example is chain formation, where robots align in a line, often for establishing multi-hop communication between two points.
- Self-assembly: This behavior connects robots to establish structures. Connections can be physical or virtual through communication links. An instance is morphogenesis, where the swarm evolves into a predefined shape.
- Object clustering and assembly involves the manipulation of spatially distributed objects by a swarm of robots, a crucial aspect for various construction processes.

Navigation

These behaviors facilitate the coordinated movement of a swarm of robots within their environment.

- Collective exploration: Guides the swarm of robots in cooperative exploration of the environment, serving purposes such as gaining a situational overview, searching for objects, monitoring the surroundings, or establishing a communication network.
- Coordinated motion: Directs the swarm of robots to move in a formation, which can take on a well-defined shape, like a line, or be arbitrary as observed in flocking behavior.
- Collective transport: Enables the swarm of robots to collectively move objects that may be too heavy or large for individual robots to handle.
- Collective localization: Empowers robots within the swarm to determine their position and orientation relative to each other by establishing a local coordinate system throughout the swarm.

Decision Making

These behaviors makes the swarm robots reach to a common on a given problem.

- Consensus: Helps individual robots within the swarm to agree on or converge toward a single common decision among various alternatives.
- Task allocation: Dynamically assigns emerging tasks to individual robots within the swarm, with the aim to maximize the overall performance of the swarm system. In cases where robots possess heterogeneous capabilities, tasks can be distributed accordingly to enhance the system's performance.
- Collective fault detection: Identifies deficiencies in individual robots within the swarm, and thus, allows for effective detection of any deviation from the intended swarm behavior, due to hardware failure.
- Collective perception: involves integrating locally sensed data from robots within the swarm to form a comprehensive overview. This enables the swarm to make informed collective decisions, such as reliable object classification, appropriate allocation of robots to specific tasks, or determining optimal solutions to global problems.
- Synchronization aligns the frequency and phase of oscillators among robots in the swarm, leading to a shared understanding of time among robots that allows them to perform tasks synchronously.
- Group size regulation allows swarm robots to organize into groups of the intended size. If the swarm exceeds the preferred group size, it divides into multiple groups.

Miscellaneous

There are additional behaviors of swarm robots that don't fall into the aforementioned categories.

• Self-healing: Enables the swarm to recover from failures caused by individual robot deficiencies, and therefore, minimizes the impact of robot failure on the rest of the swarm, which then enhances reliability, robustness, and performance.
• Self-reproduction: Allows a swarm of robots to either generate new robots or replicate patterns created by multiple individuals. The goal is to increase swarm autonomy, by eliminating the need for human engineers to create new robots.
• Human-swarm interaction: Permits humans to control the robots within the swarm or receive information from them. Interaction can occur remotely, through a computer terminal, or proximally in a shared environment, through visual or acoustic clues.

Other taxonomies classify swarm robots defined by multiple scholars, based on robot tasks, the way they approach problems, communication, position, and swarm structure. The taxonomies proposed by Bayındır and Şahin, and Brambilla et al. should therefore be noted. These taxonomies in Türkler' words are based on the:
"1-Number of individuals of swarm or size of the swarm
2-Communication ability of the swarm, perception capacity if any, and allowable communication distance

3-Communication network methods such as addressing layer levels and data bandwidth established by the swarm
4-Processes of information processing
5-Variability of the positioning of robots
6-Robot variety" -Türkler, L., et al., (2022)

The following Figure 44 & 45, show the two proposed taxonomies mentioned above. Bayındır and Şahin (2007) divide the swarm robots based on problems, behavior design, communication, modeling, and analytical studies while Brambilla et al.,(2013) classify them based on methods and collective behavior.

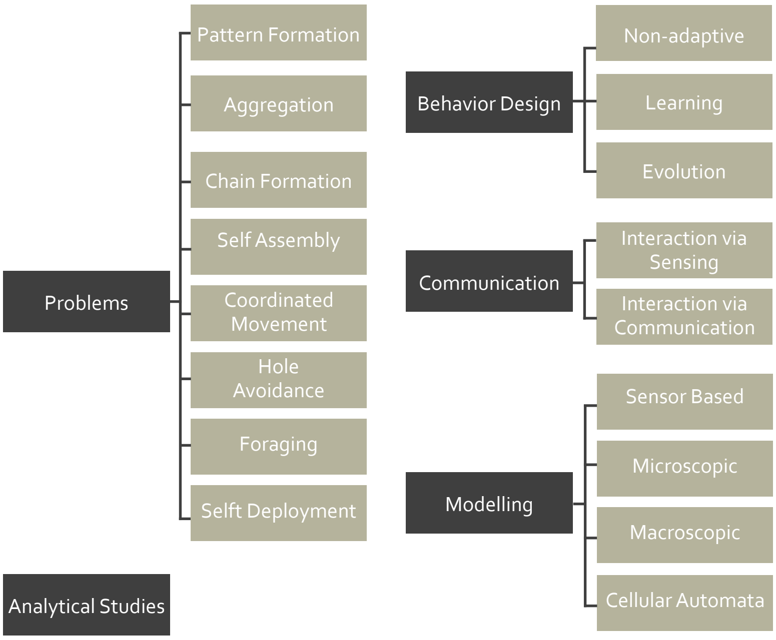


Figure 44. Taxonomy proposed by Bayındır and Şahin(2007), replicated from Usage of evolutionary algorithms in swarm robotics and design problems by Türkler, L.,et al., (2022).

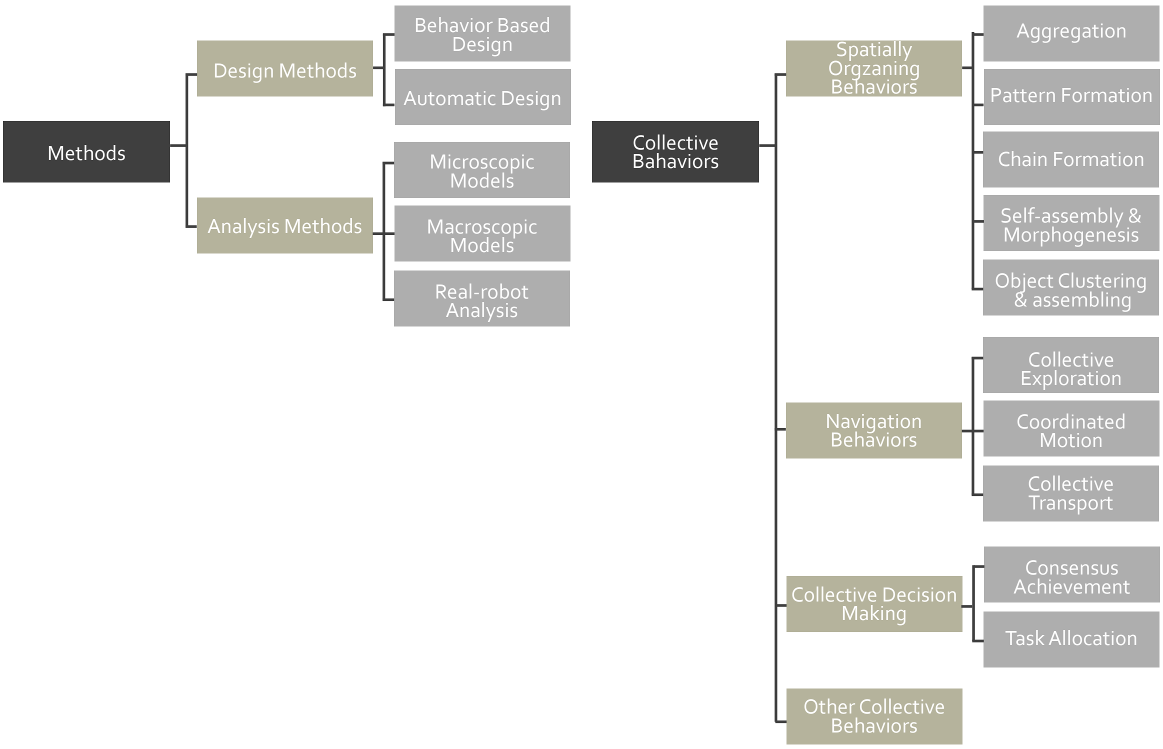


Figure 45. Taxonomy proposed by Brambilla et al., (2013), replicated from Usage of evolutionary algorithms in swarm robotics and design problems by Türkler, L.,et al., (2022).

2.1. Pattern Formation & Self-organization in Swarm Robots; Flocking, Foarging

Since the focus of this study is to build architectural layouts with a swarm of robots, it is important to note how these robots can come together to form a pattern or self-organize themselves. To perform complex tasks, certain rules have to be inferred for robots to control their movement and swarming. In most cases, each agent makes immediate decisions based on the simple rules and moves accordingly. These rules to create a global behavior or form patterns can be divided into two main categories: Biomimetics and Physicomimetics (Othman, W. a. F. W. (2019).

In the biomimetics approach, the swarm behavior emulates biological systems, from a wide variety of chemical and mechanical processes seen in nature, like how cells function or different organisms behave.

Reynolds (1987) proposes a system that simulates the flocking of birds and fish known as "boids", through animation geometries. He divides the flocking model into three navigating behaviors based on the position and velocity of neighboring members which are separation, alignment, and cohesion. This model offers insight into how biomimetic rules can inform artificial systems to provide better solutions. The aforementioned behaviors are defined by Reynolds as:

1. Separation: navigate to avoid local crowds
2. Alignment: navigate toward the average direction the local members are heading
3. Cohesion: navigate towards where the average position of local members is.

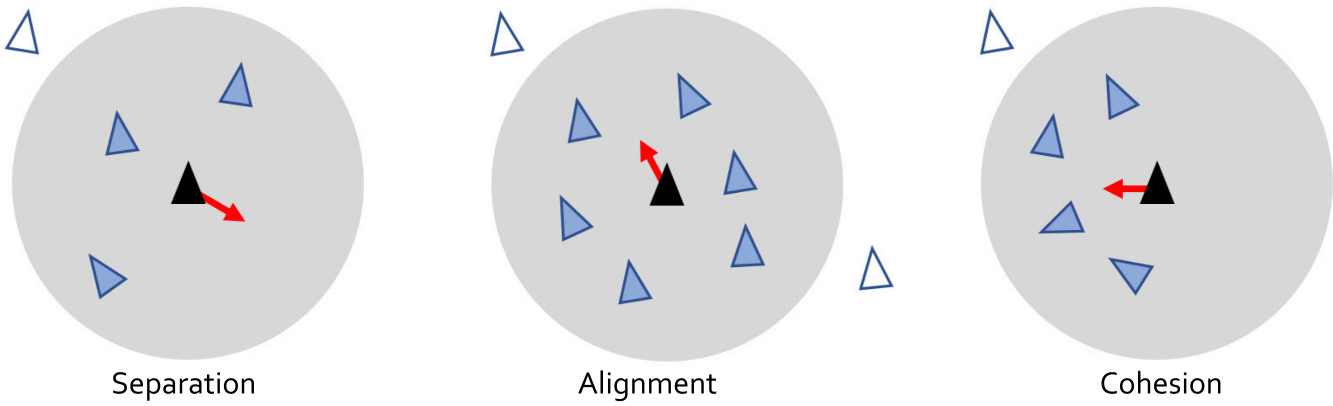


Figure 46. Shows "control rules used by Boids shown as isosceles triangles that are oriented in the direction of the corner opposite to the base. The grey circle contains the flockmates that can be perceived by the black boid located at the center. The red arrows represent the navigating behavior generated by the separation, alignment, and cohesion rules on the basis of the position and orientation of nearby boids, shown in blue. Distant boids, shown in white, are ignored. Each boid steers in the direction of the resultant of three vectors calculated with the three corresponding rules." Description and image retrived from https://bacrobotics.com/Chapter8.html

Another approach to pattern formation and self-organization of robotic swarms are mimicing the concept of releasing pheromones in insects (Na, S.,2020). Pheromones in nature are defined by some main features (Fujisawa, R.,2014):

Locality: Pheromones are fixed at a static spatial position. This indicates how insects or swarms change their space to send a message.

Diffusion: Pheromone concentration is a gradient function . An area has a maximum value and decays with any increase in the distance.

Evaporation: Over time concentration levels of pheromones decrease. Due to thia indirect communication becomes non-permanent.

To imitate ant pheromones in robot swarms, three major approaches have been used: beacon robots, physical materials, and virtual pheromones (Lu, Q., 2020).

Virtual pheromones vary from real pheromones in the sense that they are generated messages received by neighboring members of the swarm. In the field of swarm robotics, the pheromone behavior can be simply categorized into two distinct organizing behaviors attraction and repulsion. By using simple attraction and repulsion rules, swarm robots can smoothly spread/diffuse over an open space. When a robot detects a survivor, it transmits a virtual message (pheromone message like light) to the local neighbors to signal its discovery. Repulsion makes robots avoid collision and makes the swarm diffuse and cover the free space. Virtual pheromones can also repel other robots, as one robot can block others from entering a particular space. Attraction, on the other hand, makes the robots stay within the communication range to follow a message gradient back to its source (Payton, D., et al., 2001).

Another category to form patterns and global behaviors in swarm robots is called physicomimetics, which are engineering processes inspired by physical systems like behaviors shown by solid, liquid, and gas, or kinetic analyses (Spears, W., et al.,1999). Tasks that need robots to have constant connectivity or form a lattice geometry, can follow solid formation patterns. In liquid and gas-based pattern formation, they use the same approach as solid formation but with different attractive and repulsive parameters (Gordon-Spears, D., et al.,2002). Switching between the two behaviors of solid and liquid in swarm robots is like phase transition. Gas-based formation in swarm robots is good for expanding over the entire arena, while avoiding any obstacles but also covering areas behind these obstacles which minimizes free space. To achieve this swarm robots must move slowly and thus finding the optimal speed is an important factor (Spears, W., et al.,1999).

To better understand the necessary parameters for future experiment setups, ChatGPT was asked to provide very basic pseudocodes for line formation, clustering, and pheromone-based pattern formation in swarm robots that are shown below:

Basic Pseudocode for Line Fomration:

Initialize

- Number of robots (n)
- Position of each robot (x[i], y[i])
- Target formation line position (line_x, line_y)
- Formation spacing (spacing)

Repeat until convergence

For each robot i:

1. Calculate the distance to the target line: dist_to_line[i] = distance(x[i], y[i], line_x, line_y)
2. Calculate the angle to the target line: angle_to_line[i] = atan2(line_y - y[i], line_x - x[i])
3. Calculate the desired position along the line: desired_x[i] = line_x + dist_to_line[i] * cos(angle_to_line[i])
4. Move towards the desired position:
   - If x[i] < desired_x[i]:
     Move robot i right (increase x[i])
   - If x[i] > desired_x[i]:
     Move robot i left (decrease x[i])
   - If y[i] < line_y:
     Move robot i up (increase y[i])
   - If y[i] > line_y:
     Move robot i down (decrease y[i])

Basic Pseudocode for Clustering:

Initialize

- Number of robots (n)
- Positions of each robot (x[i], y[i])
- Number of clusters desired (k)

Repeat until convergence

For each robot i:

1. Calculate distance to all other robots
2. Assign robot i to the cluster with the nearest centroid:
   - Calculate centroid of each cluster
   - Find the nearest centroid to robot i
   - Assign robot i to that cluster

Update Centroids

For each cluster j:
- Calculate the new centroid as the mean position of robots in that cluster

Repeat until convergence or maximum iterations:
- If centroids do not change significantly, exit loop
- Otherwise, continue updating clusters and centroids

Results

- Each robot is assigned to a cluster
- Centroids represent the positions of the clusters

Basic Pseudocode for Pheromone Pattern Fomration:

Initialize

- Number of robots (n)
- Positions of each robot (x[i], y[i])
- Pheromone grid representing the desired pattern

Repeat until convergence

For each robot i:
  1. Sense pheromone concentration in its vicinity
  2. Move towards areas with higher pheromone concentration:
    - If nearby pheromone concentration is higher than current position:
      Move robot i towards that direction
    - Otherwise, move randomly or based on exploration strategy

Update pheromone grid:
  For each grid cell:
    - Decrease pheromone concentration over time (evaporation)
    - If a robot is present at the grid cell, increase pheromone concentration

Repeat until convergence or maximum iterations:
  - If the pheromone pattern stabilizes or reaches a desired state, exit loop
  - Otherwise, continue updating robot positions and pheromone grid

Result

- Robots form a pattern guided by the pheromone concentrations on the grid

Initialize

- Number of robots (n)
- Positions of each robot (x[i], y[i])
- Liquid-like behavior parameters (e.g., viscosity, surface tension)
- Desired pattern or goal configuration

Repeat until convergence or maximum iterations

For each robot i:

1. Sense local environment (e.g., neighboring robots, obstacles)
2. Compute forces acting on the robot:
   - Inter-robot forces based on desired spacing or alignment
   - Boundary forces to avoid obstacles or stay within boundaries
   - Surface tension-like forces to maintain cohesion within the swarm

Move robots based on computed forces:

- Update robot velocities based on the sum of forces
- Integrate velocities to update robot positions

Repeat until convergence or maximum iterations:

- If the swarm reaches a stable configuration or desired pattern, exit loop
- Otherwise, continue updating robot positions based on forces

Results

- Robots form a pattern influenced by liquid-like behaviors and desired configurations

3. Swarm Robots Interaction

To interact with swarm robots different means can be used. These interaction means can be based on either human commands or visual- based systems like cameras or graphic interfaces. Human-centred command involves commands that come directly from the human body including voice or gesture commands. On the other hand, visual based interaction involves using a visual interface or product to command the swarm to perform a behavior. The diagram below shows the potential for various interaction methods based on the support utilized. It suggests a hybrid approach, such as employing Augmented Reality for visualizing the swarm, Haptic feedback for controlling the swarm's structure, and an electrocardiogram to regulate parameters like velocity and orientation.

Bowley et al.(2017), propose a method to command a swarm of robots using a smartphone or tablet with a touchscreen interface. The interface offers multiple functions that respond to finger movements (such as touching or releasing fingers, screen scanning, zooming in or out with two fingers, etc.). Through this interface, the operator employs an algorithm to influence the swarm's behavior by manipulating several attractive or repulsive beacons.

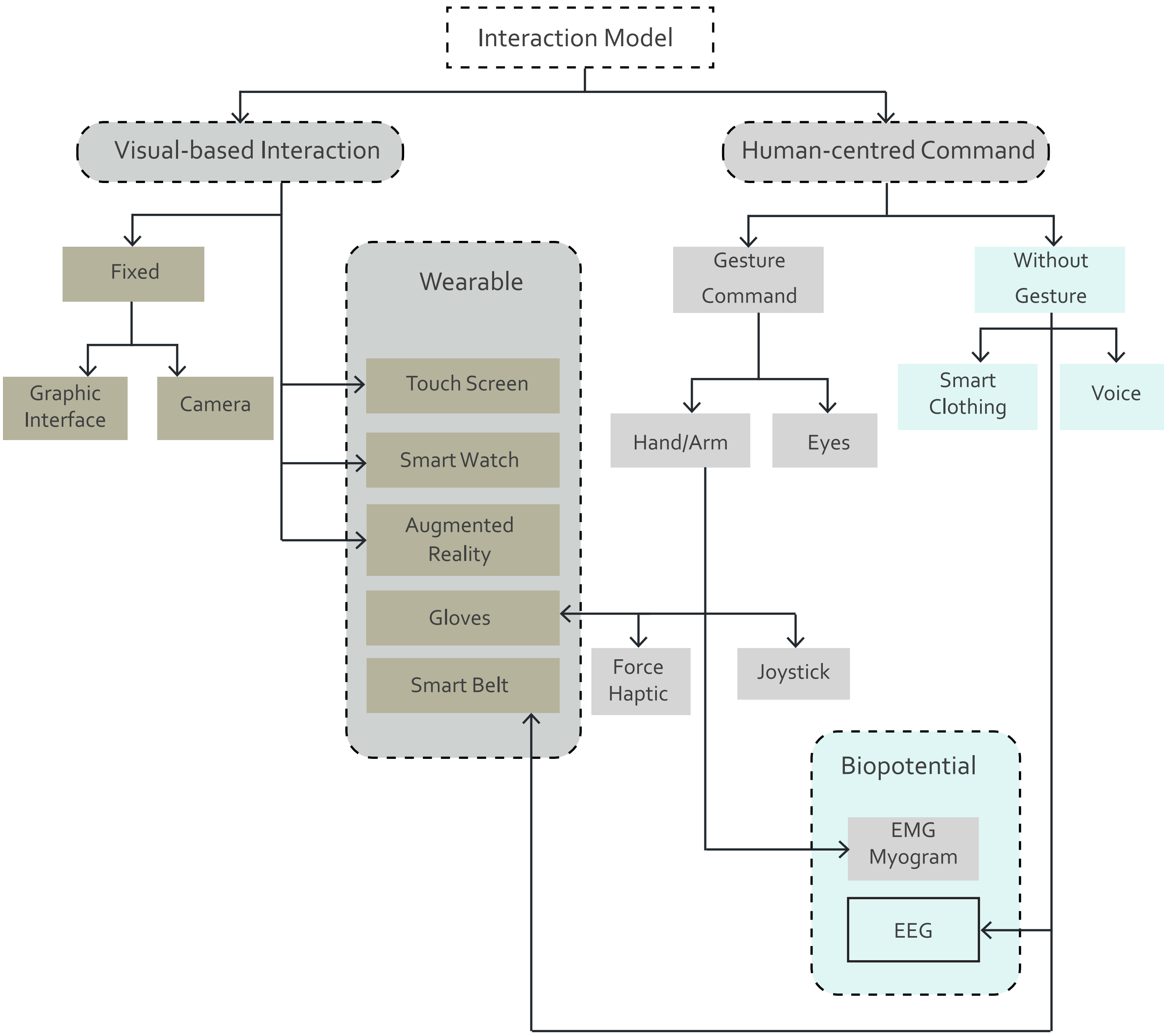


Figure 47. Taxonomy of interaction for mobile robot swarm. Replicated from Swarm Robotic Interactions in an open and cluttered environment: a survey by Vaidis (2021)

4. Swarm Intelligence Algorithms

These algorithms abbreviated as SI are a collective intelligence that has distinct inspirations and is from separate categories, but they share the same concept of social interaction (Bonabeau, E.et.al.,1999). They aim to enable a swarm to perform a challenging task through members' collaboration. The core of these algorithms is that successful individuals are more likely to influence the population of the system. Though the definition of success depends on the algorithm, it generally relates to the quality of a solution. The agents navigate through a metaheuristic space relying on the information from other agents and the environment (Shahzad.M, et.al., 2023).

Dutta.T, et.al. (2020), list some of the commonly used swarm algorithms as shown in the following diagram: Below, some of the most famous and currently used algorithms from the list above are briefly explained (Shahzad.M, et al.,2023).

Swarm Algorithms	Year
1. Ant Colony Optimization	1992
2. Particle swarm optimization	1995
3. Bacterial foraging	2002
4. Honey bee swarm optimization algorithm	2005
5.Artifical bee colony (ABC)	2007
6.Cuckoo search (CS)	2009
7.Bat algorithm	2010
8.Firefly algorithm	2010
9.Fruit fly optimization algorithm	2011
10.Flower pollination algorithm	2012
11.Krill herd algorithm	2012
12. Grey wolf optimizer	2014
13.Spider monkey optimization	2014
14.Moth-flame optimization algorithm	2015
15.Ant lion optimizer	2015
16.Dragonfly algorithm	2015
17.Bird swarm algorithm	2015
18. Whale optimization algorithm (WOA)	2016
19.Crow search algorithm (CSA)	2016
20. Grasshopper optimization algorithm (GOA)	2017
21. Salp swarm algorithm	2017
22. Spotted hyena optimizer	2017
23.Squirrel search algorithm	2019
24. Harris hawk optimization (HHO)	2019
25. Red deer algorithm	2020
26.Wingsuit flying search	2020
27.Tunicate swarm algorithm	2020
28. Vortex swarm optimization	2020
29. Artificial cell swarm optimization	2020
30. Orcas algorithm	2020

Table 6. showing list of commonly used swarm intelligence algorithms, replicated from Dutta, T. et al., (2020). Border Collie optimization. IEEE Access, 8, 109177–109197. https://doi.org/10.1109/access.2020.2999540

For the list of papers please refer to the document https://doi.org/10.1109/access.2020.2999540

1- Ant Colony Optimization (ACO)

In ACO, a heuristic search-based algorithm, each ant moves across the environment (a graph) following higher concentrations of pheromone and depositing pheromone at visited edges accordingly. Dorigo (1992) who proposed the algorithm defines four basic components of the foraging algorithm which are the ant, pheromone, daemon action (a mechanism introduced to enhance the algorithm's performance and efficiency through pheromone updating. It includes pheromone reinforcement, pheromone decay, global pheromone update, intensification of promising regions) and decentralized control.

The ant serves as an imaginary agent who copies exploration and exploitation processes within a search space, generating pheromones. The intensity of these pheromones changes over time through evaporation and forms a global memory of the ant's travel path. Daemon activity is employed to collect global data, while decentralized control ensures the robustness of the ACO algorithm and preserves the flexibility of a dynamic environment (Dorigo, M., et al., 2006)

What we see in the image are the three stages in which the ant travels from the nest to the food source.

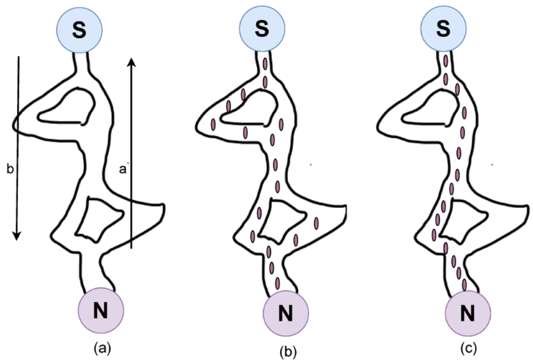


Figure 48. Letters N and S represent Nest and Food-Source respectively.
(a) shows the early phase of the process, in which ants begin to discover a path between their nest and the food source and begin to lay pheromones.
(b) shows the intermediate stage when the ants have taken all the possible paths.
(c) depicts that the majority of ants select the path with the highest concentration of pheromone.
Retrieved from Shahzad. M, et al., (2023), https://www.mdpi.com/2504-446X/7/4/269#B18-drones-07-00269

2- Particle Swarm Optimization (PSO)

Kennedy & Eberhart (1995), introduced the Particle Swarm Algorithm as a simple method to help particles find the optimal solutions. In the PSO algorithm, particles move towards the best particle (i.e., the most successful one) in their neighborhoods at each iteration. Note that particles move using information from only one individual in their neighborhood. This algorithm is based on flocking birds and schooling fish behaviors, and shares three similar behaviors: separation (to avoid congestion), alignment(to travel in the same average direction as other flock members), & cohesiveness (to move toward the average position of flock members)(Poli. R, et al., 2007).

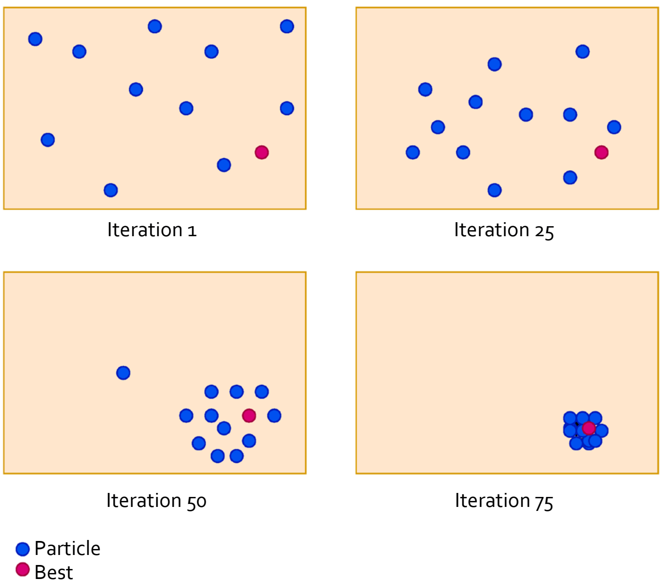


Figure 49. Shows an example of PSO environment, where initially with the first iteration the particles are spread out to find the most ideal solution. The best solution is selected with regards to neighbourhood topology, and each member's personal and global best particles are updated. As seen in the diagram, convergence happens when all particles are attracted towards the particle with the best solution. Population size is important for a precise and fast convergence(Gong, D, et al. 2009).
Retrieved from Shahzad. M, et al., (2023), https://www.mdpi.com/2504-446X/7/4/269#B18-drones-07-00269

3-Artificial Bee Colony

In 2005, Dervis Karaboga introduced Artificial Bee Colony (ABC) as an influential SI algorithm. It follows honey bees' intelligence in finding food sources and communicating food-related information with other bees. ABC like PSO divides artificial agents into three types: employed, observer, and scout bees. Each agent bee has a particular task in the process. The employed bee memorizes where the food is located. The observer bee receives information about the hive's supply from the employed bee. The scout bee always finds new nectar sources. The following diagram shows the ABC flow. It is worth noting that ABC has only two control factors, colony size and maximum cycle number. Karaboga, D. et al.,(2007) define a few steps for the ABC method which are mentioned below.

Step 1. Initialization: Food sources, are initialized with the number of scout bees in the population
Step 2. Employed Bees: The search capacity for finding new neighbour food source increases to accumulate more nectar around the neighbour food source. Once they identify a nearby new food source supply, its profitability and fitness value are assessed.
Step 3. Onlooker Bees: After calculating the fitness value and obtaining information from employed bees, a probability value is computed and this value is then shared with the waiting bees, known as onlooker bees, in the hives for selecting food sources.
Step 4. Scout Bees: Employed bees that cannot raise their fitness values after multiple repetitions become scout bees. These unemployed bees choose sources at random.
Step 5. Best Fitness: The best fitness value and the exact position with an associated value are memorized.
Step 6. Termination Checking Phase: The program terminates upon meeting the termination condition. If the termination condition may not be reached, the program goes back to step 2 and repeats the process until it is.

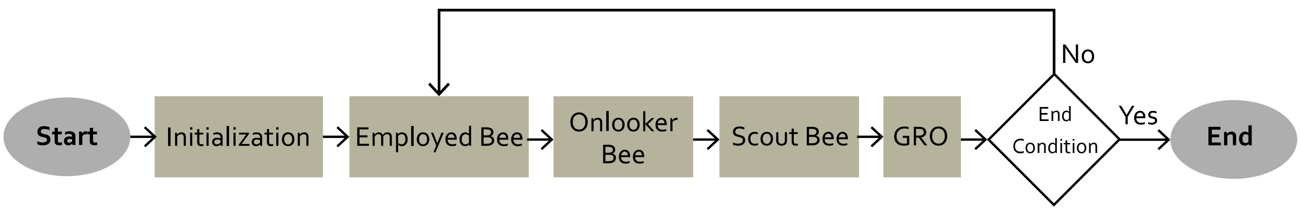


Figure 50. Steps of ABC method proposed by Karaboga, D. et al. Replicated from Karaboga, D.; Basturk, B. A powerful and efficient algorithm for numeric function optimization: Artificial Bee Colony (ABC) algorithm. J. Glob. Optim. 2007, 39, 459–471.

5.Application of Swarm Robotics

Swarm robotics is an area of research that has not yet gained major industrial applications. Swarm robotics research platforms help with experimenting and verifying swarm algorithms in labs. The categories of swarm research and its industrial application are terrestrial, aerial, aquatic, and extraterrestrial. Robotic vehicles include Unmanned Submarine Vehicles (UUVs), Unmanned Aerial Vehicles (UAVs), Unmanned Surface Vehicles (USVs), and Unmanned Ground Vehicles (UGVs). The platforms are shown in the following diagram (Shahzad, M., et al., 2023):

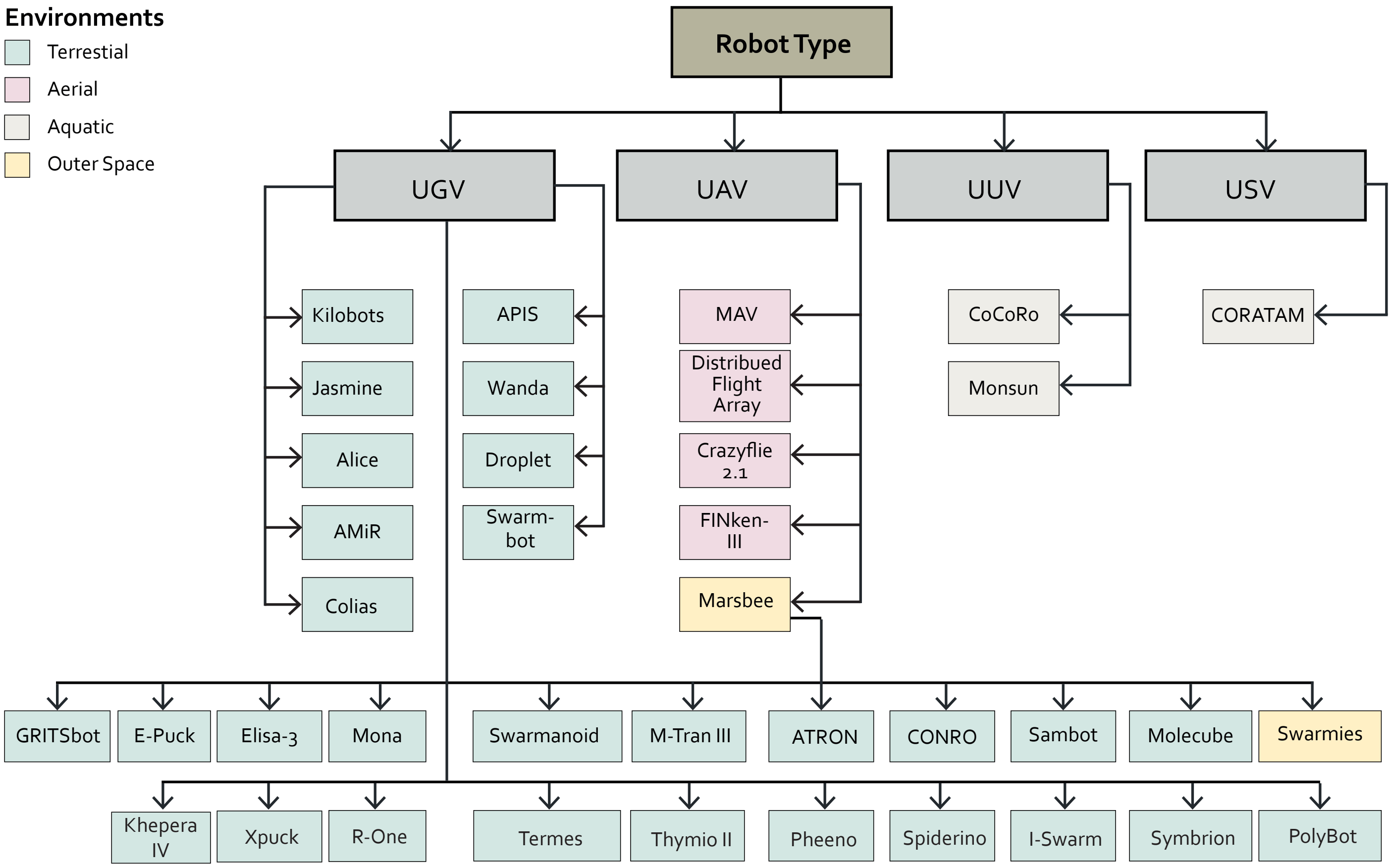


Figure 51.Classification of platforms for swarm robotics. Diagram replicated from A Review of Swarm Robotics in a NutShell, by Shahzad, M., et al., (2023)

Calderón-Arce,C.,et al., (2022), lists the most commonly used robots for swarm robotics as shown in following table:

Table 7. Most Commonly Used Robots for Swarm Robotics

E-puck	2004	École Polytechnique Fédérale de Lausanne (EPFL)	USD 1000
Khepera IV	2015	K-Team (EPFL spin-off)	USD 3200
Kilobot	2010	Harvard University	USD 130
Swarmanoid: footbot	2011	Future and Emerging Technologies (FET-OPEN) project	
Colias	2014	University of Lincoln	USD 32 (GBP 25)
Mona	2017	University of Manchester	USD 129 (GBP 100)
Psi Swarm	2016	University of York -	
GRITSBot	2015	Georgia Tech	USD 50 (parts)
Thymio	2011	Mobsya (EPFL spin-off)	USD 173

Table replicated from Swarm Robotics: Simulators, Platforms and Applications Review by Calderón-Arce,C., (2022)

Furthermore, for simulation of swarm robots, Calderón-Arce,C.,et al., (2022), lists the most commonly used interfaces together with their feature as shown in following table:

Software/Feature	**Last Update**	**Free**	**Open-Source**	**Linux**	**MacOS**	**Windows**	**Swarm**	**Source (Accessed: 11 May 2022)**
Stage	2020	✓	✓	✓	✓		✓	Repository: https://github.com/rtv/Stage
Bio-PEPA	2010	✓		✓	✓	✓	✓	Website: https://homepages.inf.ed.ac.uk/jeh/Bio-PEPA/biopepa.html
TeamBots	2000	✓	✓	✓	✓	✓	✓	Website: https://www.cs.cmu.edu/~trb/TeamBots/
Swarm-bots	2014			✓	✓		✓	Website: https://www.swarm-bots.org/
ODE	2022	✓	✓	✓	✓			Website: https://www.ode.org/
Gazebo	2019	✓	✓	✓	✓		✓	Website: http://gazebosim.org/
Webots	2021	✓	✓	✓	✓	✓		Website: https://cyberbotics.com/
MSRS	2015	✓				✓		Not available
USARSim	2013	✓	✓	✓	✓	✓	✓	Repository: https://sourceforge.net/projects/usarsim/
ARGoS	2022	✓	✓	✓	✓	✓	✓	Website: https://www.argos-sim.info/
CoppeliaSim	2022	✓	✓	✓	✓	✓		Website: https://www.coppeliarobotics.com

Table 8. showing most common simulation platforms for swarm robots and their features, replicated from Swarm Robotics: Simulators, Platforms and Applications Review by Calderón-Arce,C., (2022)

6-Coordination & Communcation of Swarm Robots

Communication in swarm robotics is for the coordination of the swarm action and the sharing of information about the environment. According to Lu, Q., (2020), there are three forms of communication in swarm robots: direct communication, stigmergy, and shared memory which are defined as follows: In direct communication robots directly exchange information among themselves, while stigmergy is when robots communicate through modification of the environment or leaving their influence on the behavior of other robots (e.g. pheromones). In simulation settings, stigmergy is basic. In shared memory, information is accessed and added to a shared memory by robots.

7.Swarm Robotics in Architecture

Swarm robotis in architecture have never been used for spatial organization and architectural layout configuration. The only applications of swarm robots in architecture found, have been around manufacturing and assembly in construction process, which were out of the scope of this study.

This also justifies why this study is needed in the architecture field to offer an innovative solution that might help keep up with the rapid transformations of our world today and in the future.

The collective intelligence inherent in these robots enables them to navigate real-time assessments of their surroundings, which can help create structures that continuously respond to the changes in the environment.

E. Conclusion

In conclusion, this research delved into the realm of spatial flexibility in architecture and explored principles of swarm robotics together with different simulation platforms and robot types, to be able to use them for the creation of user-centric autonomous architectural layouts. The in-depth study of strategies to achieve flexibility in architectural layouts which were mentioned throughout this research, will help with the design and pattern configuration of further experiments using swarm robots. It also enabled us to have a better vision of what the next steps for the Methodology section would be.

Furthermore, exploring swarm intelligence algorithms provided valuable insights into the behavior and coordination mechanisms of swarm robots, which can make it easier for informed decision-making in their integration and use within architectural simulations or scenarios.

In mixing these diverse disciplines, this study hopes to help architects use technology that efficiently respond to human needs and helps them create better spatial experience, use, and satisfaction, for building occupants.

III Methodology

A. Research Design

1. Introduction

To have a more concrete vision of the approach and methodology of this research concerning spatial flexibility, a comprehensive analysis of selected case studies was deemed essential. This decision aimed to identify some of the most flexible building typologies (based on their function), to guide the subsequent stages of this thesis. Among these typologies are educational facilities, innovation hubs, and performance spaces. According to Nuñez and Parra-González (2023), educational spaces need to promote collaboration, participation, and socialization, and therefore, must have the possibility to get updated to new pedagogical methods while giving the users a chance to contribute to their learning process. Flexible planning is also an important part of the design of innovation hubs, as it enhances communication and interaction and allows the users to navigate openly through different activities and services and to customize the spaces around them (Holubchak et al., 2020). Moreover, in performative and theatrical spaces, the need for flexibility, rises from the imperative to accommodate shifting narratives and to actively engage and captivate audiences. Thus, the ideal architectural layout of contemporary educational buildings, innovation hubs, and performative buildings, from a social aspect, should provide a versatile and collaborative environment with some essential amenities. These amenities include open learning spaces, conference rooms, private office workstations, lounge spaces, and self-service bars, as well as diverse cultural and artistic facilities such as exhibition halls, galleries, and spaces for entertainment events (Schuermann, 2014).

To better understand how spatial flexibility has been achieved in the above-mentioned typologies, this chapter will first discuss the two selected innovation hubs namely; Haier Global Research Center in China, and Tata Innovation Center in New York in detail with their programs and spaces. Later three other buildings with similar features and flexibility as an important design aspect of them will be discussed. These buildings are the Echo Building & the Pulse Building in TU Delft, known as collaborative educational spaces for innovation and creativity, and the Amare Theatre in The Hague as a flexible performance and cultural events space. Subsequently, the results of these studies will be presented, and the key findings that will inform the next steps of this research will be discussed.

In the next part of this chapter, based on the cases studied, a few programs to be included in the flexible space configuration by swarm robots will be mentioned. Then the design process of the robots with the panels installed on them will be explained and the integration of these panels as building blocks for spatial configuration based on the space syntax method will be shown.

Later, the experiment set up on Rhino Grasshopper and then Pyhton will be shared in detail and the steps for each part will be discussed along with the outcome of each step. In the Python simulation, three different methods with different control systems (Centralized & Decentralized), which were used for spatial configuration by swarm robots will be explained. The pros and cons of each method will be then evaluated. In the end, the results will be summed up in the conclusion section.

2.1. Haier Global Creative Research Center in China

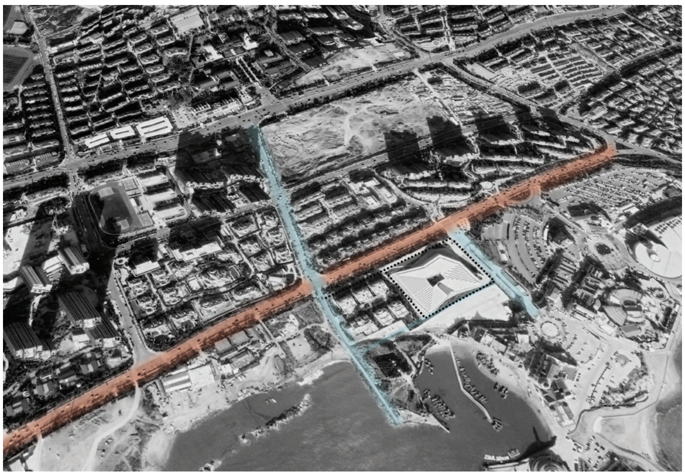
Location: Qingdao/ China
Size: 35451.0 sqm
Architects: DC ALLIANCE & Snohetta

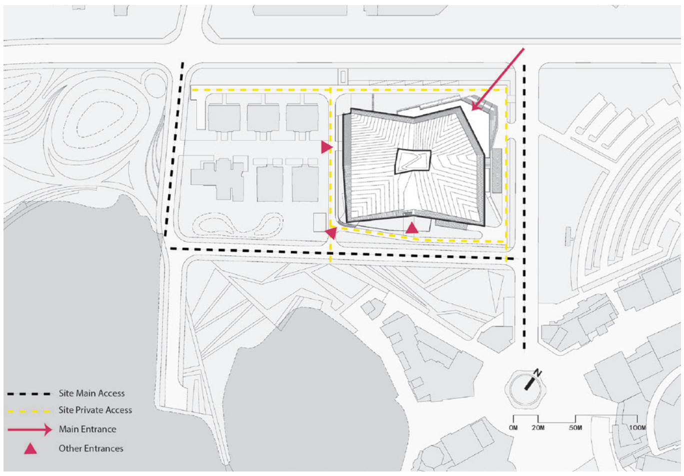
As published on Archdaily (2018) the architects DC Alliance & Snohetta describe the project as follows:

> Haier Group already has been the leading brand of global "white goods" and has become an international-renowned Chinese enterprise at the same time. In 2012, it was awarded the Top 50 among the world's most innovative enterprises. Its development direction gradually entered the network strategy stage and applying new ideas to lead the enterprise innovation in the Internet age has been the biggest challenge for Haier in this stage. In this context, the enterprise needs to create a cultural symbol reflecting the value of Haier, and to provide an innovative entrepreneurship platform for idea-exchange and thought- collision.

The client had requested a building that occupies 355,000 square meters, which would also be an outstanding architectural piece that is highlighting the city landscape. The programs needed to be included in the building were a co-working center, Library, Business institute, and a 750 people Auditorium. Meanwhile, it had to provide open spaces for art and leisure activities to be used during the week such as an exhibition space to showcase Haier innovations, an art gallery and an IMAX theatre.

Figure 52, 53. Haier Global Creative Research Center. Retrieved from https://www. archdaily.com/893893/haier-global-creative-research-centre-dc-alliance-plus-snohetta





Site access
Main access Local access Private access

Figure 54, 55. Haier Global Creative Research Center access routes. Own work created using google maps and archdaily site view of Haier Global Center.

Site Climate Data

The building design is highly influenced by the climatic conditions of the site. The form in general, mimics the mountainous landscape of the city. The elevated corners in the building are placed according to the prevalent wind direction and the winter sun. The courtyard in the center of the building ensures the rooms inside get enough light during summer while controlling unnecessary heat gain. Figure 62 shows the site with seasonal climate data.

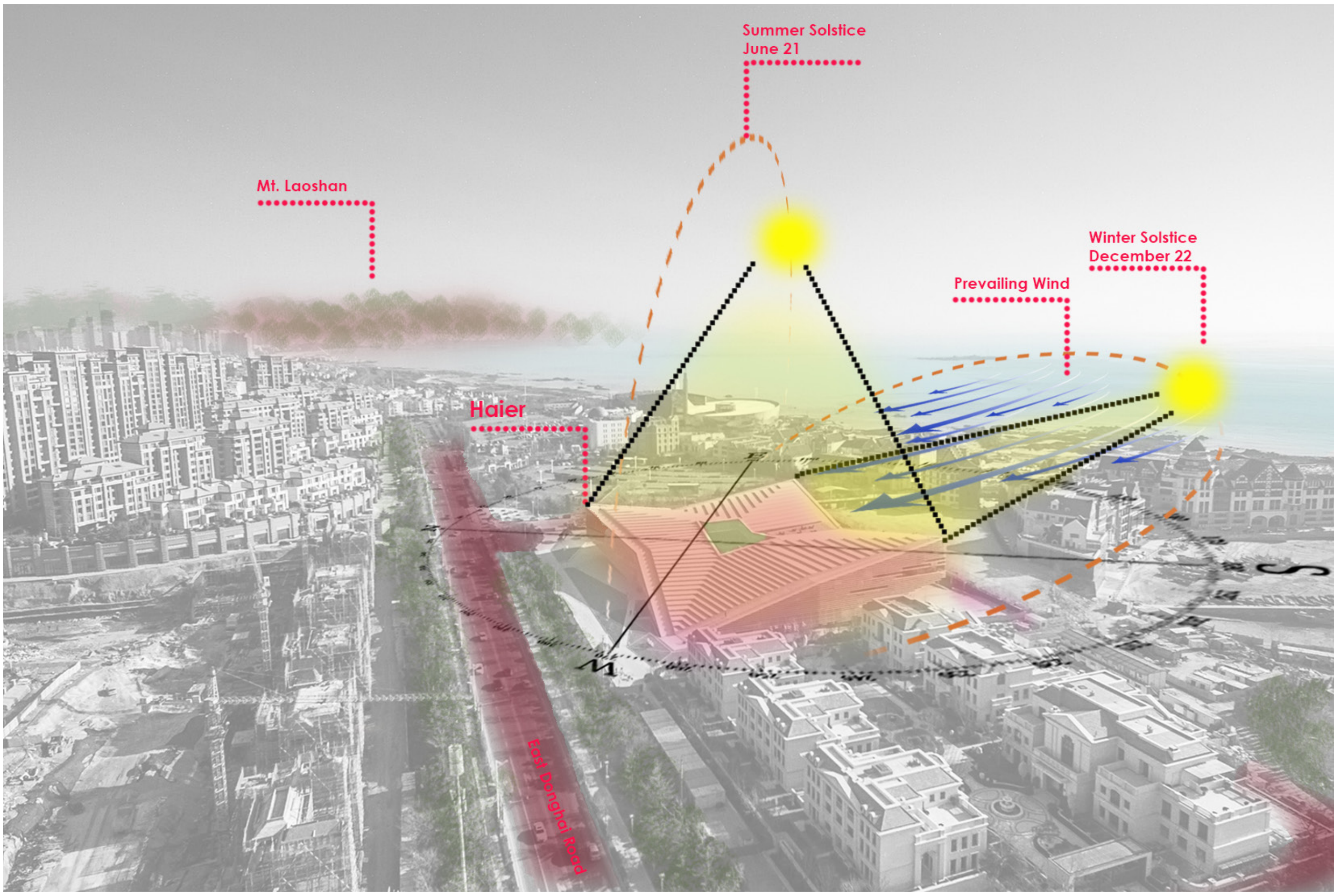
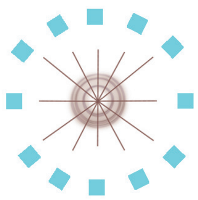


Figure 56. Haier Global Creative Research Center climate data. Own Work

Spatial Organization

The building is thoughtfully designed with all the functions arranged around a central courtyard, forming a unified layout. This courtyard is not only a source of natural light and ventilation but also enhances visual connections between the interior and exterior through its raised architecture. Such a design is instrumental in improving communication and interaction, which are vital for the research activities conducted within the building. Moreover, the arrangement of the landscaping of the building defines a city landmark and disrupts the conventional internal 'layering,' which allows for a vertical flow of space that promotes further interaction and communication (Archdaily, 2018).

Spatial Organization: Central



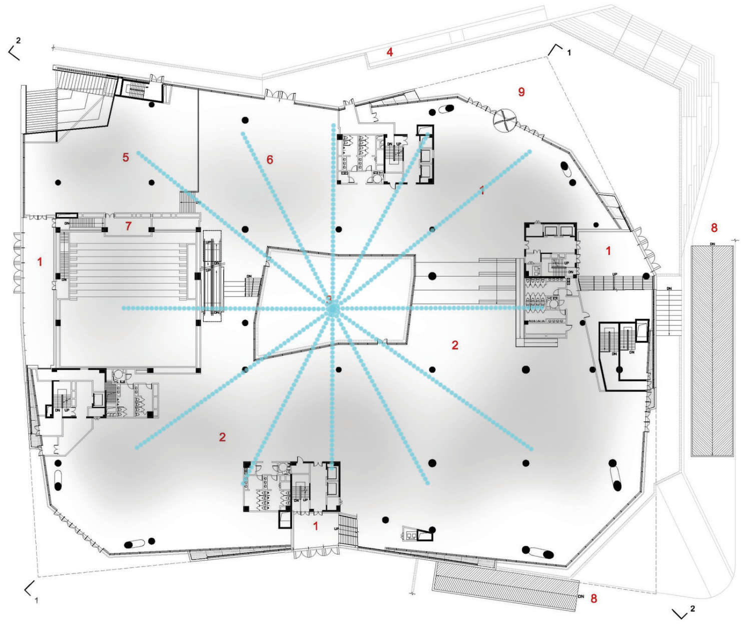


Figure 57. Haier Global Creative Research Center diagram showing spatial organization. Own work created using archdaily images of Haier Global Center.

Figure 58,59. Haier Global Creative Research Center courtyard. Retrieved from https://www. archdaily.com/893893/haier-global-creative-research-centre-dc-alliance-plus-snohetta

The Creative Research Centre's roof resembles a natural landscape, sloping gently towards the street on its northwest corner while elevating on the other corners to offer views of the ocean and horizon. This design integrates the roof into the public space, and connects the building with the city by provding an outdoor theater with communal areas. The alignment from the main entrance toward the sea is subtly adjusted, and creates a new connection from the city to the North and the sea . This overlap of architectural and natural elements is also reflected in the facade design (Archdaily, 2018).

Figure 60,61. Haier Global Creative Research Center rooftop. Retrieved from https://www. archdaily.com/893893/haier-global-creative-research-centre-dc-alliance-plus-snohetta

The spatial arrangement of the Haier Global Center revolves around the concept of interaction. The design foucses on connections between the building and its natural surroundings, between individuals and the spaces, between research and practice, and between people and technology. Its open-plan layout promotes freedom of movement and socialization,and encourages conversation and innovative thinking through elements such as natural light, views, and thoughtful use of color. The spatial organization is open and transparent. It utilizes a stepped system throughout the building to create a sense of constant activity and movement. Additionally, the design prioritizes user-friendliness and human-centered principles in terms of scale, materials, and overall aesthetics. Despite its distinctiveness, the structure remains humble and contextually sensitive (Archdaily, 2018).

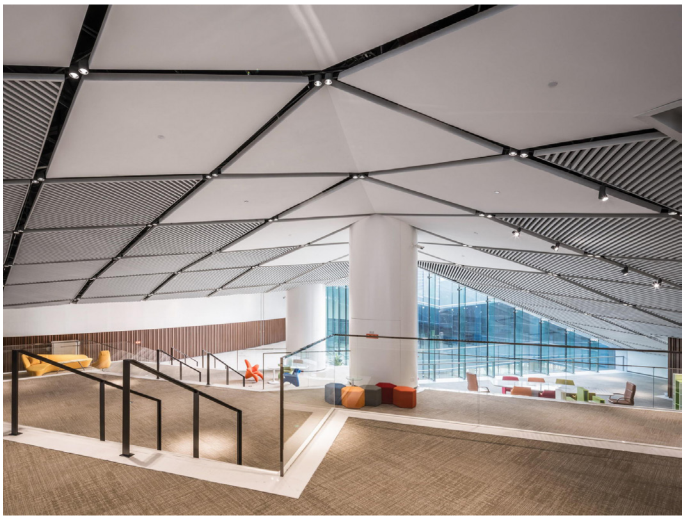
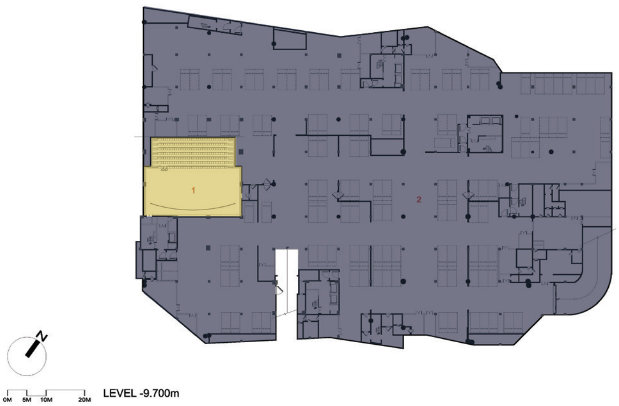


Figure 62,63. Haier Global Creative Research Center co-working spaces. Retrieved from https://www. archdaily.com/893893/ haier-global-creative-research-centre-dc-alliance-plus-snohetta

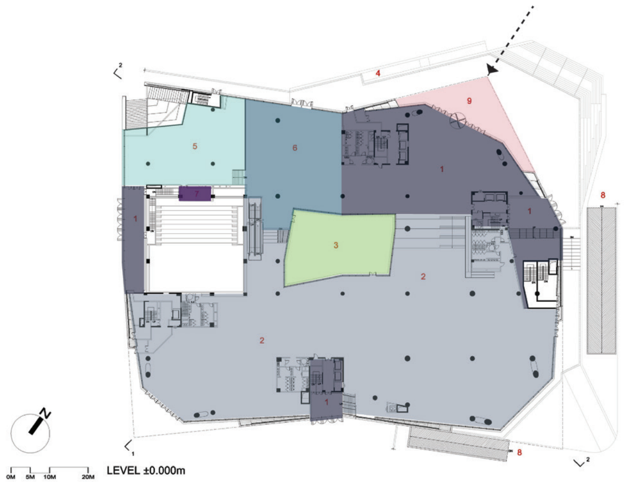
Building Plans

Building plans are shown below in Figures 70-75 with their color-coded programs.

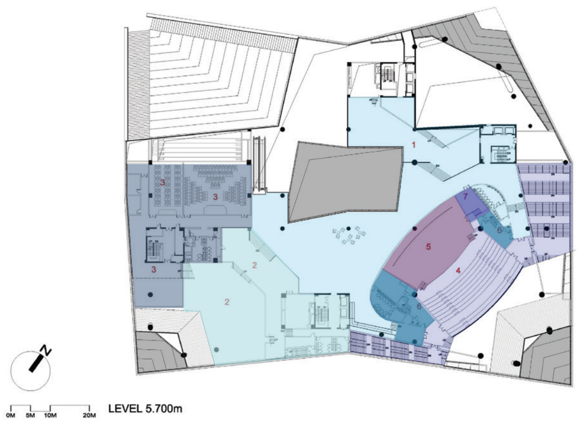


IMAX
Garage

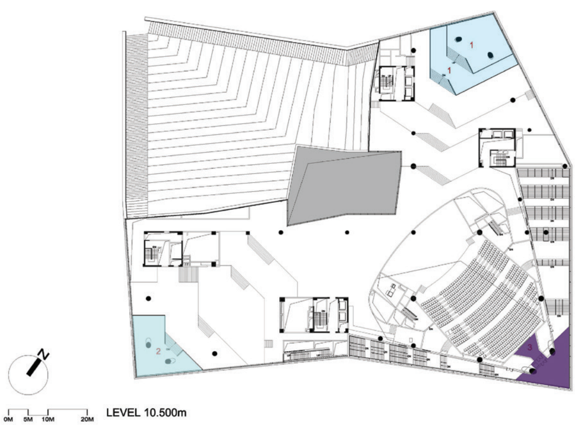
1 IMAX
2 Cafeteria
3 Storage
4 Kitchen
5 Equipment
6 Garage



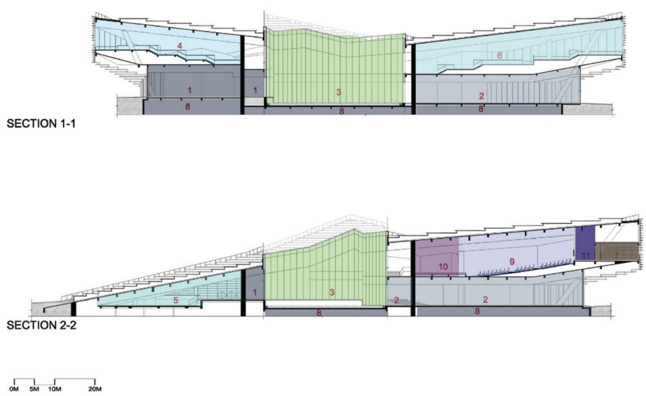
1- Lobby
2-Exhibition
3-Courtyard
4-Ramp
5-Cafeteria
6-Art Gallery
7- Projection Room
8-Garage Entry
9-Main Entrance



1-Co-working Area
2-Open Library
3-Business Institute
4-Auditorium
5-Stage
6-Dressing
7-VIP



1-Co-working
2-Open Library
3-Projection Room



1 Lobby
2 Exhibition
3 Courtyard
4 Co-working Area

1 Cafe
2 Open Library
3 Terrace
4 Garage

1-Auditorium
2-Stage
3-Sound Control Room

Figure 64-69. Haier Global Creative Research Center plans with color-coded programs. Own work created using archdaily images of Haier Global Center.

Building Programs

The table below does not represent all the programs and rooms of the Haier Global Research building, but, rather, lists the ones that are commonly present in other innovation hubs as well. This exclusion is deliberately done to focus only on the programs that will be deemed essential to help with the methodology part of this research.

Table 9. Case Study 1 Programs

Space	Number of Spaces	Total Area
Research Section/Huddle	1	835
Exhibition	1	3260
Auditorium	1	990
Gallery	1	390
Virtual Reality Room/ IMAX	2	1070
Library	1	765
Lobby	3	735
Roof Garden/ Courtyard	1	-
Marketing/ Business	1	600
Kitchen	1	161
Cafeteria	1	700
Technical Rooms	5	3401
Total		12907

Circulation Diagram

The vertical circulation of the building is divided into three parts:
The light blue part connects the two basements to the ground floor.
The purple line provides access to all the floors and the red line is the stairs used in the auditorium.

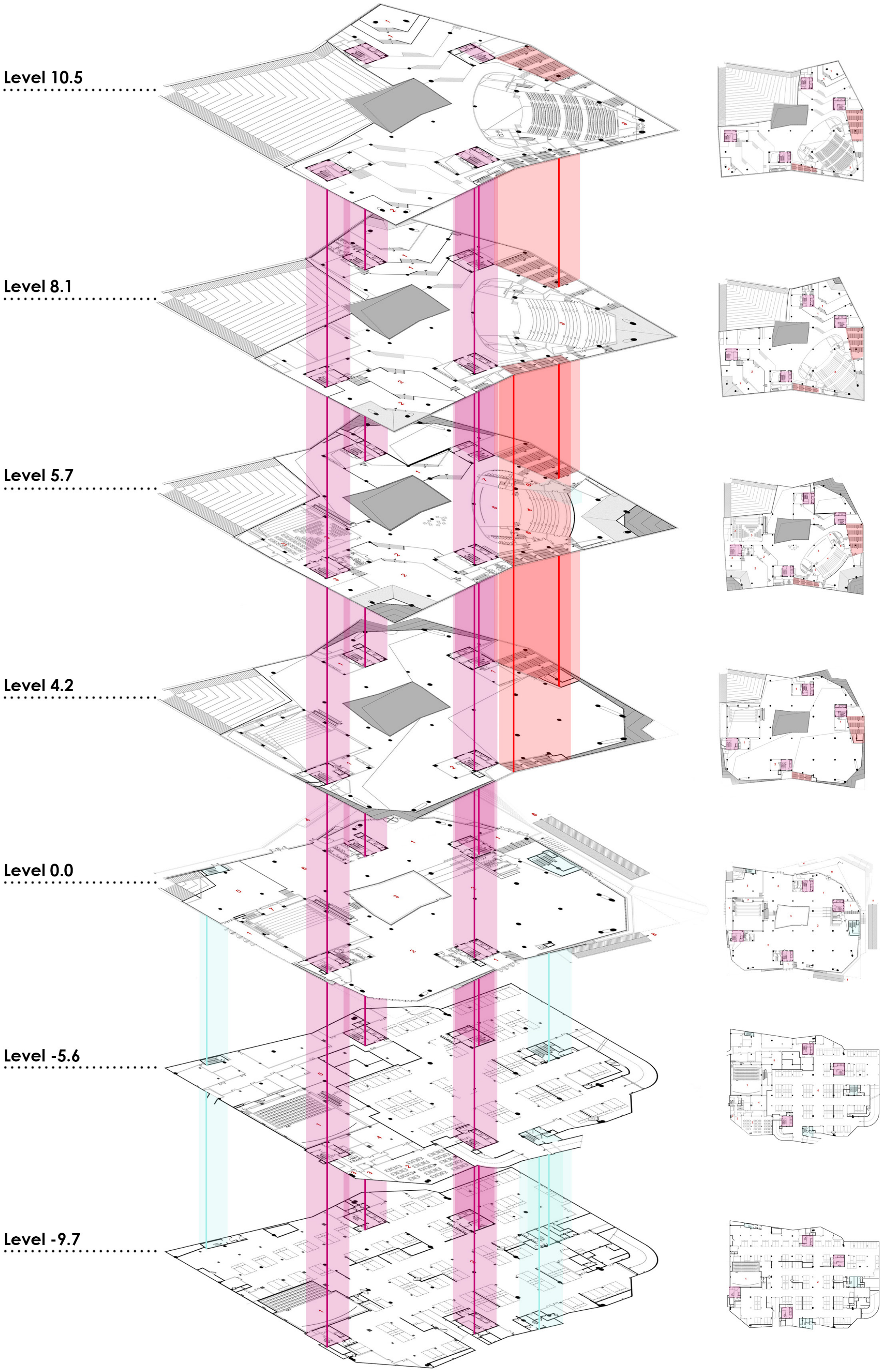


Figure 70. Haier Global Creative Research Center vertical circulation. Own work created using archdaily images of Haier Global Center.

2.2. Tata innovation Center

Location: Cornell Tech University/ NY, USA
Size: 21832 sqm
Architects: WEISS/ MANFREDI & Forest City Newyork

The Bridge at Cornell NYC Tech represents a significant advancement in the university's endeavor to bridge the gap between industry and academia at its pioneering Roosevelt Island campus. with seven stories, the building serves as a focal point for research and development (R&D), aimed at accelerating innovation within Cornell NYC Tech. Termed a "flexible incubator" by its architect, its loft-like style offers versatile spaces which facilitate collaborative entrepreneurial and academic activities. With a focus on improving interaction between academic researchers and start-ups, the design aims to enhance the university's collaborations with leading technology-focused companies and promote invention through "programmatic configurations" (LoopNet, 2017).

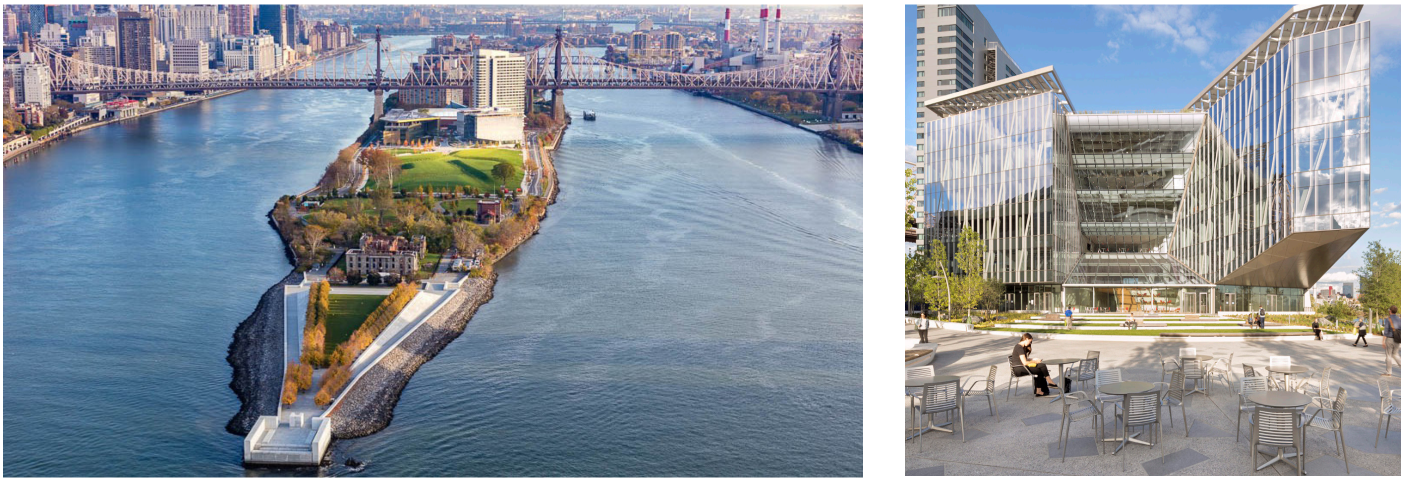


Figure 71. Tata Innovation Center. Retrieved from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

In the words of design partners Marion Weiss and Michael A. Manfredi, "The main design concept and theme of Tata Innovation Center (The Bridge) at Cornell Tech is connection. It started with aiming at creating an environment where creative thinking can flourish and innovative ideas can meet the real world of enterprise. Its main goal is bringing people, technology, research, and making together in order to provide the world with professional innovative solutions.

The building's crystalline geometries frame river to river views and bring daylight into all the spaces of the building. At the campus level, Tech Gallery, the building's entrance atrium, opens to the central campus green and is linked to the campus grounds with a series of landscaped terraces. The gallery and atrium open to views across the campus and create a three dimensional crossroads that encourages spontaneous conversations and collaboration throughout the building (Archdaily, 2015)."

Spatial Organization : Clustered

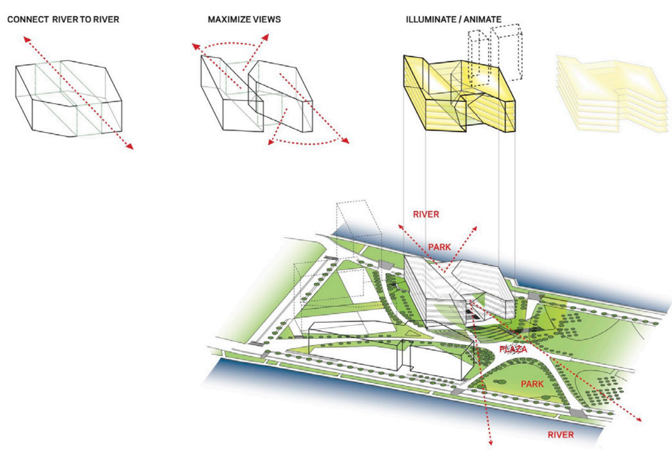


Figure 72. Tata Innovation Center design process. Retrieved from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

The cantilevered southwest and northeast wings provide outdoor communal areas, that bring life to the retail spaces on the ground floor and the entrance terrace. The outline of the PV canopy on the roof serves as a unifying element in the architectural design of the campus and symbolizes the University's dedication to sustainability. As a crucial component of Cornell NYC Tech's fresh graduate campus, The Bridge serves as a crystalline incubator hub, which reshapes conventional academic and corporate frameworks to create an environment that stimulates research and innovation.

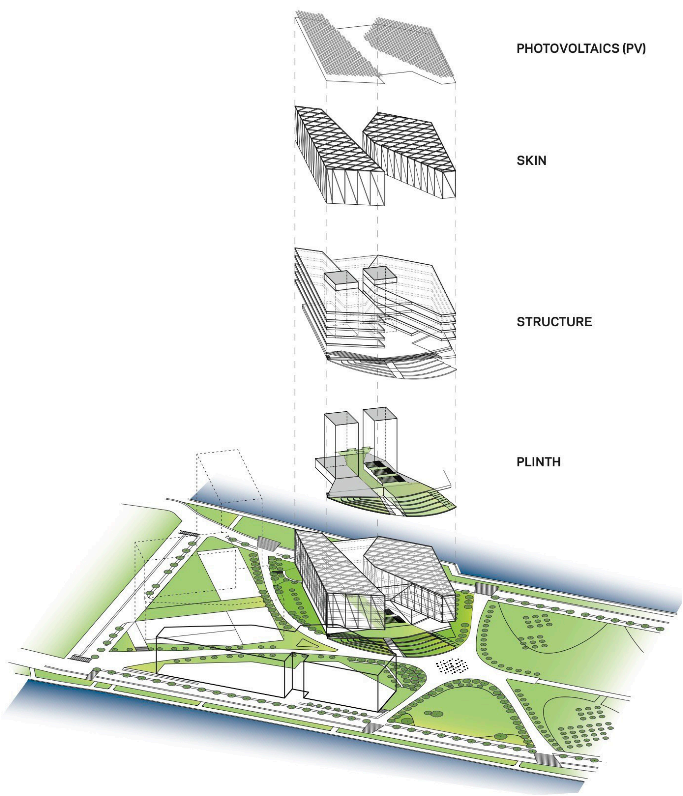


Figure 73. Tata Innovation Center building layers. Retrieved from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

Connection is achieved through the stepped layout of the building as shown in Figure 80 below. All the interior spaces are arranged around these steps and create distinct spatial layers. This strategy together with the open plan allows for better visibility and interaction. The height variation also creates a very dynamic atmosphere, ideal for creativity. The open plan mixed with the steps allows for maximum publicity and interaction (Archdaily,2015).

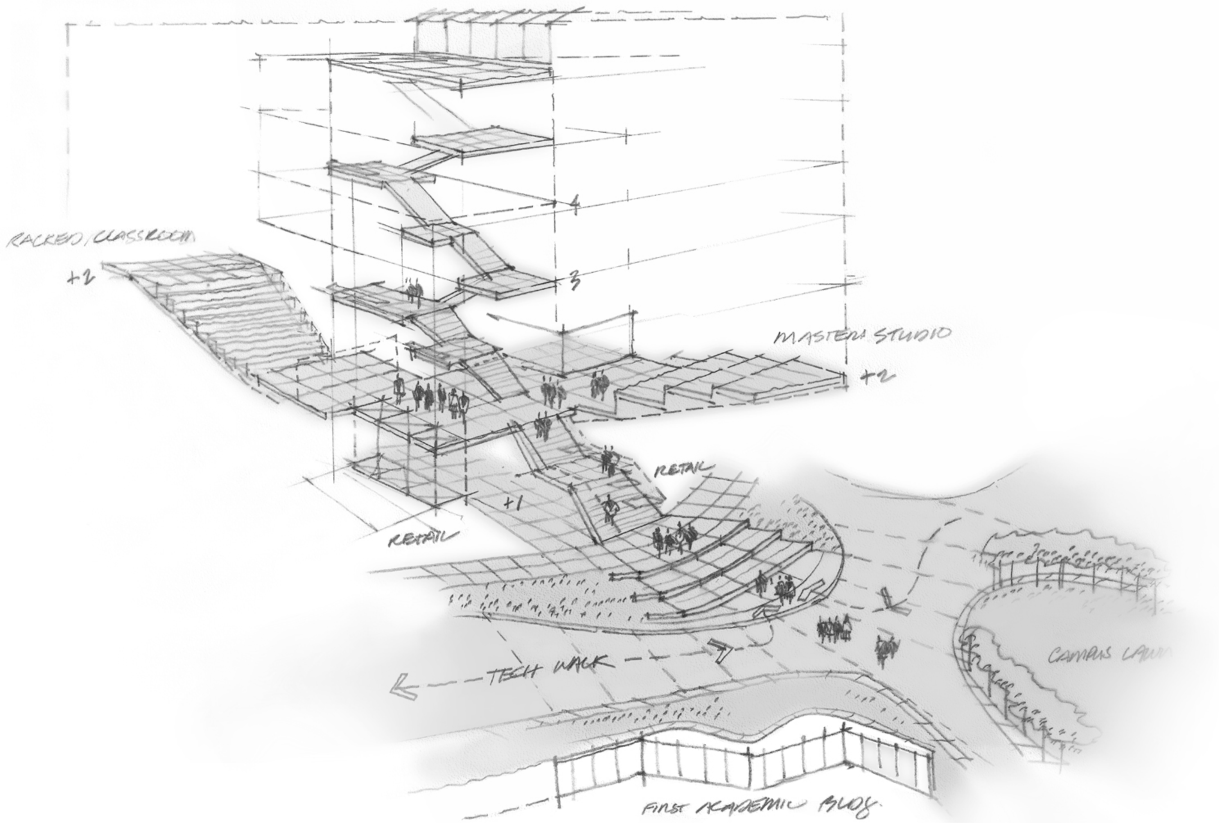


Figure 74. Tata Innovation Center stepped layout. Retrieved from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

Figure 75-78. Tata Innovation Center stepped layout. Retrieved from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

Site's Climate Data

Figure 85 below, shows how the building design was affected by the site's climate context. The central gap between the two building blocks is to ensure better ventilation and heat control based on the prevaling wind direction. It also functions as the central atrium that allows for effective light gain and control during different seasons.

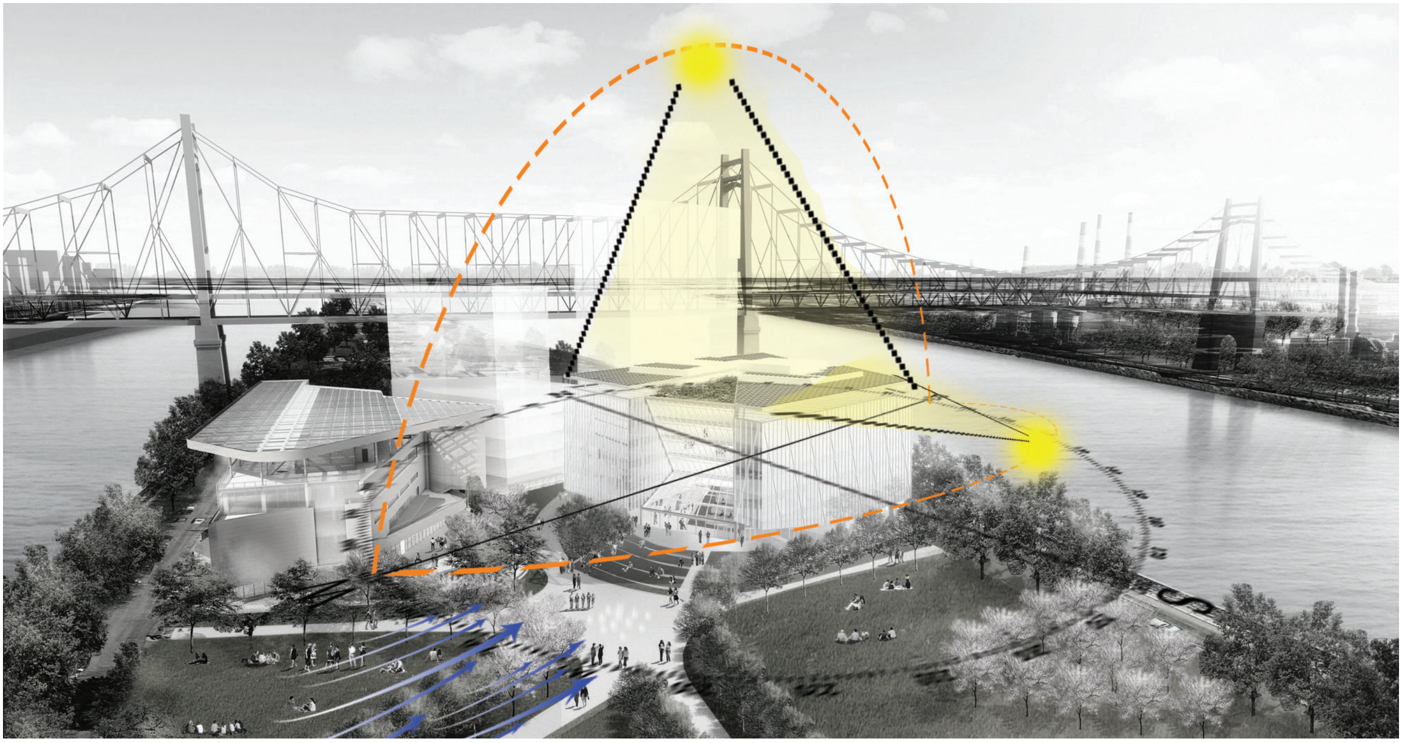


Figure 79. Tata Innovation Center climate data. Own work created using the image retrieved from https://www.thorntontomasetti.com/project/tata-innovation-center

Building Plans

Building plans are shown below in figures 80-82 with their color-coded programs.

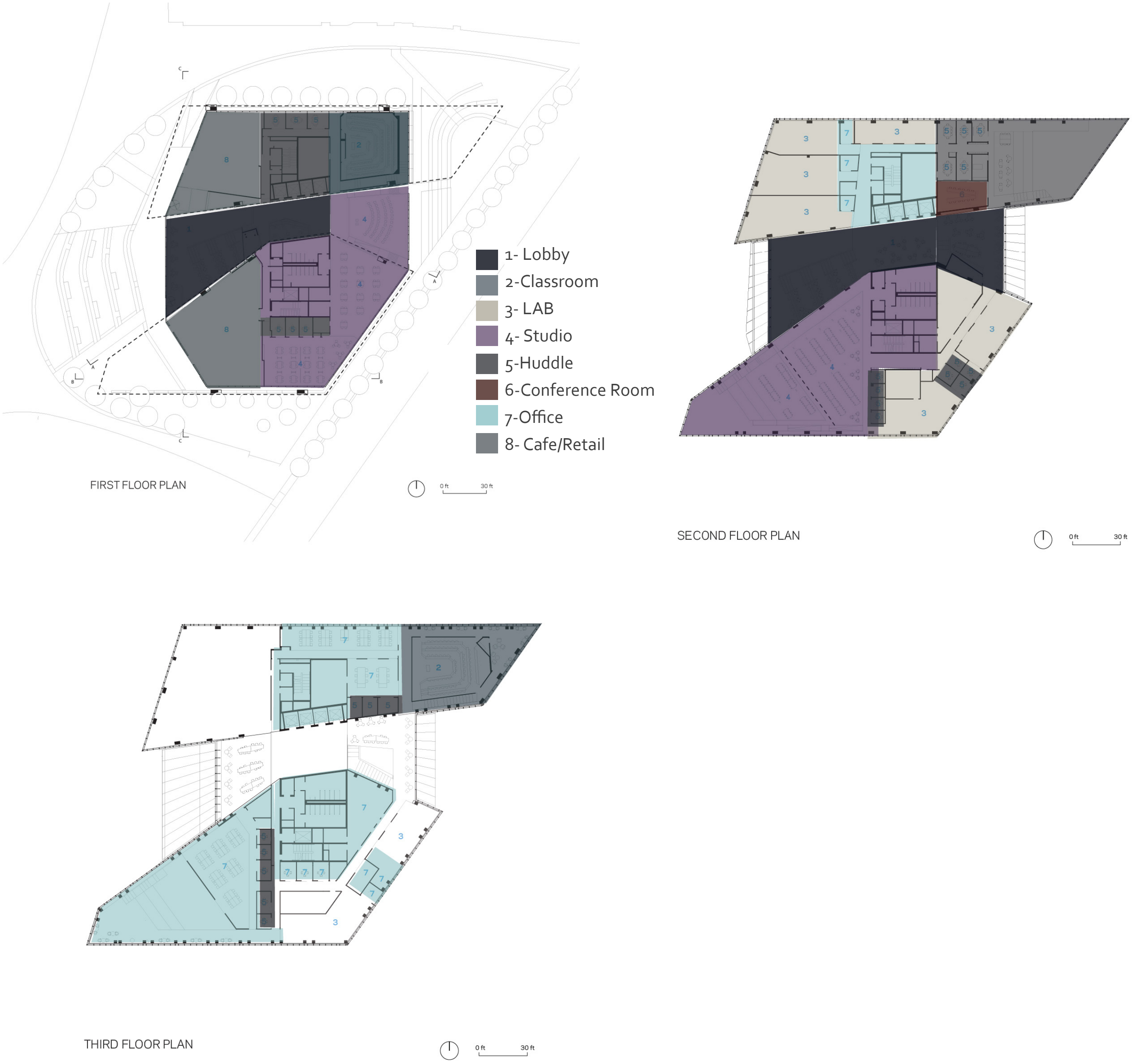


Figure 80-82. Tata Innovation Center plans with color-coded programs. Own work created using images from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

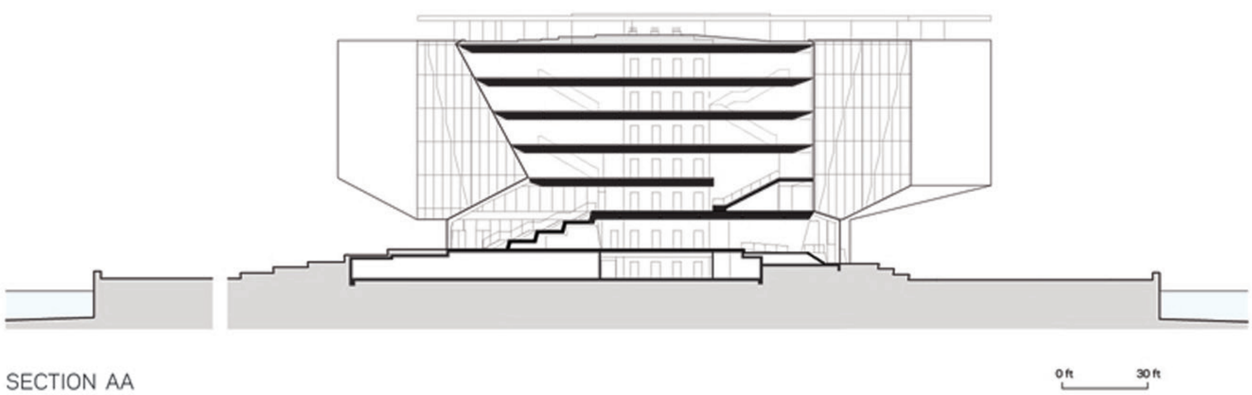


Figure 83. Tata Innovation Center plans with section. Retrieved from https://architizer.com/projects/the-bridge-at-cornell-nyc-tech/

Table 10. Case Study 2 Programs

Space	Number of Spaces	Total Area
Huddle	19	800
Workshops	5	3115
Conference	1	175
Classroom	2	1341
Research Section/Huddle	27	782
Lab	8	2943
Lobby	2	1341
Roof Garden/ Courtyard	1	-
Offices	13	1912
Total		14041 sqm

3. Educational Case-studies

3.1 Echo Building TU Delft

Location: Echo, TU Delft Netherlands, 2017 - 2022
Size: 8,844 sqm
Architects: UN Studio, Arup ,BBN

With the constant rise in student population, there was a need for additional educational facilities at TU Delft. To address the univeristy's demand for adaptable teaching spaces, the Echo building was created as an interfaculty building. The architects, made sure the building fulfills the various demands of educational models while paying a strict attention to the issues of sustainability and user well-being.
The building is an energy-generating hub, which aligns with the university guidelines for a fully sustainable campus by 2030 (UN Studio, 2017).

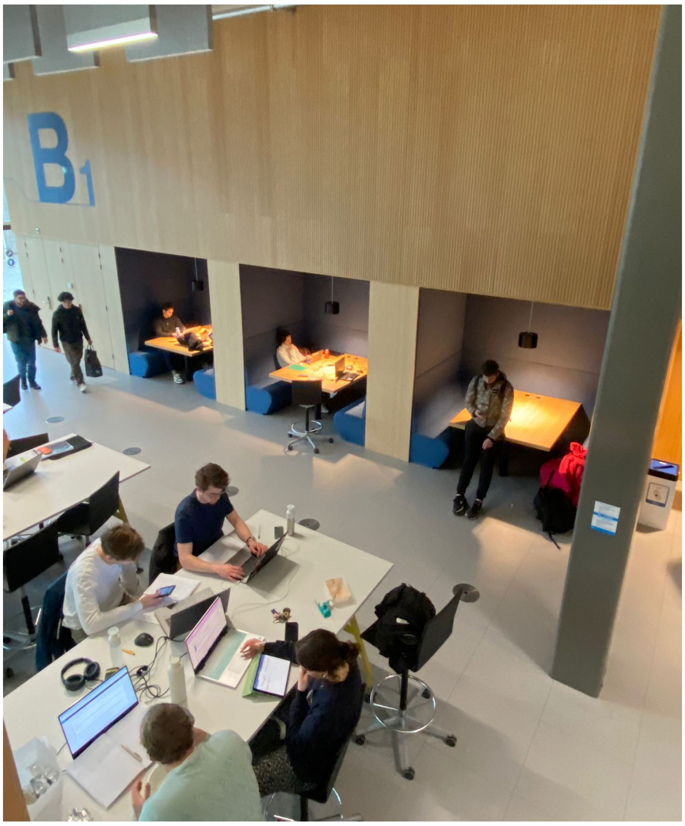


Figure 84 - 86. Echo building. Own photos.

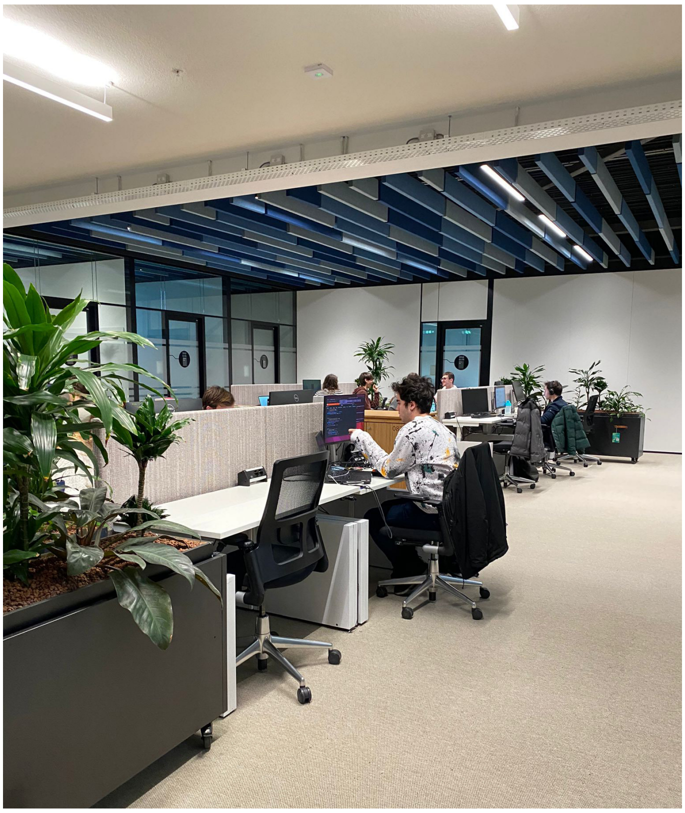


Figure 87 & 88. Echo building. Own work.

The architectural concept elevates modern educational settings, while implementing principles of the modern culture of 'Everything Anywhere', with a highlight on the significance of transitional spaces. Echo extends beyond its confines to integrate and shape the communal outdoor areas. The transformed ground level, now a versatile public plaza, is adorned with two striking sculptural forms that guide visitor movement. The building's sturdy yet refined façade invites the outside in, showcasing the internal dynamics to the external environment. The building's integration with the surrounding public space not only fosters connectivity but also establishes it as a defining element of the university landscape.

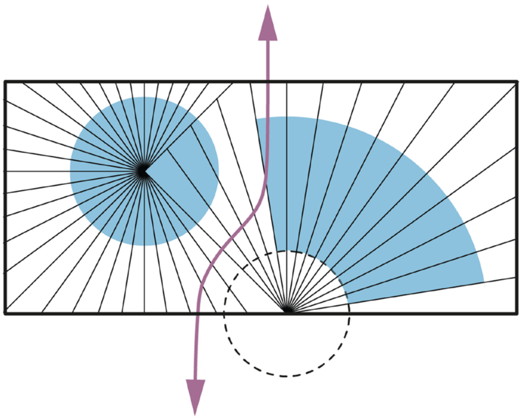


Figure 89. Echo building design. Retrieved from https://www.archdaily.com/941954/unstudio-designs-a-multifunctional-and-flexible-education-building-for-tu-delft-in-the-netherlands

Transparency played a pivotal role in Echo's architectural concept. It guarantees an abundance of natural light inside and good views of the campus and the adjacent natural landscapes. This design strategy helps to convert a confined, institutional experience to one in an open, communal, inviting , and positive atmosphere for both staff and students.

With the right use of solar shading and glass excessive solar heat gain is controlled and with an adaptable raised floor system over hollow-core slabs clean air is provided from below while allowing for future room layout alterations.

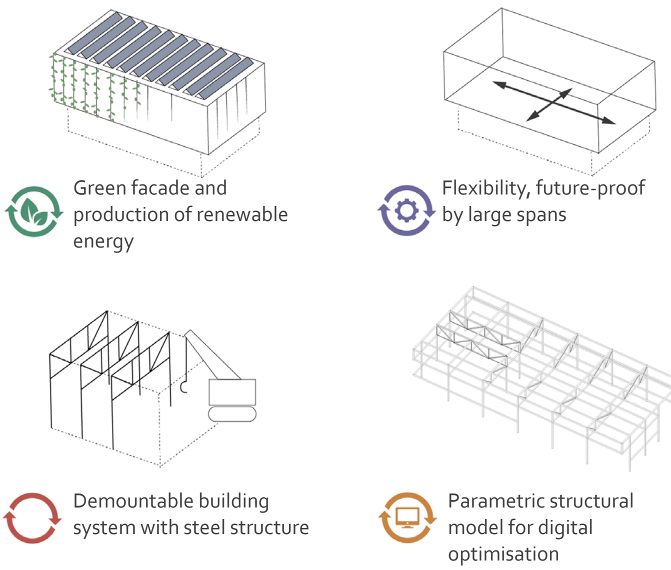


Figure 90. Echo building design process. Retrieved from https://www.unstudio.com/en/page/13592/echo-tu-delft

Echo is a structure that emphasizes the flexibility and comfort of its occupants. The building accommodates various teaching rooms and over 300 spcaes for studying, featuring adaptable arrangements. It includes a large lecture hall with a capacity for 700 people, which can also be divided into three distinct spaces.

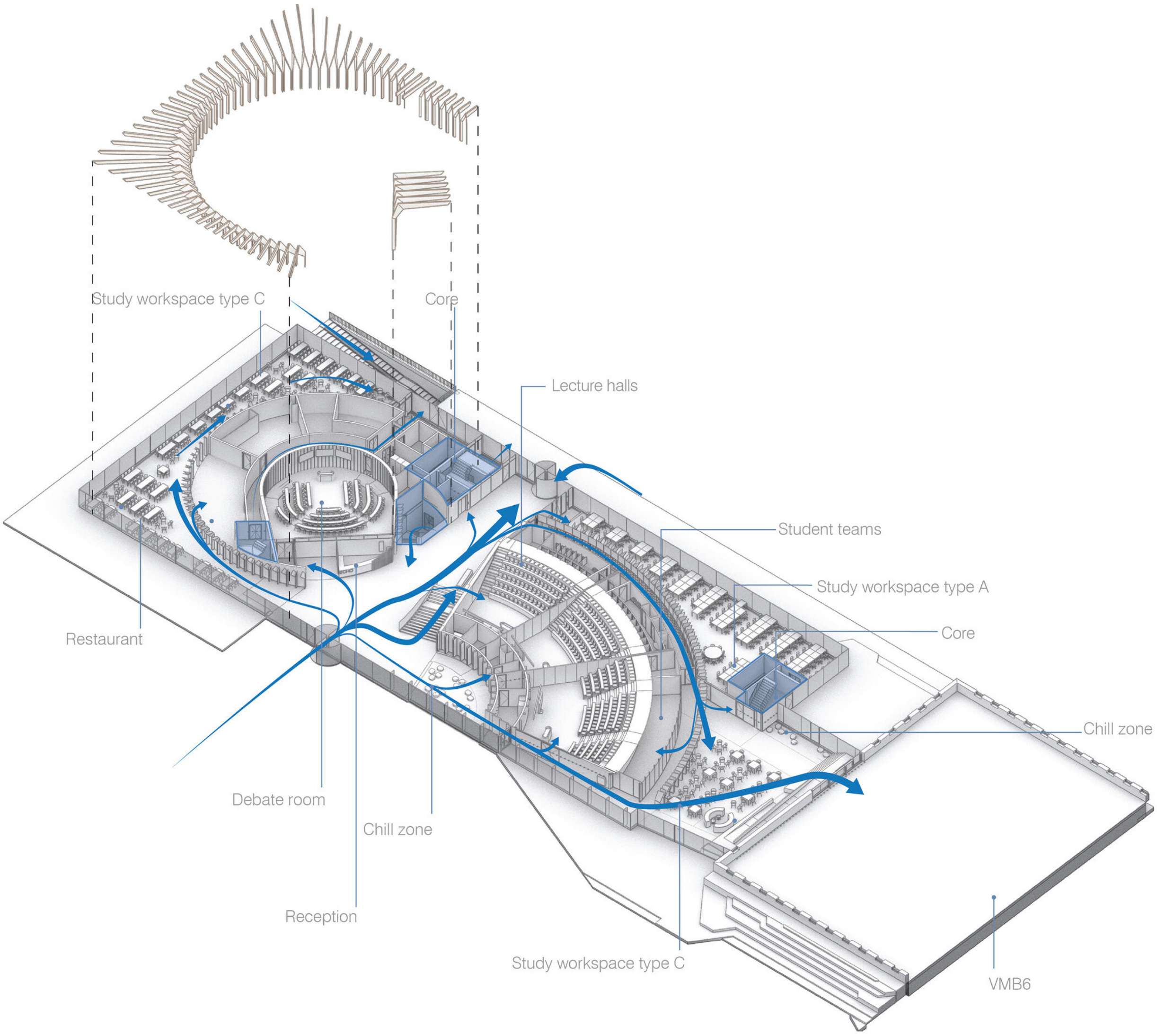


Figure 91. Echo building ground Floor. Retrieved from https://archello.com/news/unstudio-completes-an-innovatory-and-future-proof-interfaculty-teaching-building-for-tu-delft

In Ben van Berkel from the UN studio's words "*The future campus needs to be programmed with a series of agile spaces that invite students and faculty to learn, collaborate and co-create. As student numbers continue to grow, educational buildings need to be extremely flexible: they not only need to operate for shared, interfaculty use, but also need to house a large variety of flexible spaces that cater for various ways of teaching and studying and varying class sizes.*"

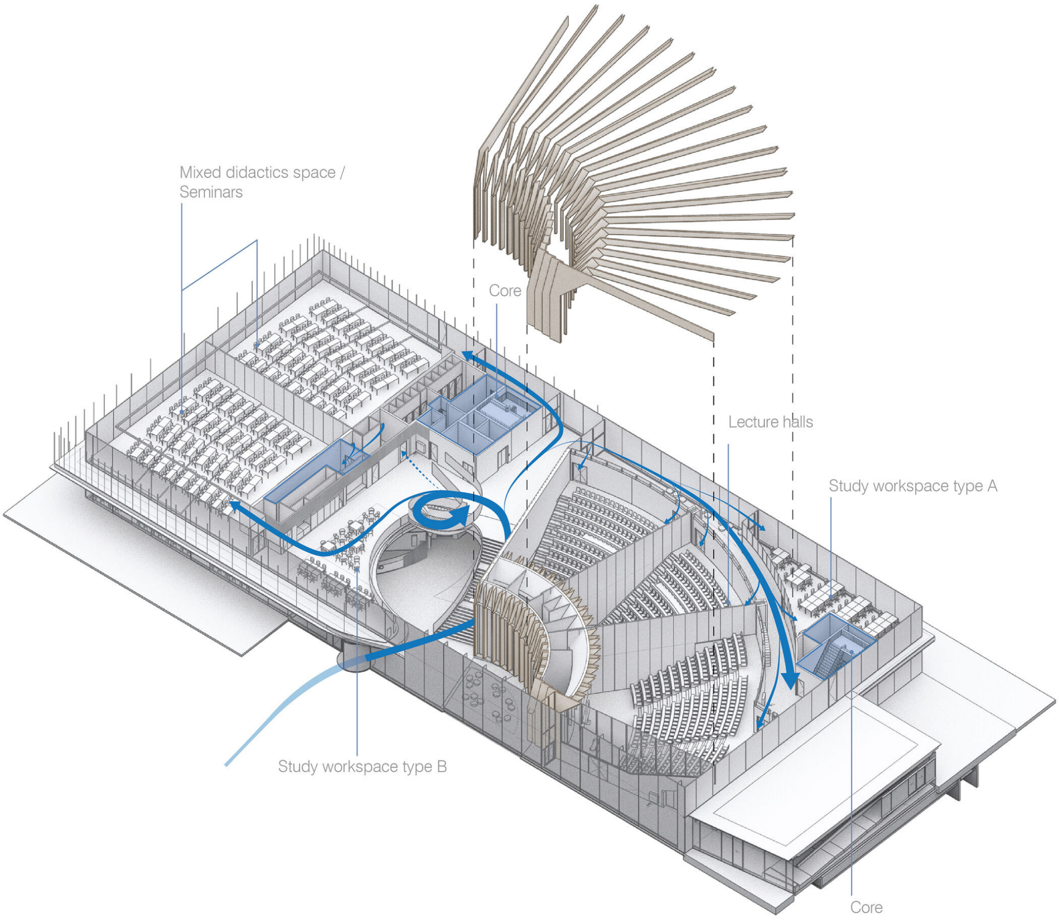


Figure 92. Echo building first floor. Retrieved from https://archello.com/news/unstudio-completes-an-innovatory-and-future-proof-interfaculty-teaching-building-for-tu-delft

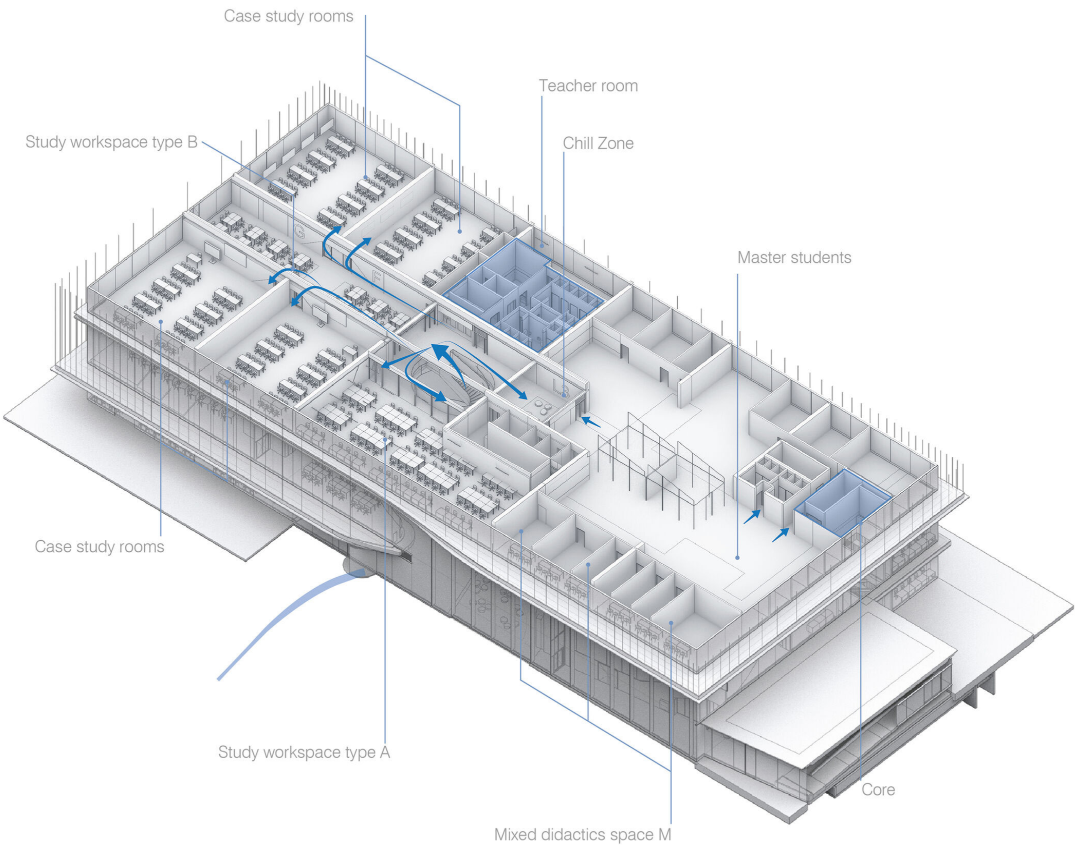


Figure 93. Echo building second floor. Retrieved from https://archello.com/news/unstudio-completes-an-innovatory-and-future-proof-interfaculty-teaching-building-for-tu-delft

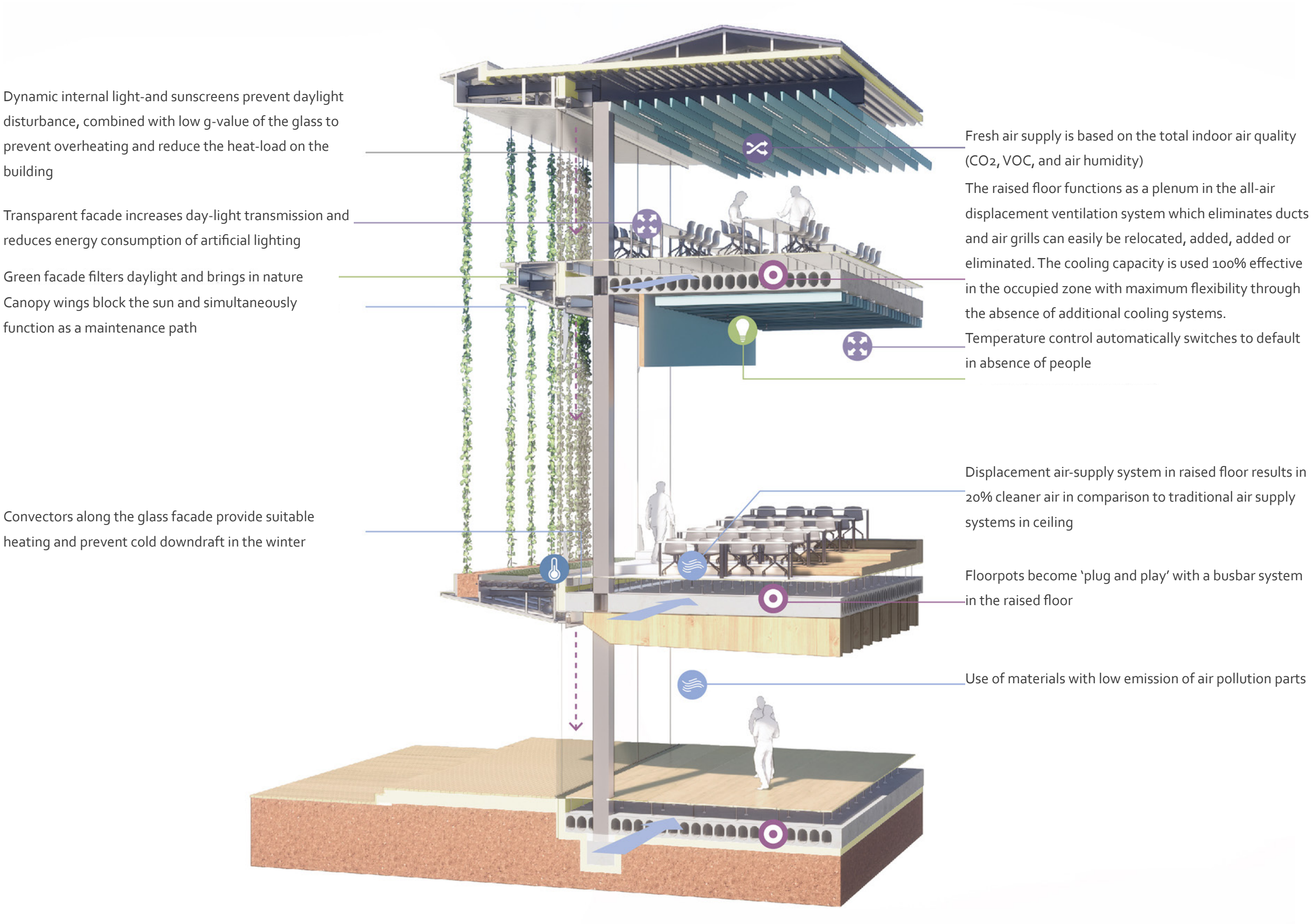


Figure 94. Echo building systems. Retrieved from https://www.unstudio.com/en/page/13592/echo-tu-delft

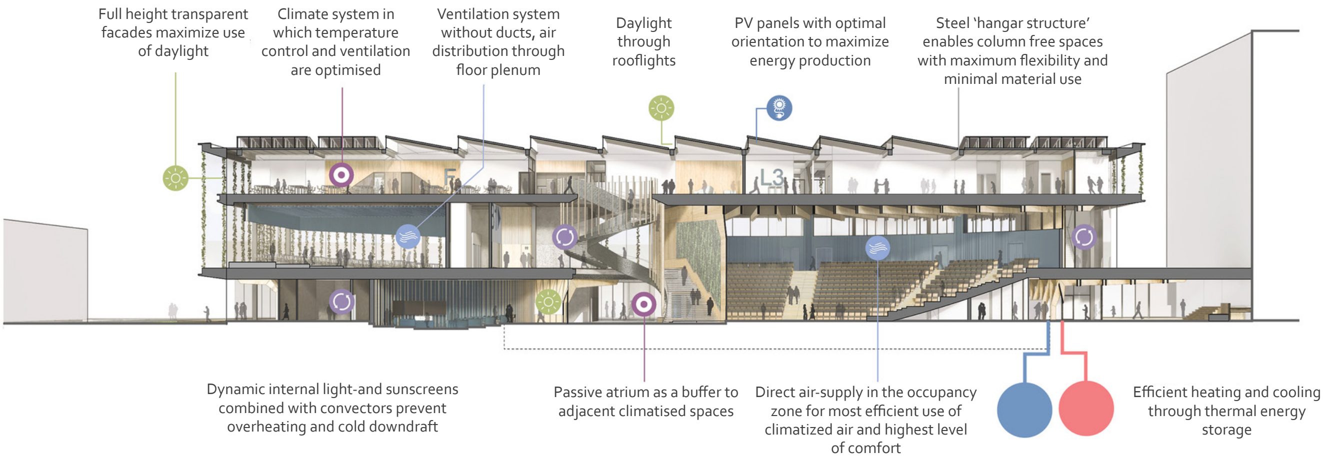


Figure 95. Echo building systems. Retrieved from https://www.e-architect.com/holland/echo-tu-delft-building-unstudio?utm_content=cmp-true

Echo is designed to meet the present and anticipated requirements of faculty and students, providing spaces for a diverse range of educational activities, including lectures, seminars, collaborative projects, discussions, and individual study for approximately 1,700 students. The versatile teaching spaces are designed to accommodate groups ranging from 150 to 700 individuals, with specialized project-based teaching of four-level rooms each hosting 70 people. There's also a case-study room designed to foster dynamic interaction and inspiration between instructors and pupils. The building's design incorporates two large lecture halls that contribute to the dynamic atmosphere of a spacious and open central square, suitable for a host of different functions. A prominent staircase is strategically placed to encourage and facilitate movement throughout the building (Archdaily,2023).

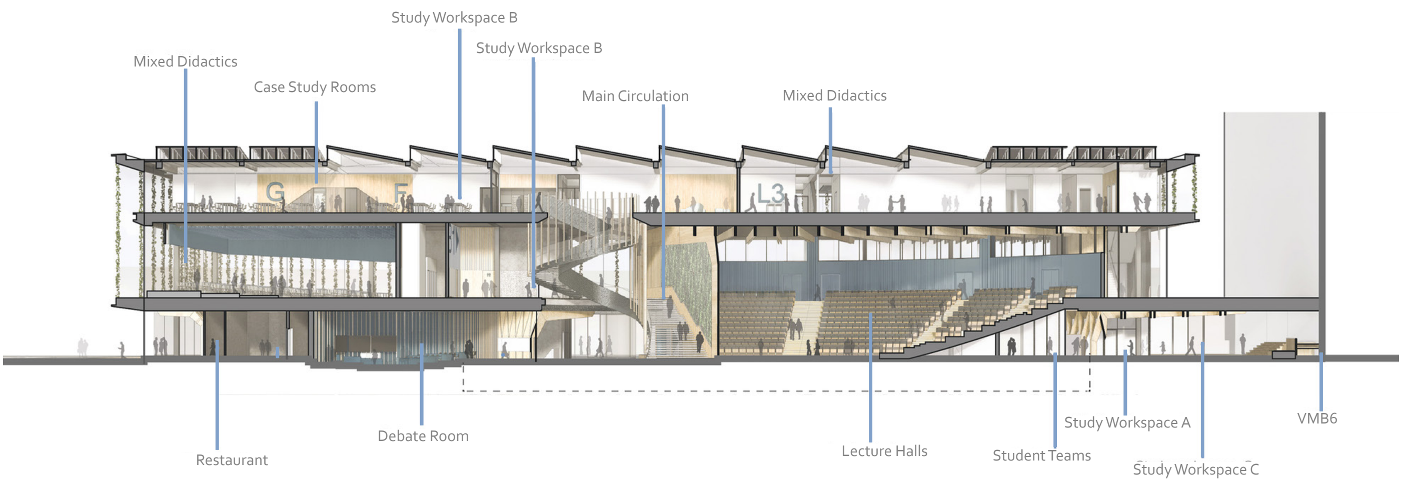


Figure 96. Echo building programs. Retrieved from https://www.archdaily.com/941954/unstudio-designs-a-multifunctional-and-flexible-education-building-for-tu-delft-in-the-netherlands?ad_medium=gallery

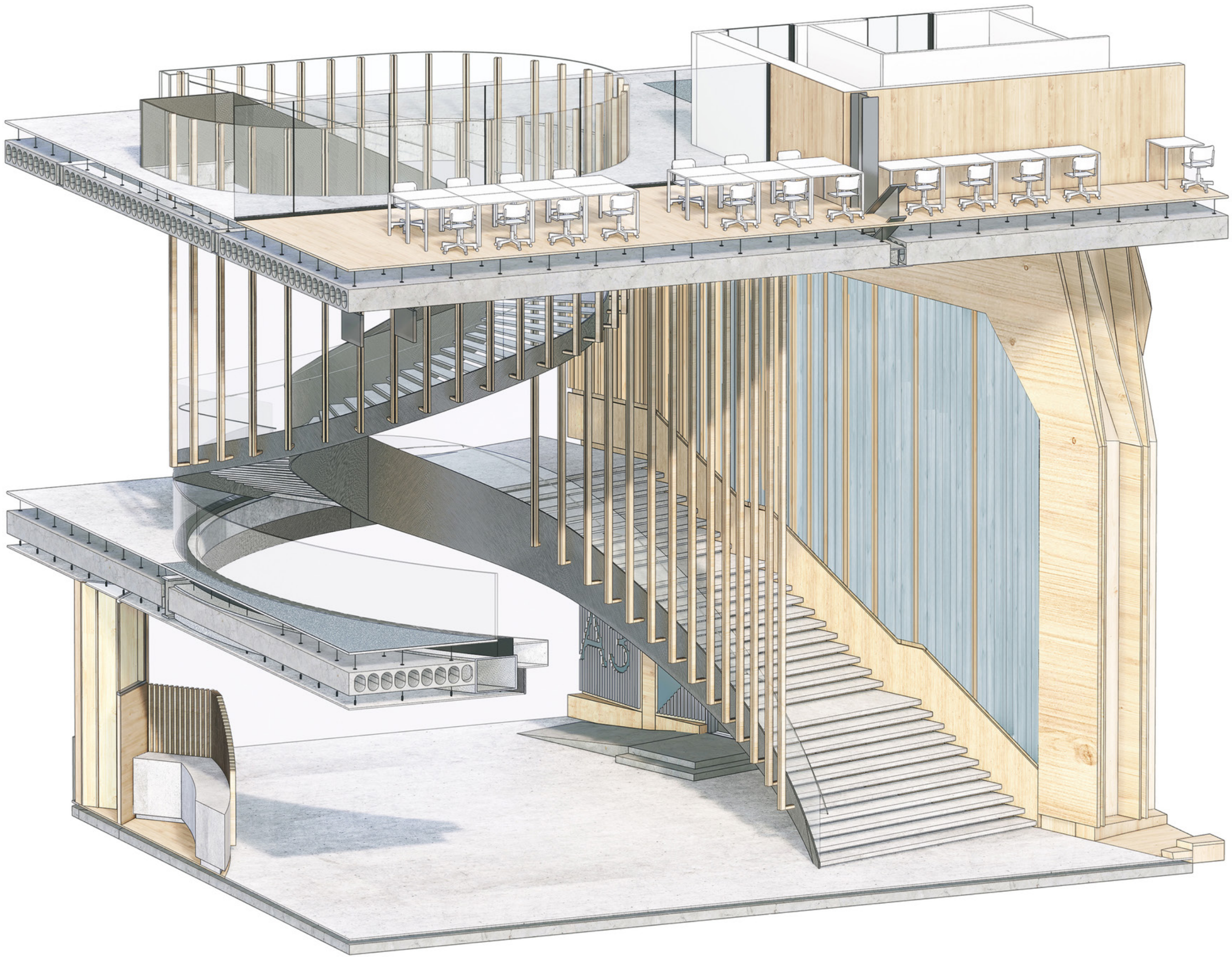


Figure 97. Echo building programs. Retrieved from https://www.e-architect.com/holland/echo-tu-delft-building-unstudio?utm_content=cmp-true

Table 11. Case Study 3 Programs

Program	Number of Spaces
Study Workspace	7
Mixed Didactics	2
Student Teams	1
Teacher Room	1
VMB6	1
Chill Zone	3
Debate Room	1
Seminar Rooms	1
Lecture Halls	3
Master Student Room	1
Case Study Rooms	2
Reception	1
Restaurant	1
Total Area	8884 sqm

3.2. Pulse Building Tu Delft

Location: TU Delft, TheNetherlands
Size: 1,500 sqm
Architects: Ector Hoogstad Architecten

The initiative for the project was driven by the need to expand facilities for the university's increasing student population, introducing versatile educational and communal spaces. Pulse, tries to represent practice, unity, learning, sharing, exploring, in a shift towards interactive and skills-focused learning by including flipped classrooms and video-conferencing. Moreover, it features a food court with a capacity for 200 people, which encourages social interaction and studying in a welcoming atmosphere. This space serves all faculties, where informal connections and communities can form (Ectorhoogstad Architects).

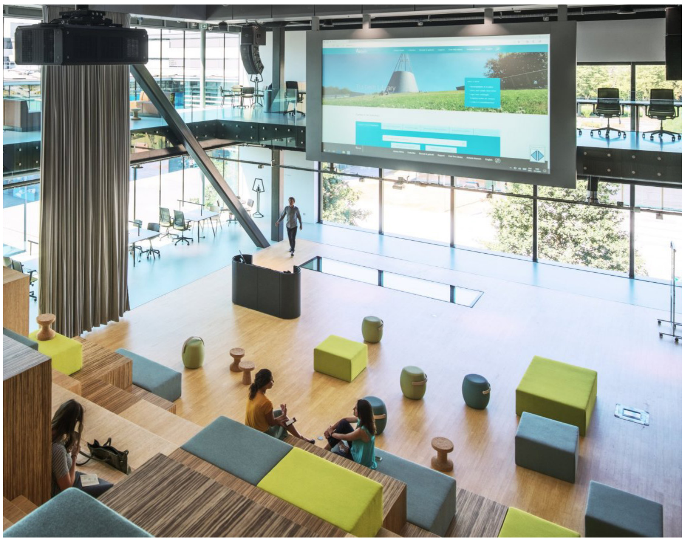


Figure 98 & 99. Pulse Building TU Delft. Retrieved from https://www.ectorhoogstad.com/en/project/pulse-delft-university-technology

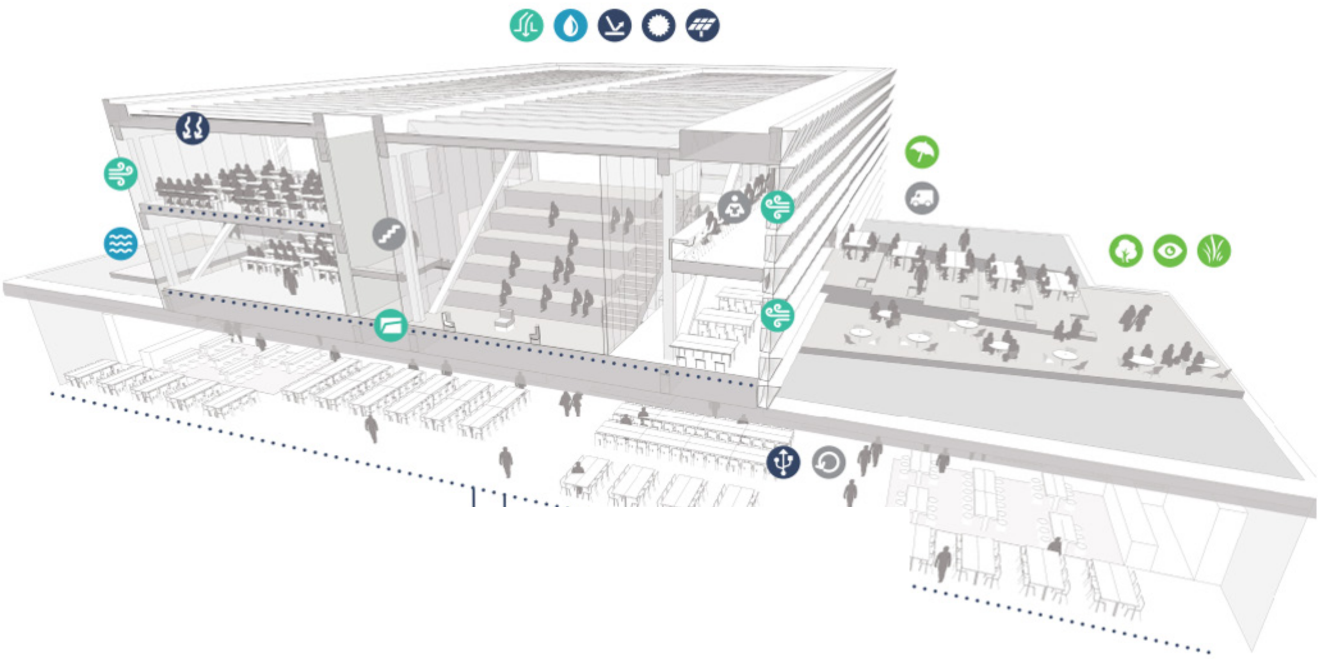


Figure 100 . Pulse Building TU Delft. Retrieved from https://www.schooldomein.nl/kloppende-duurzaamheid-bij-tu-gebouw-pulse/19-dgmr-afbeelding2-energieneutraal-ontwerp-ector-hoogstad-architecten/

The building's interior blends advanced technology with warm materials, through the use of refined finishes together with exposed installations. A mix of aluminum, various types of glass, concrete, wood, and textile creates a versatile environment. Natural light is a key feature in the building, with its intensity varying across the space, thanks to elements like the glossy glass walls of Qbiq. This design mirrors the university's goal of nurturing engineers who are creative, critical, and community-oriented.

Figure 101 & 102 . Pulse Building TU Delft. Retrieved from https://www.ectorhoogstad.com/en/project/pulse-delft-university-technology

According to the architects Van Benthem & Hoogstad *"Daylight penetrates the new PULSE building everywhere; sometimes very direct, sometimes dosed and filtered, for instance by the nicely glossy glass walls."*

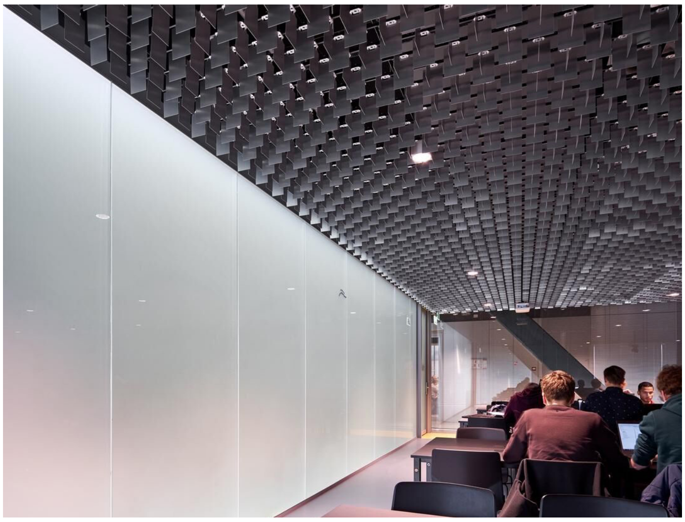


Figure 103 & 104 . Pulse Building TU Delft. Retrieved from https://archello.com/project/pulse-delft

Figure 105 . Pulse Building TU Delft. Retrieved from https://www.gispen.com/en/projects/education-projects/delft-university-of-technology--pulse/

Pulse's compact design not only proved to be cost-effective but also simplified the layout, enhancing connectivity between educational spaces. Ground and first-floor corridors link directly to the Industrial Design Engineering (IDE) and 3ME faculties, making Pulse a key crossroads on campus. Furthermore, the extensive use of clear glass removes visual barriers, and encourages connection and collaboration between people and integrating the space with its surroundings

Figure 106 - 109 . Pulse Building TU Delft. Retrieved from https://www.gispen.com/en/projects/education-projects/delft-university-of-technology--pulse/

4.1. Amare Theatre in Den Haag

Location: Den Haag, TheNetherlands
Size: 50000 sqm
Architects: NOAHH

Amare stands as the vibrant heart of the performing arts in The Hague, Netherlands, providing a home for renowned entities like the Nederlands Dans Theater (NDT), the Residentie Orkest, the Royal Conservatoire, and the Amare Foundation. Seamlessly integrated into the cityscape, Amare represents the cultural spirit of The Hague. The design, a collaborative creation by NOAHH, JCAU, and NL Architects for the city, stands out with its global appeal. Amare welcomes the public into its spaces, presenting a wide range of opportunities for engagement and use (Archdaily,2023).

Figure 110 - 111 Amare Theatre. Own photos.

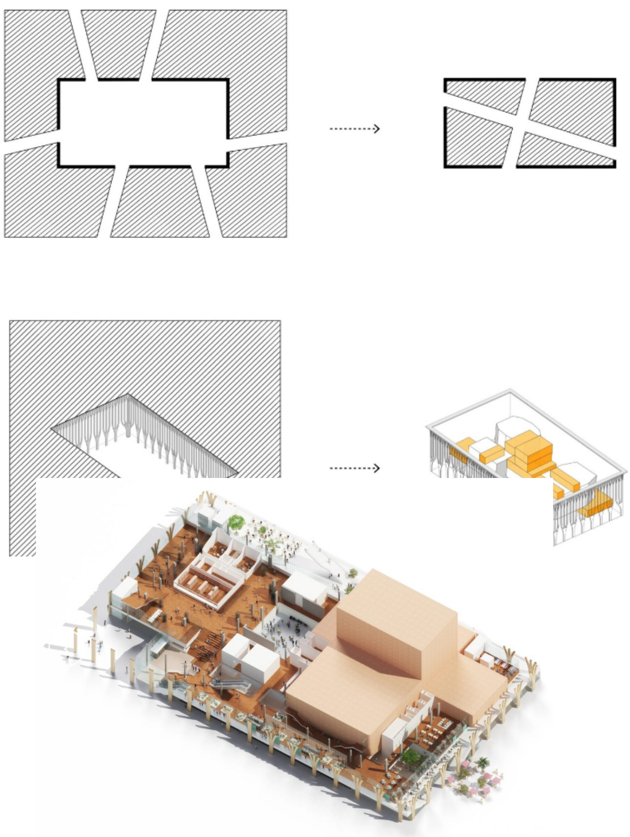


Figure 112 & 113- Amare Theatre. Retrieved from https://noahh.nl/portfolio_page/amare-the-hague/

Figure 114- Amare Theatre. Own Photo.

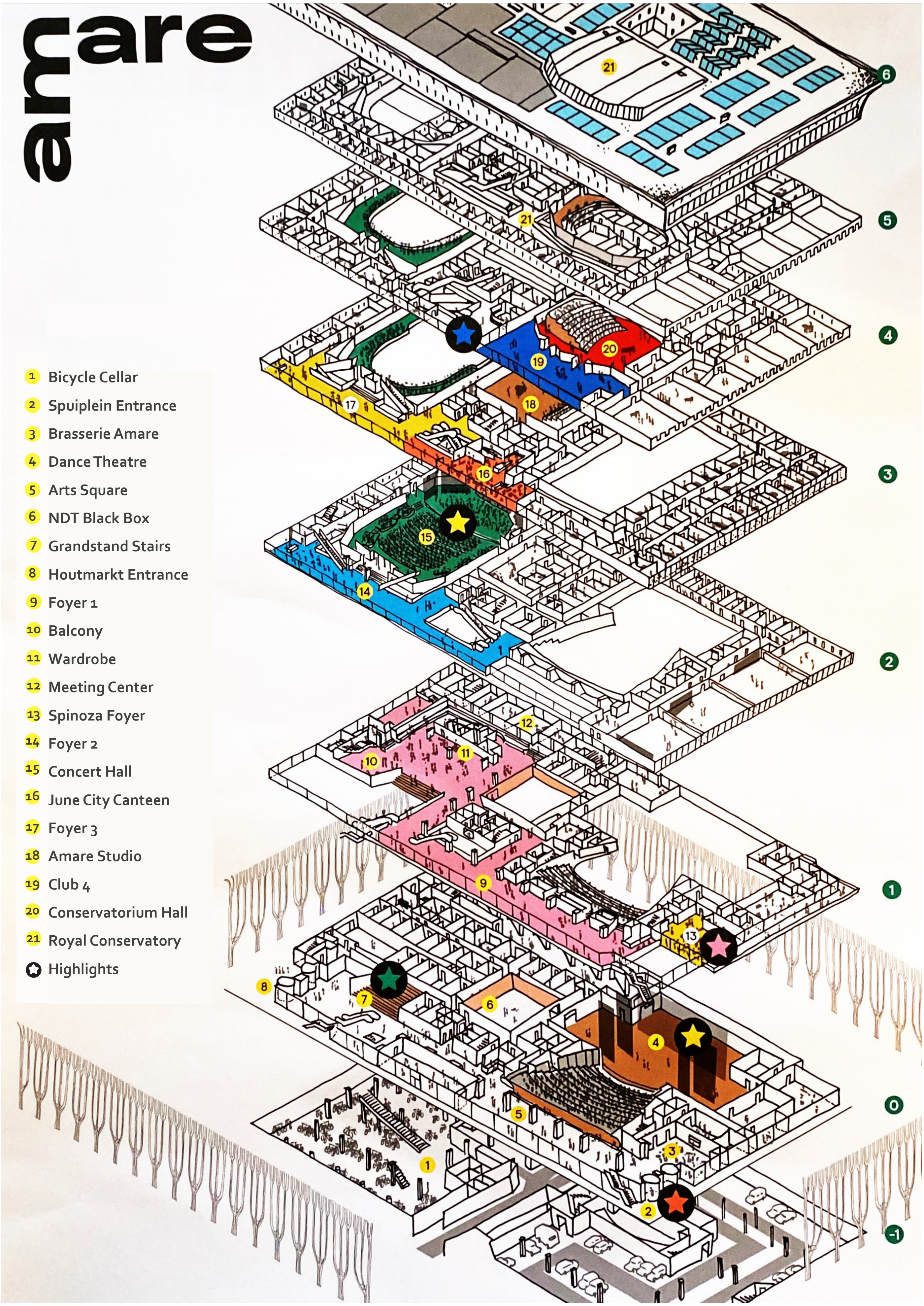


Figure 115 . Amare Theatre. Brochure retrieved from the building information desk.

Amare enriches the vibrancy and adaptable nature of the city center of the Hague, by adding a significant value to its cultural landscape. Serving as an urban hub, it accomodates 24/7 activities, and offers a seamless and welcoming passage for all. Conceptualized as a 'Multiversum', Amare epitomizes an inviting and dynamic cultural and social space, simiar to a bustling cityscape with its interconnected streets, alleys, and squares nestled inside the building. Beyond its four grand auditoriums,there are numerous smaller studios, where students, professionals, and the public can co-exist in one space. The internal connections between building parts facilitate interactions,and collaboration (Archdaily, 2023).

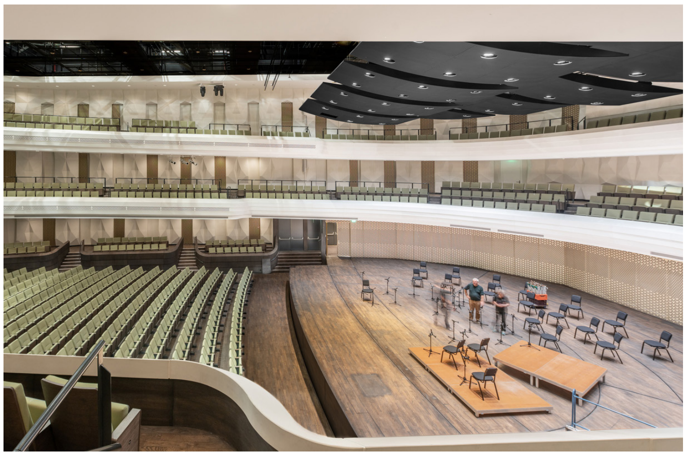


Figure 116 & 117 . Amare Theatre, ground floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

Amare houses diverse worlds within a single building by using an extensive variety of materials and colors. Each auditorium is distinctively finished, ranging from a bamboo exterior to golden metal cladding. Around the auditoriums there are foyers with matching ambiances. The Dance Theatre's numerous adjustable wall panels allow for perfect acoustics for dance, speech, and opera performances. In contrast, the Concert Hall's design is characterized by concrete wall finishes and golden sliding panels for acoustic adjustment.

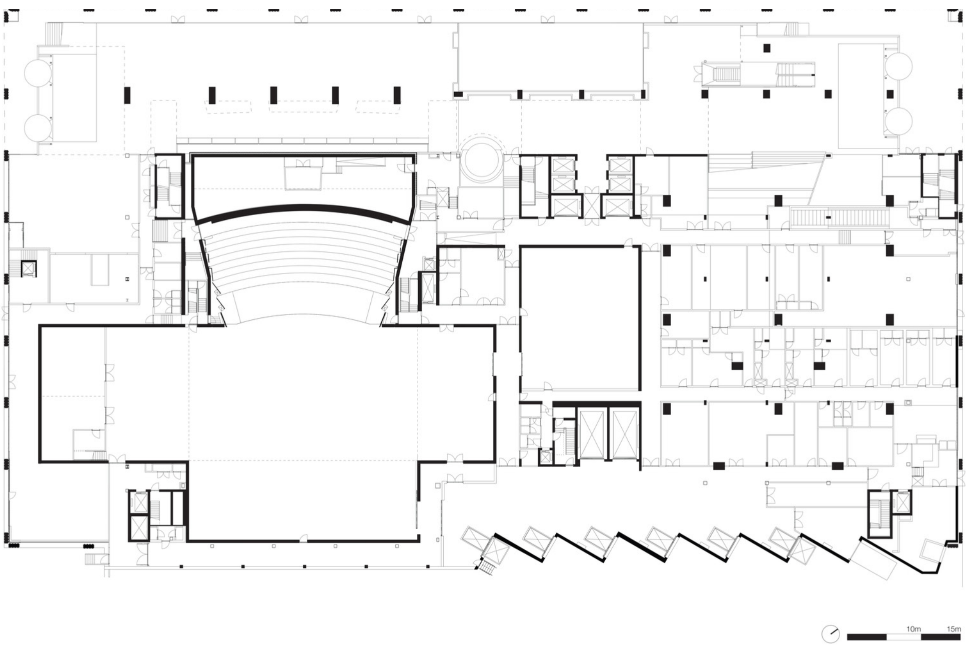


Figure 118. Amare Theatre, ground floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

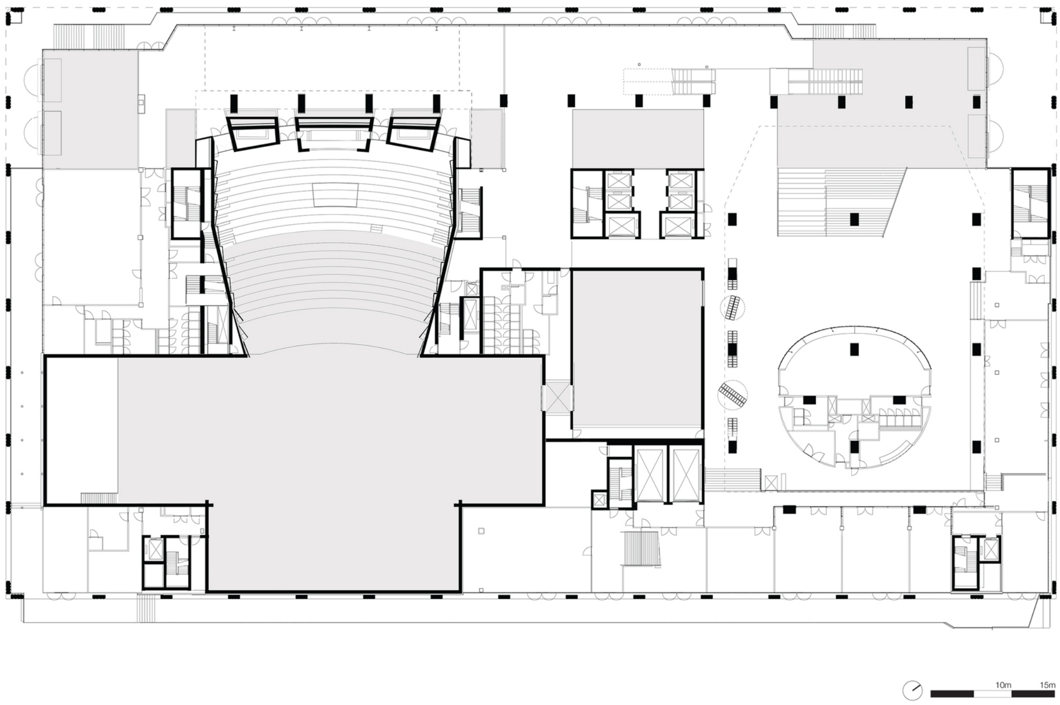


Figure 119 . Amare Theatre, first floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

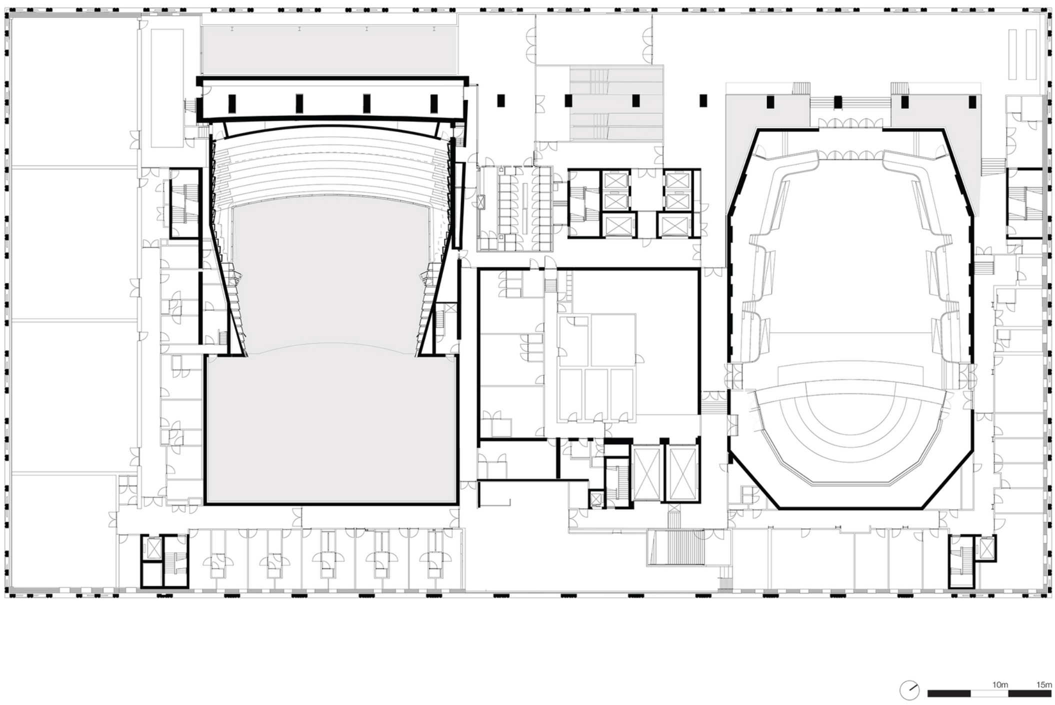


Figure 120 . Amare Theatre,second floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

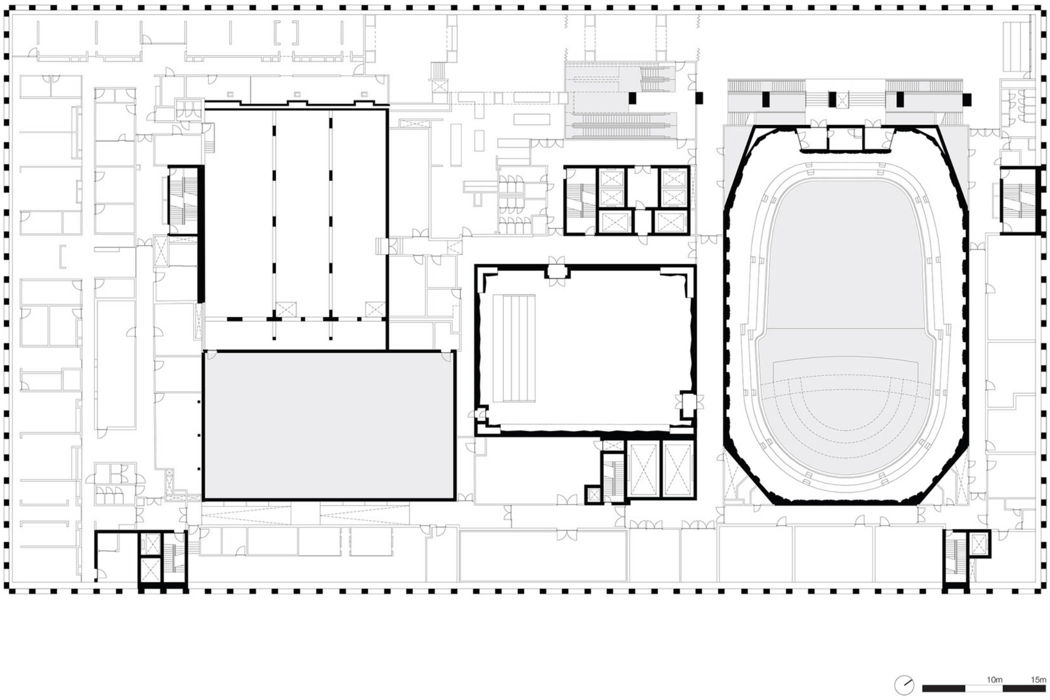


Figure 121 . Amare Theatre,third floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

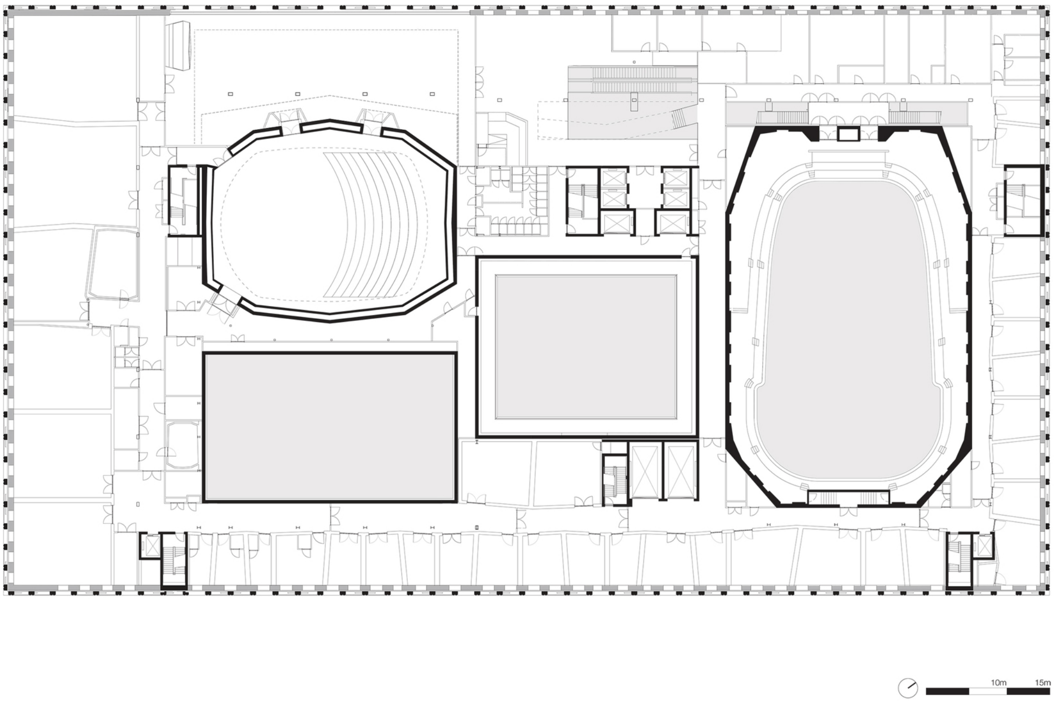


Figure 122 . Amare Theatre,fourth floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

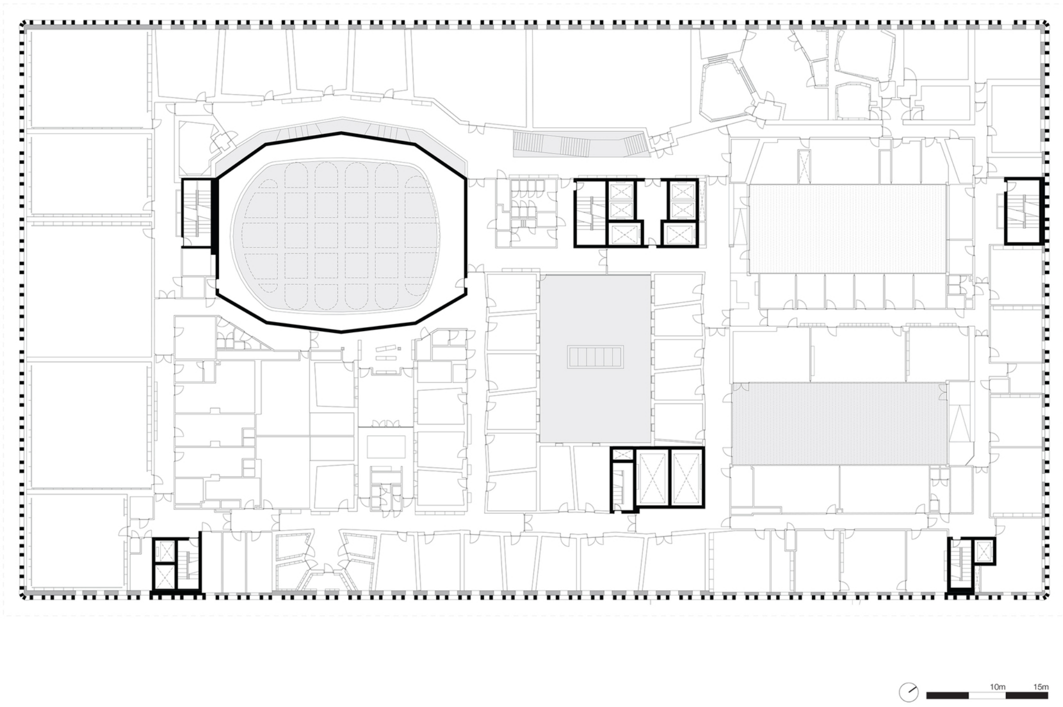


Figure 123 . Amare Theatre, sixth floor. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

Identities blend seamlessly within Amare, where diverse worlds coalesce within its architectural confines, owing to a rich tapestry of materials and hues. Each auditorium has a distinctive exterior finish, offering a unique visual image. For instance, the Dance Theatre showcases a façade crafted from bamboo, while the Concert Hall gleams with a golden-hued metal cladding. Surrounding these performance spaces are foyers meticulously crafted to evoke corresponding atmospheres. The Dance Theatre's interior, with its anthracite-black hues, pays homage to the historic Lucent Dance Hall, enhanced by movable wall panels ensuring optimal acoustics for various performances, be it dance, speech, or opera. In contrast, the Concert Hall exudes classical elegance, characterized by concrete wall finishes and gold-toned sliding panels designed to modulate acoustics, a bespoke feature imbuing Amare with its distinctive charm. The world-class acoustics of Amare owe their excellence to the expertise of Federico Cruz Barney from Studio DAP Paris.

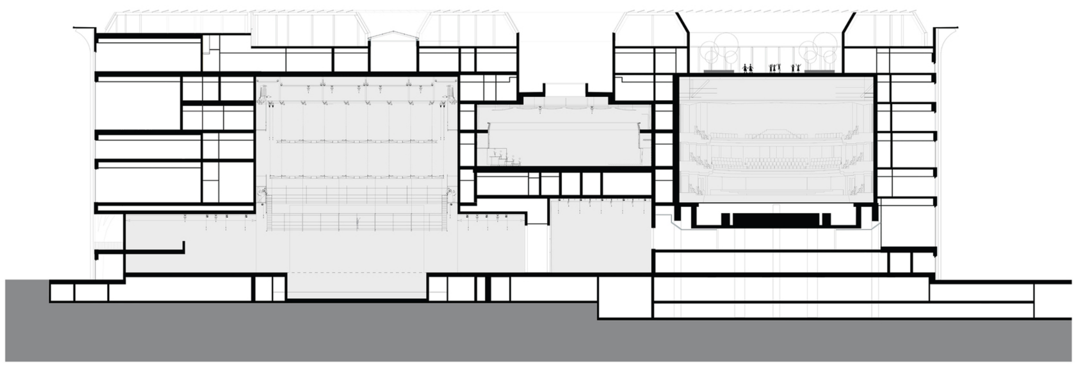


Figure 124 . Amare Theatre, longitudinal section. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

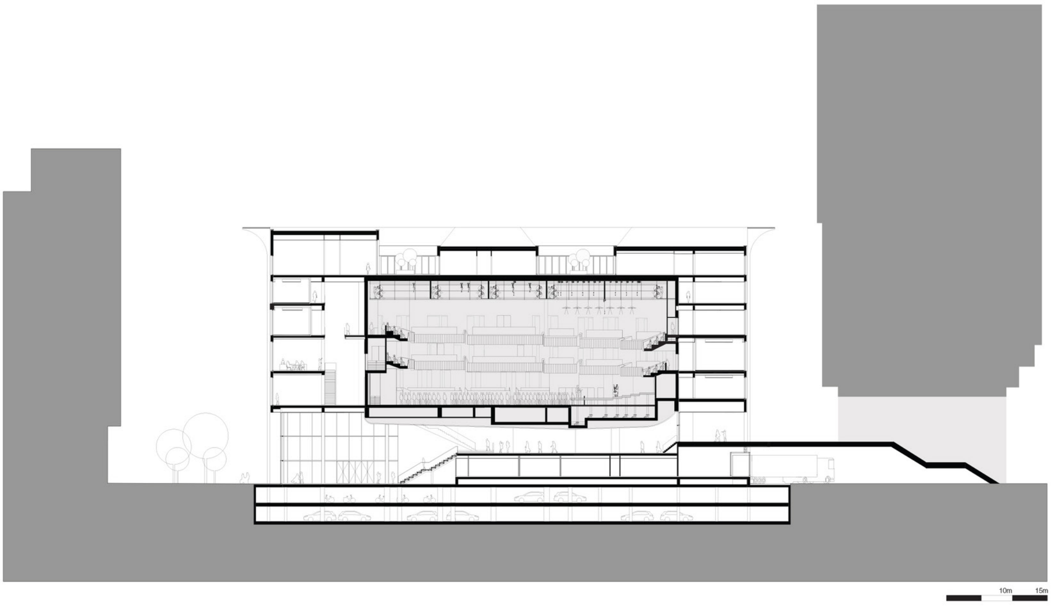


Figure 125 . Amare Theatre, section BB. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

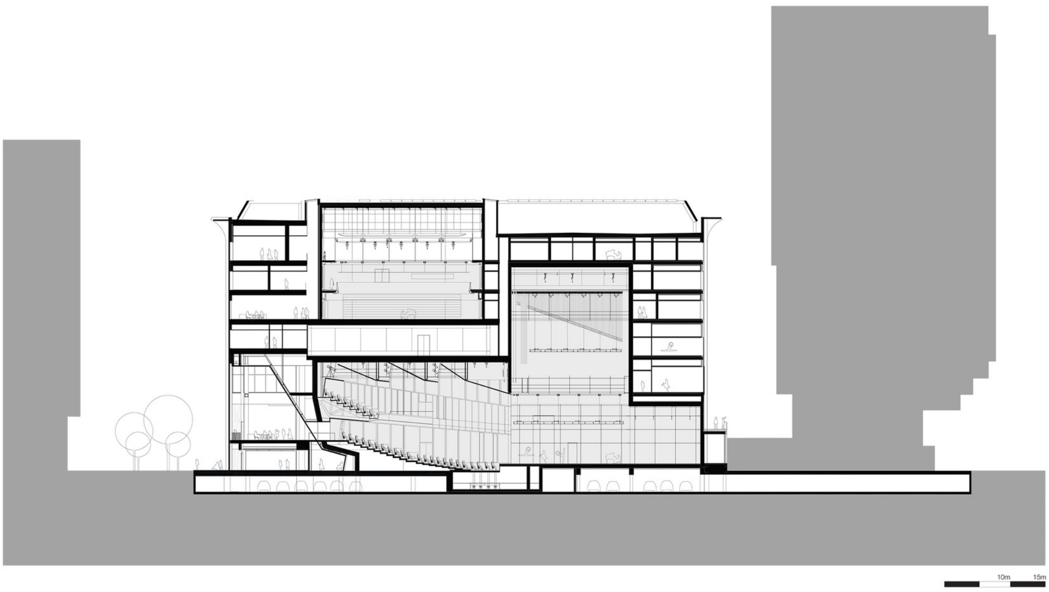


Figure 126 . Amare Theatre, section DD. Retrieved from https://www.archdaily.com/982101/amare-home-of-the-performance-arts-noahh

5.Insights and Interpretation of the Case Studies

5.1. Strategies Used to Achieve Spatial Flexibility

In the projects studied in this chapter, many similar architectural strategies were used to achieve flexibility. Almost all of these projects embodied several key qualities to improve collaboration and creativity, through flexible architectural layouts. Firstly, it was noted that transparency was an essential part of the planning, to ensure that information flows freely and openly among participants while encouraging trust and cooperation. This was achieved by using open plans and a lot of glass. Moreover, openness in architectural plans encourages inclusivity and collaboration, by welcoming individuals from various disciplines to contribute their unique perspectives and ideas. Secondly, to achieve an environment with equal views and access which promotes equal participation and decision-making, and empowers all members to contribute and shape the direction of innovation initiatives, all of the studied projects incorporated steps that were not only used for circulation but also for sitting, learning, and collaboration. Lastly, polyvalency as a strategy to achieve flexibility as discussed in Chapter II, was achieved by the use of partition walls and non-fixed furniture and open plans. Overall, these qualities of flexible architectural layouts, collectively create an environment conducive to innovation, where ideas can flourish and solutions can be developed collaboratively, while allowing for the adaptation to the evolving needs and accomodation of different working styles and projects.

Transparency
Open Plan
Glass

Equal Views and Access
Steps
Glass

Polyvalency
Partition Walls
Non-fixed Furniture

Figure 127-129. Strategies for the design of flexible spaces. Own work created with the assistance of DALL·E 2

5.2. Flexible Programs

In the studied projects which included two innovation hubs, two educational buildings, and one cultural hub/theatre, many spatial programs/functions were present in all the buildings like cafe, exhibition, lobby, co-working, and huddle. The following tables aim to put together some of the main spaces that were seen in the studied projects. Table 12 shows the main programs in the first 4 case studies, whereas the spaces in the Amare Theatre are represented in Table 13, since they are mostly different than the spaces seen in the other 2 innovation hubs and 2 educational projects.

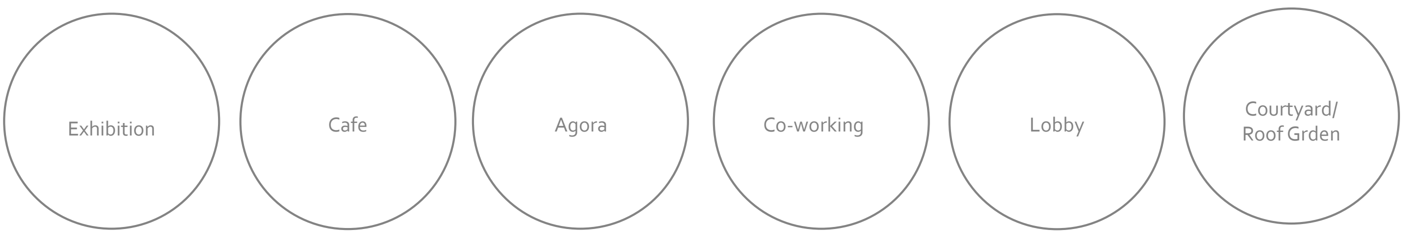
Auditorium
Exhibition
Technical Rooms
Research Section
Library
Co-working/Studio
Workshop
Classroom
Lobby
Cafe
Offices
Business Section
Gallery
Conference
Agora/ Debate Room
Lab
Roof Garden/ Courtyard
Lounge
Restrooms
VR

Table 12. Main programs seen in the four first case studies and excluding the Amare Theatre

Brasserie Amare
Dance Theatre
Arts Square
NDT Black Box
Grandstand Stairs
Foyer
Balcony
Wardrobe
Meeting Center
Concert Hall
Canteen
Amare Studio
Club
Conservatorium Hall
Royal Conservatory
Offices
Restrooms

Table 13. Main programs seen in the Amare Theatre

In the studied projects, out of the spaces shown in the tables above, only some of the spaces/rooms had the ability to accommodate multiple programs or could be adjusted or changed to include new activity due to their open plans, unfixed furniture, dismantlable partition walls, and their lack of need for heavy and fixed equipment. These spaces with open plans and transparency are usually functioning as exhibition, cafe, agora/huddle, co-working/studio, and lobby, courtyard/roof garden.



B. Introduction to Experiment Setup

A common method for spatial analysis and configuration in architecture and urban design is the Space Syntax method. Although it is mostly used on an urban scale to understand the relationship between street networks, public and private spaces, other urban units, the traffic flow, etc., it has also been commonly used for interior space configurations in buildings. According to Karimi, Space syntax takes a direct approach, and starts by identifying the primary and common ways people interact with space. This is supported by a strong emphasis on human senses of visibility and movement—arguably the two most essential aspects without which a space would be unrecognizable, and in his words " People comprehend their surroundings through their fields of vision, navigate in straight lines, and engage in convex spaces (Karimi,2023)"

In the interior spatial configuration, space syntax turns a continuous space into discrete units by using convex space partitioning or axial mapping which are explained below. This iterative process begins by breaking down a spatial structure into the "fewest and fattest" convex spaces (Hillier and Hanson, 1984). It identifies the largest convex space and continues by locating progressively smaller ones until the entire area is divided into convex spaces. An axial map is then created over this convex map by drawing the longest straight lines that pass through these convex spaces. In representing these as a graph, space syntax treats each line as a node and each intersection as an edge (Kim et al., 2008).

In space syntax, a centrally located space, usually suggests its attractiveness. Attractor spaces are mostly located along the most integrated paths or in other words, highly integrated paths attract more people (Van Nes, 2014). Moreover, the integration and permeability of spaces affect the level of activity in them, while the sequencing of integration enables interaction among the space users (Mustafa, 2010). In space syntax, the notion of depth suggests where a room/space is located in a sequence of all the existing rooms. Thus, while minimum depth suggests connectivity, a linear sequence suggests maximum depth.

According to UCL Space syntax, there are multiple syntactic methods to analyze the interior layout of a building for spatial configuration. The online platform defines them as follows:

> "1. Convex map or J-graph analysis
>
> One of the basic tools for analysing building layout is convex map analysis. Below is an example of how to create or undertake the analysis.
>
> a. Construct graph
>
> Convert a building layout into a graph, in which each node indicates a room and the links between them indicate doorways.
>
> b. Step depth
>
> Step depth measures from the root space, the number of steps required to reach all the other rooms in the building. A Justified or J-graph is a representation of step depth from a particular room.
>
> c. Integration measure
>
> Integration values can be then calculated according to the number of steps required to reach every other room in the system. The higher the integration, the fewer the steps required to traverse every room in the building.

2. Visibility graph analysis (VGA) is a widely used technique to analyse spaces within a building based on their visibility from other spaces/rooms.

3.Agent analysis
Visibility graphs can also be analysed through agent analysis, which studies movementpatterns shaped by spatial configuration. An agent is an automata which navigate using visibility information available to them through the visibility graph."

Figure 130 on the right shows how the convex map and justified graph work. Every line between the circles means the connection between those two spaces through a doorway.

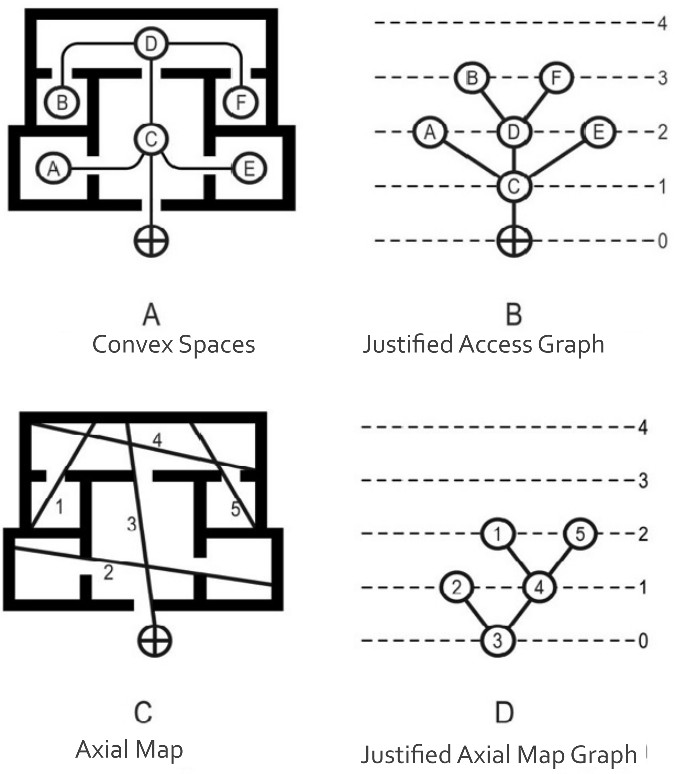


Figure 130. (A) Plan view of a small villa identifying convex spaces, (B) that plan represented as the justified graph, (C) the axial line map of the same plan, and (D) its equivalent justified graph. Retrieved from Dawes, M., & Ostwald, M. J. (2013). Precise Locations in Space

In the following steps of this research, the above-mentioned methods are used to analyze the interior layout of spaces to find the most optimum spatial configuration with maximum flexibility.

Based on the insights and interpretation of case studies in section A of this chapter, the most flexible programs selected for the spatial configuration to be formed by swarm robots are the lobby, cafe, agora(huddle), exhibition, co-working spaces, and workshops.

1. Designing for an Architectural Layout

1.1. Logic and Basic Layout Creation on Grasshopper

The experiment setup was defined with a circular spatial 2D grid. According to Adnan and Yunus, the curvilinear environments/forms encourage communication, fluidity of movement, navigation, social engagement, psychological mood-lifting, and a feeling of safety by dissolving social boundaries (Adnan & Yunus, 2012). Non-orthogonal, curvilinear architecture that follows the principles of Neo-organic design, takes inspiration from the fluidity and dynamism of natural form. Although it enjoys the complexity of forms and masses, it allows the user to feel a sense of integration, balance, and harmony within the space (Elmoghazy, 2014). These forms also result in gradual changes of direction. In alignment with what was previously discussed, a flexible space is one which allows the user to be free of the implication of rigid architecture, and not only helps with dynamic movement but also with encouraging collaboration and social interaction. Hence, curvilinear forms have not only proven to be structurally and thermally optimal (Middendorf,2019) but also, to have great potential for flexible architecture (Kronenburg, 2005).

To move on further with the experiment, based on the spaces defined in Section A of this chapter, the project boundary was divided into 6 zones, each program defined by circles accordingly. The grid size and the area of the boundary and zones were parametrically defined and can be adjusted based on user preference. The use of circles for zones were merely to simplify the process, and they can be alternated with any other form of curves if wished.

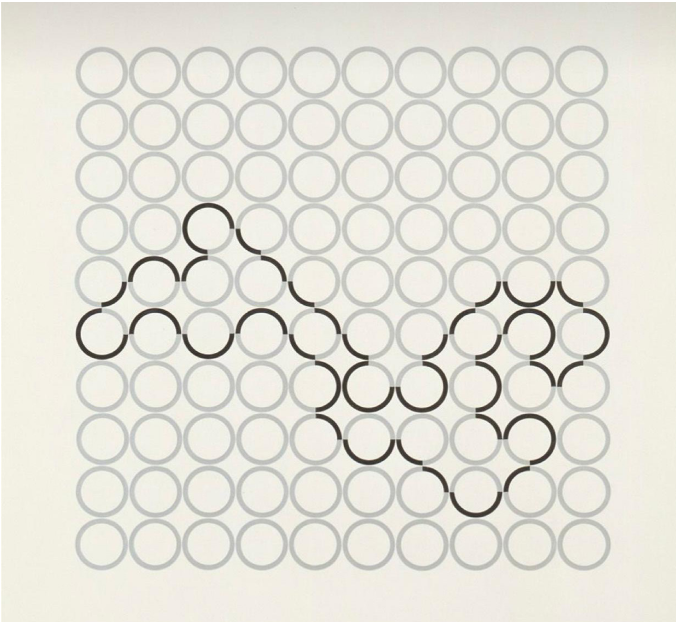


Figure 131. Geometric pattern. Image as inspiration for the grid and form of robots.Retrived from https://nl.pinterest.com/pin/760475087075061755/

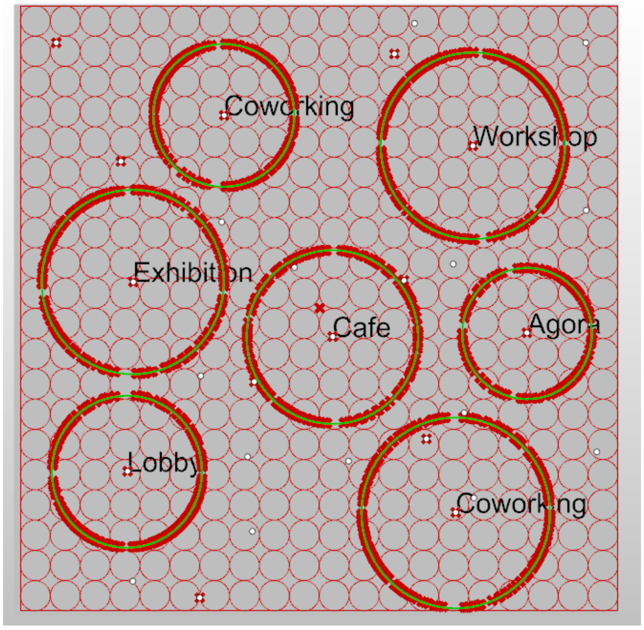


Figure 132. Creating the circular grid and defining program zones with circles

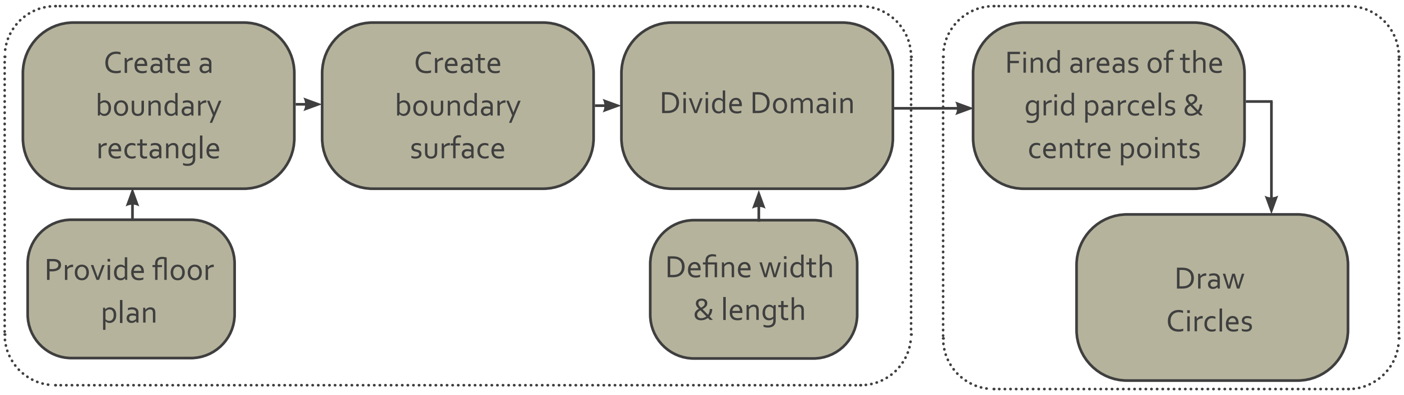


Figure 133. Diagram explaining the logic of the grasshopper code to create and control the circular grid as shown in figure 134.

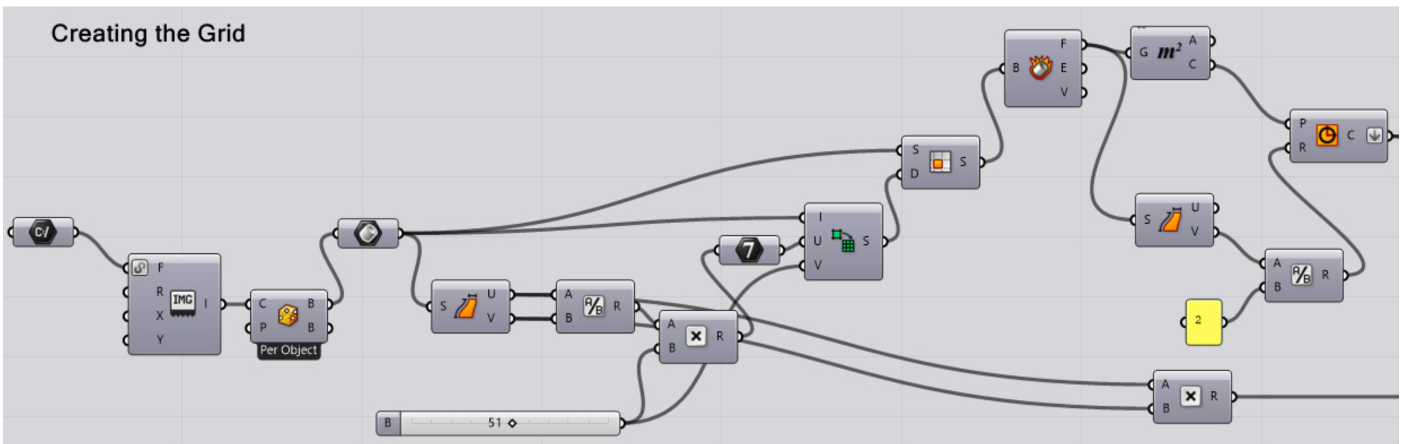


Figure 134. The above-mentioned logic in grasshopper algorithm.Creating the circular grid . Step 1 in the algorithm.

Each grid circle is then divided into 4 equal arcs and each arc is an input of a data list to be used into the next step. The reason for the division of arcs into four segments was to have smoother arrangements on the grid curves and thus more practical spaces with less limitations in angles for the connection of arcs and also to avoid space waste that does not fit furniture or a person. The figures 140 & 141 below show the two options for arc length and their possible angles of connections with the possible movement direction along the grid.

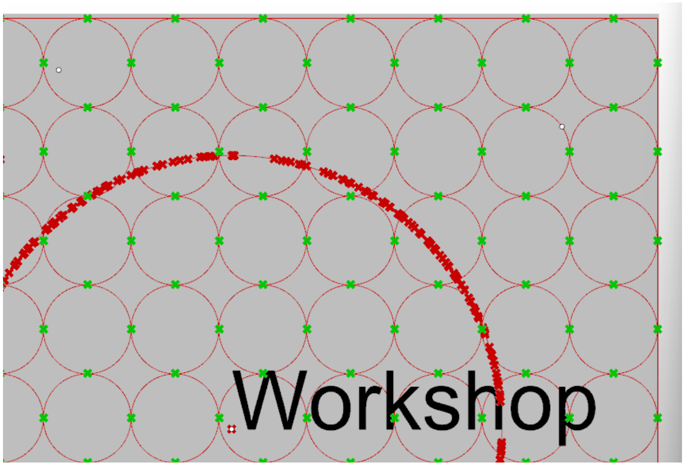


Figure 137. Extracting the circles' arcs.

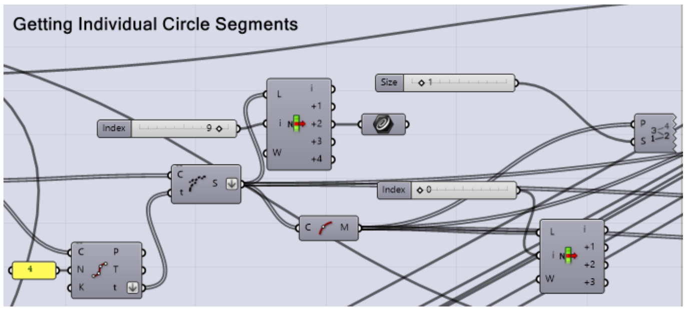


Figure 138. Extracting the arcs of each circle to input in the next step.

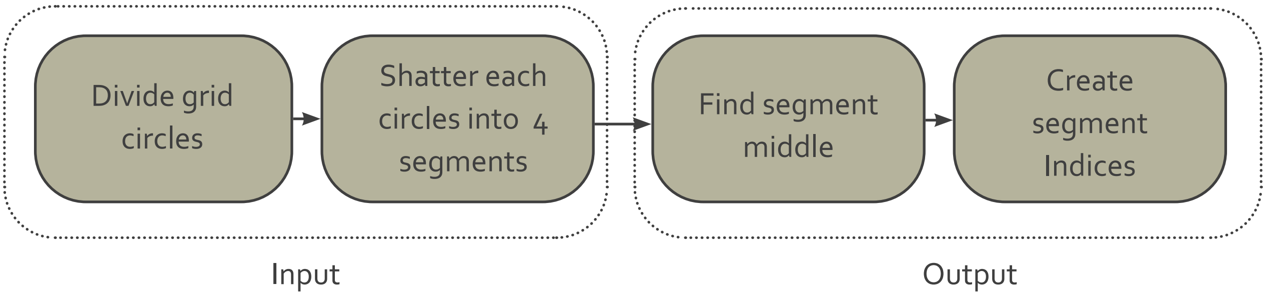


Figure 139. Diagram explaining the logic of the grasshopper code shown in image 138 to create circle segments and indices

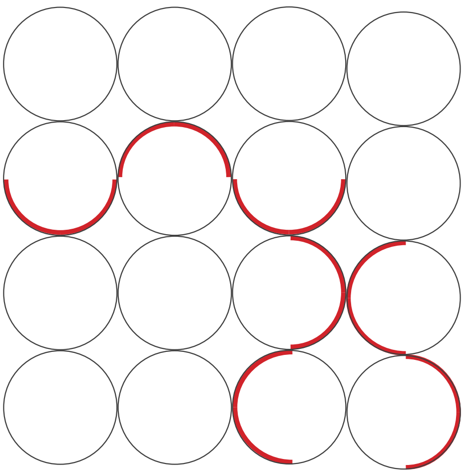


Figure 140. Half Circle Arcs

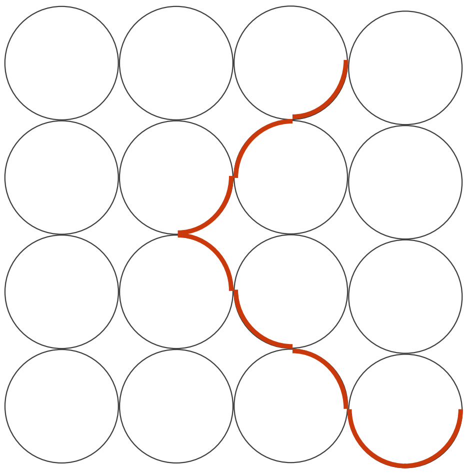


Figure 141. Quarter of Circle Arcs

The robots were then designed as quarter circle arcs with very light wood and Shoji paper panels installed on them. The material selection of panels was to reduce the weight that each robot has to carry which also makes building them easier and less energy is needed for the robots to carry them. In addition to that, the selection was to ensure that 90% of the robot prototype is made of recyclable material. These panels will be of three different heights and the robots with lower heights will make rooms with smaller areas whereas the robots with higher panels will form rooms with larger areas.

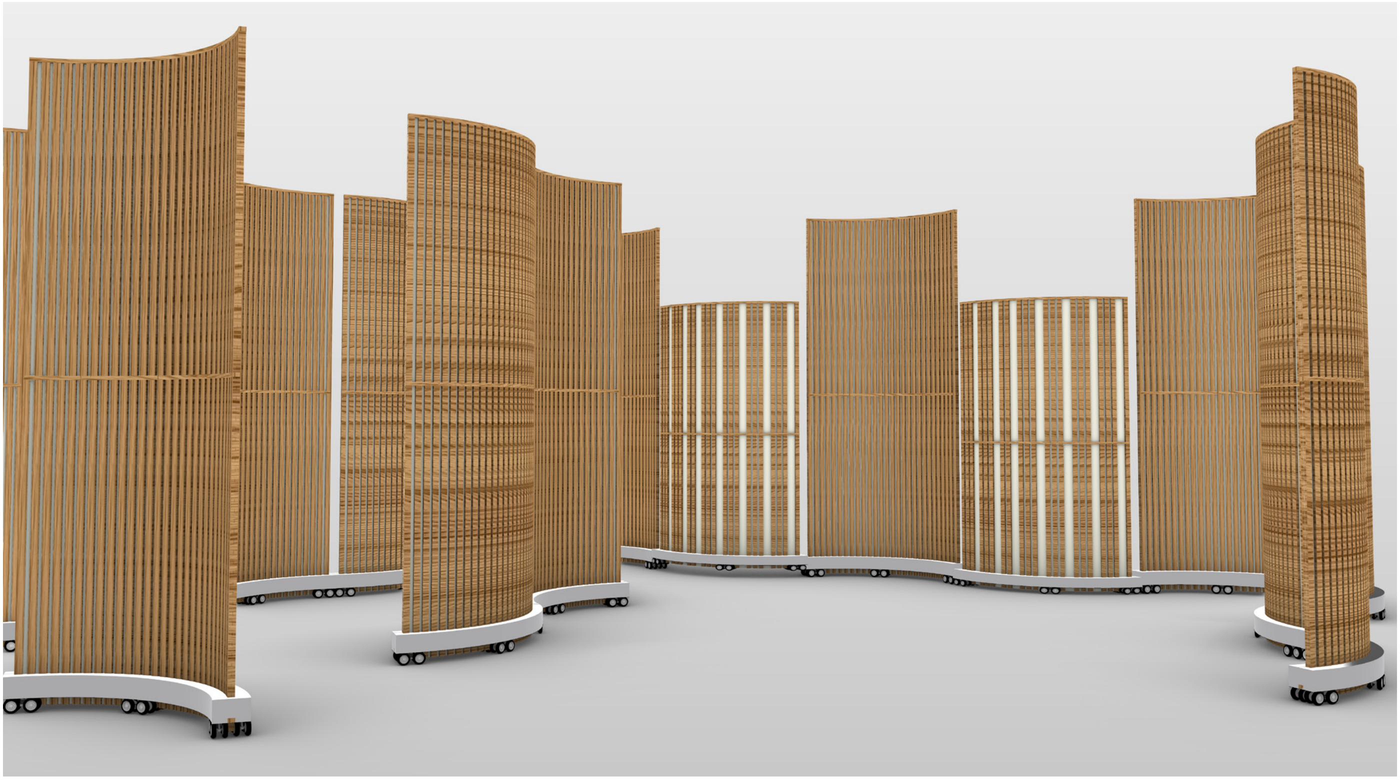


Figure 142. Robots designed as quarter circle arcs with different heights which carry light wood and Shoji paper panels.

In the next step, a threshhold was introduced to get the cirlce's arcs whose midpoint distance from the zone's circles were within this range. These arcs were then culled.

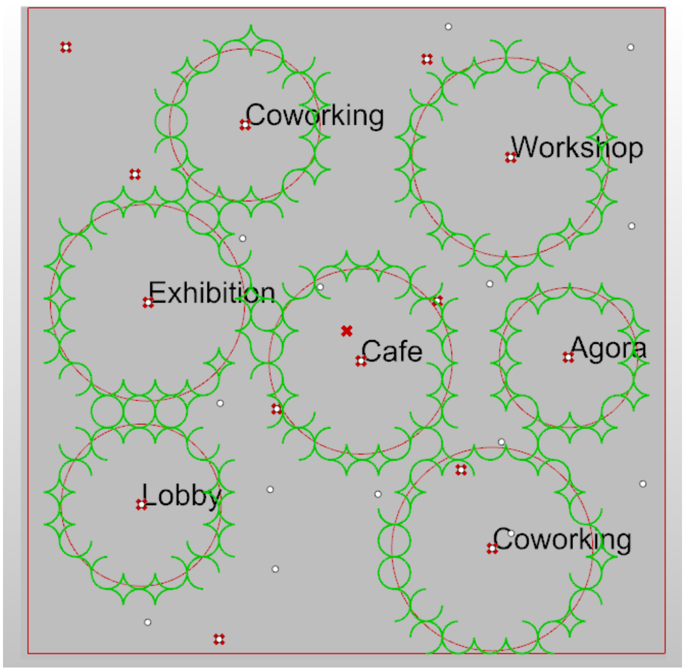


Figure 143. Extracting the closest arcs of grid circle's to the zone's circles.

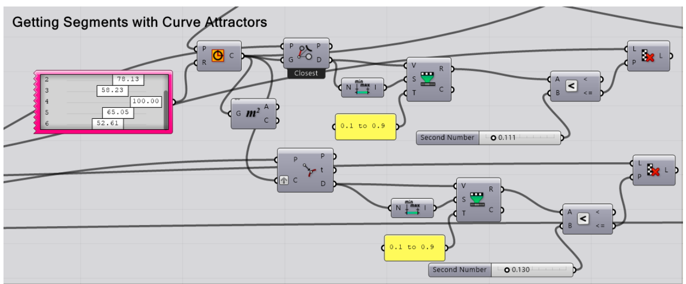


Figure 144. Defining zone's areas and the threshhold of distance for the grid's circles' arcs' mid points to the zones'circles.

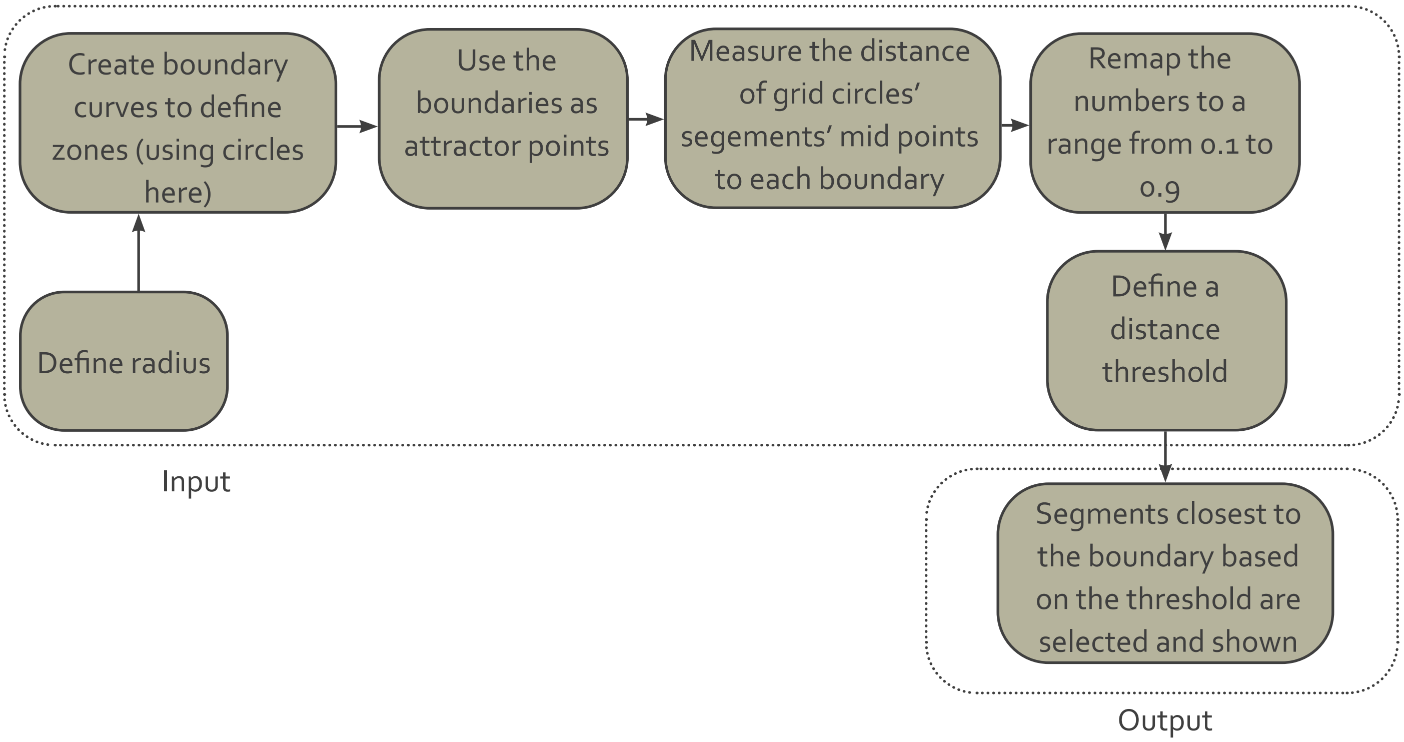


Figure 145. Diagram explaining the logic of the grasshopper code shown in figure 144 to select circle segments and indices based on their distance to the boundary curves

After the layout workflow was initially defined, a sample floor plan; Amare Theatre ground floor plan, was input to the workflow in order to imagine it better in a context. The same process was applied to the sample floor plan.

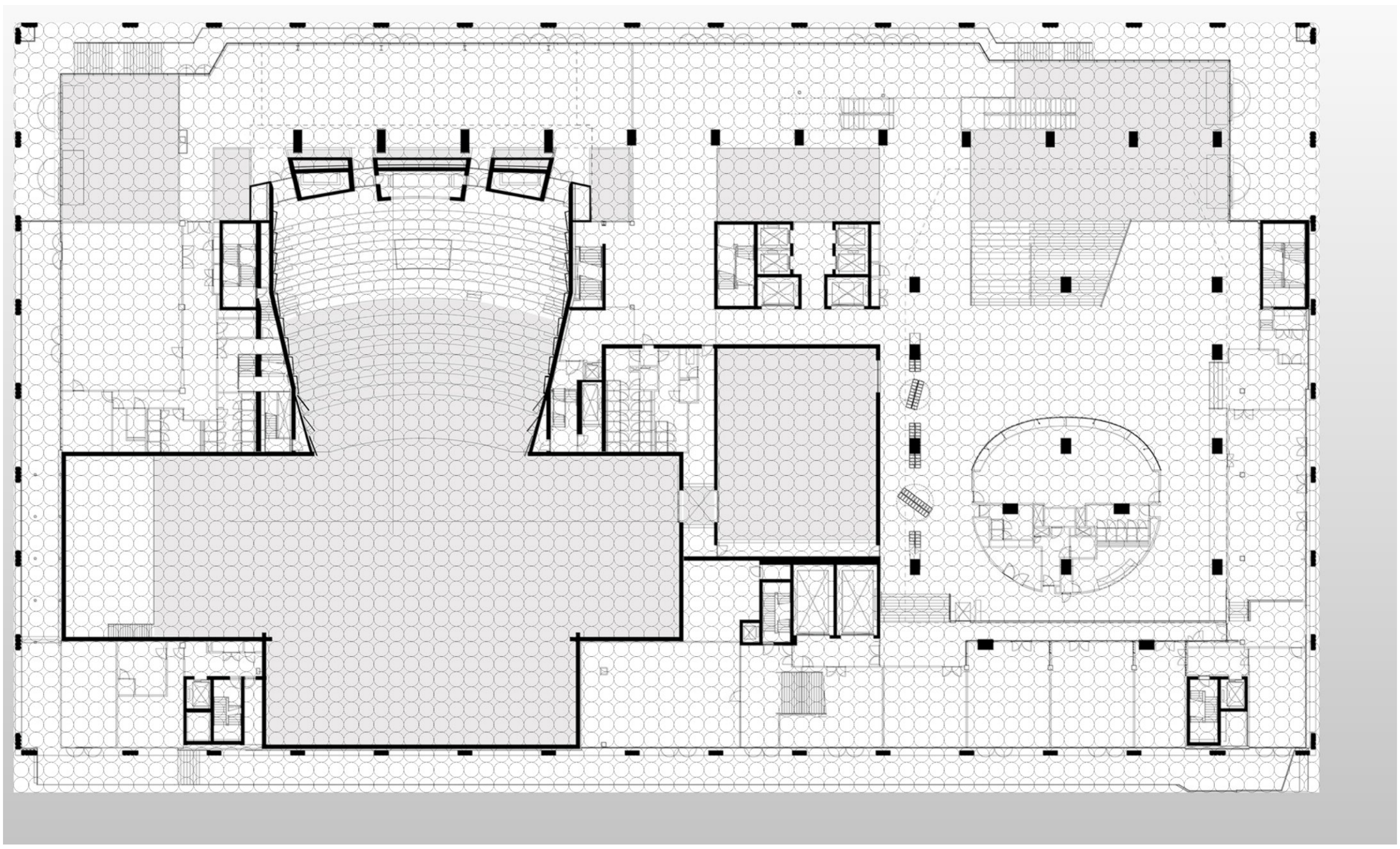


Figure 146. A floor plan is given to the algorithm, then the circular grid is projected on to the plan.

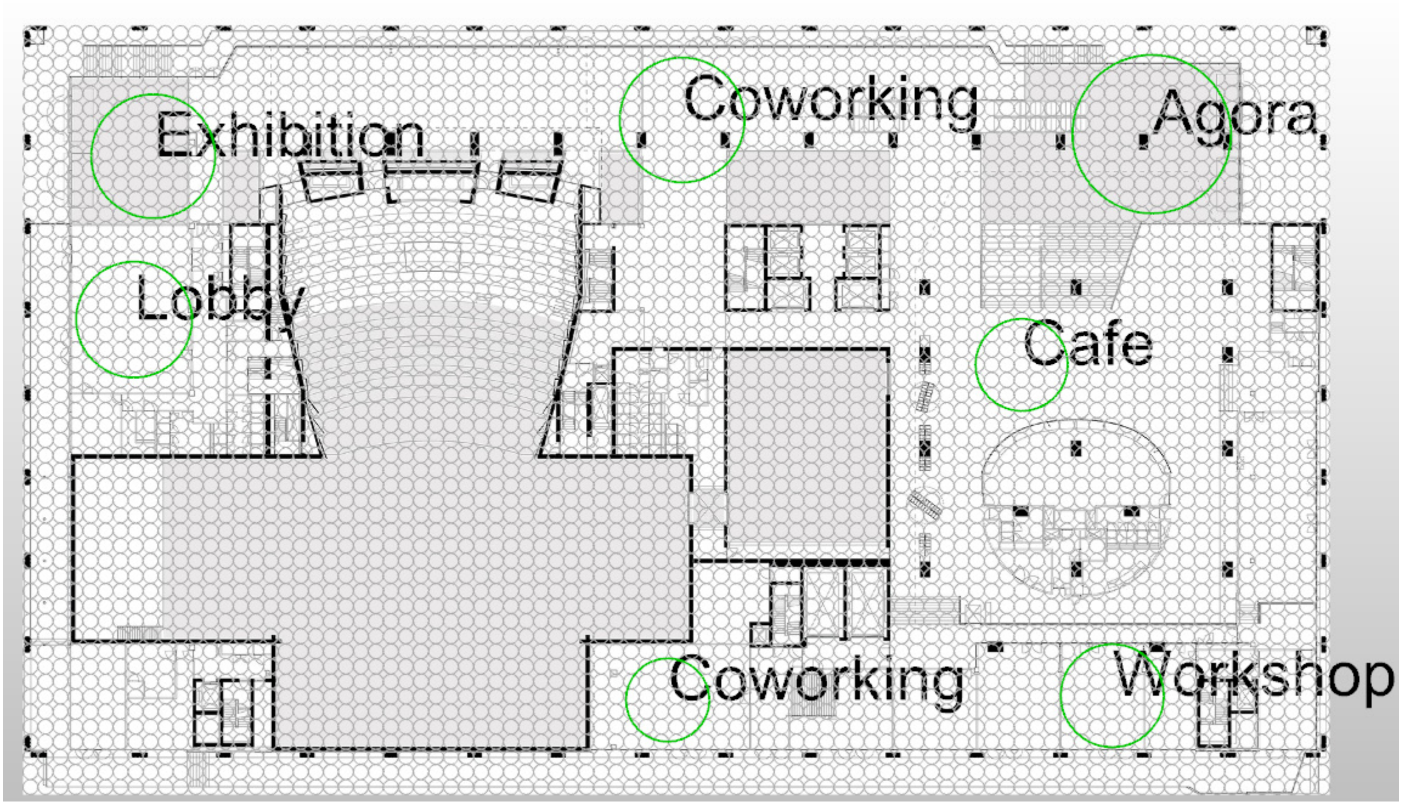


Figure 147.Different zones are defined on the floor plan as an approximation of the area in which various spatial functions will be located.

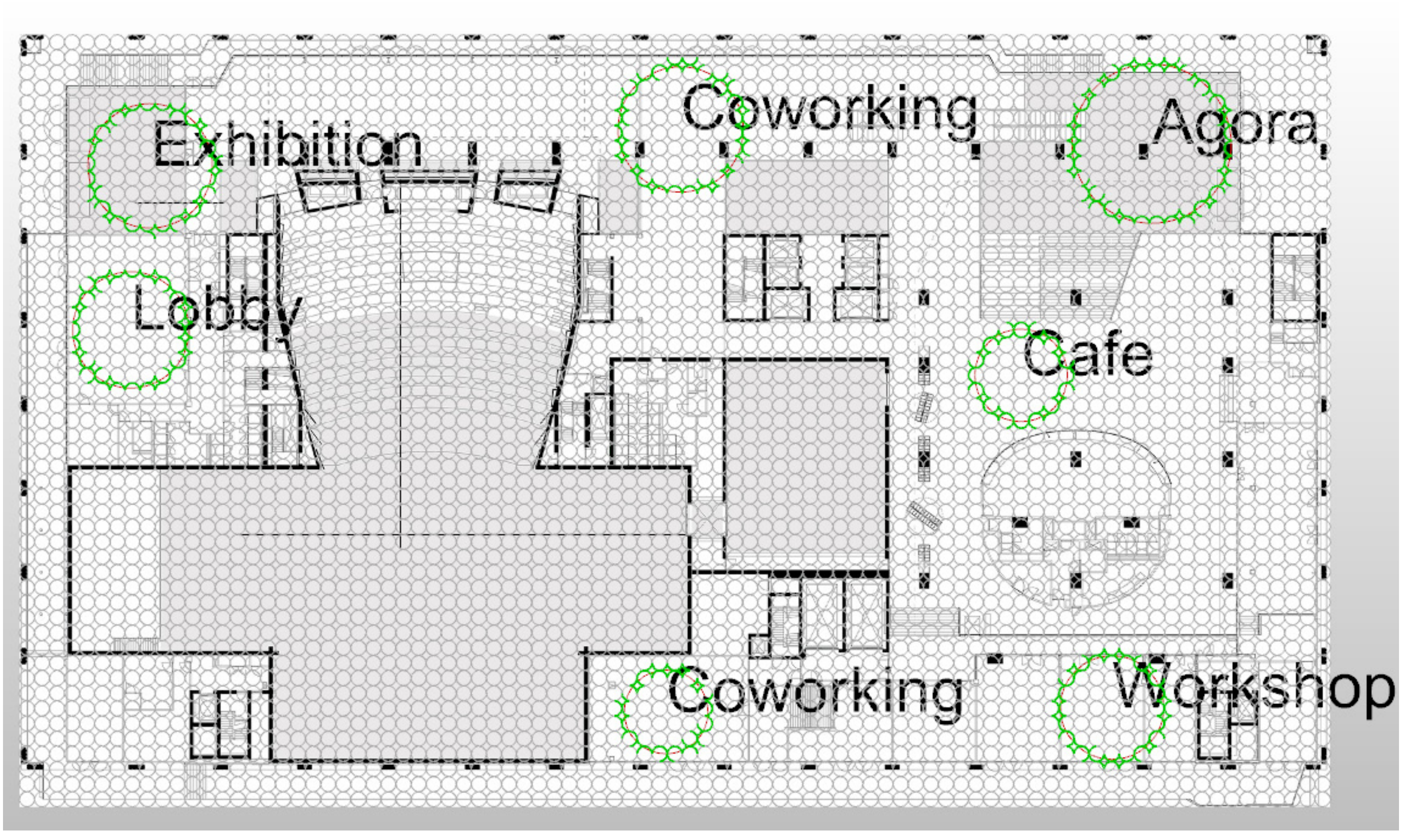


Figure 148.Curve segments close to the zone boundaries are selected as shown in green. These can be adjusted based on the distance threshold that is parametrically defined. These selected segments can act as target positions for robots.

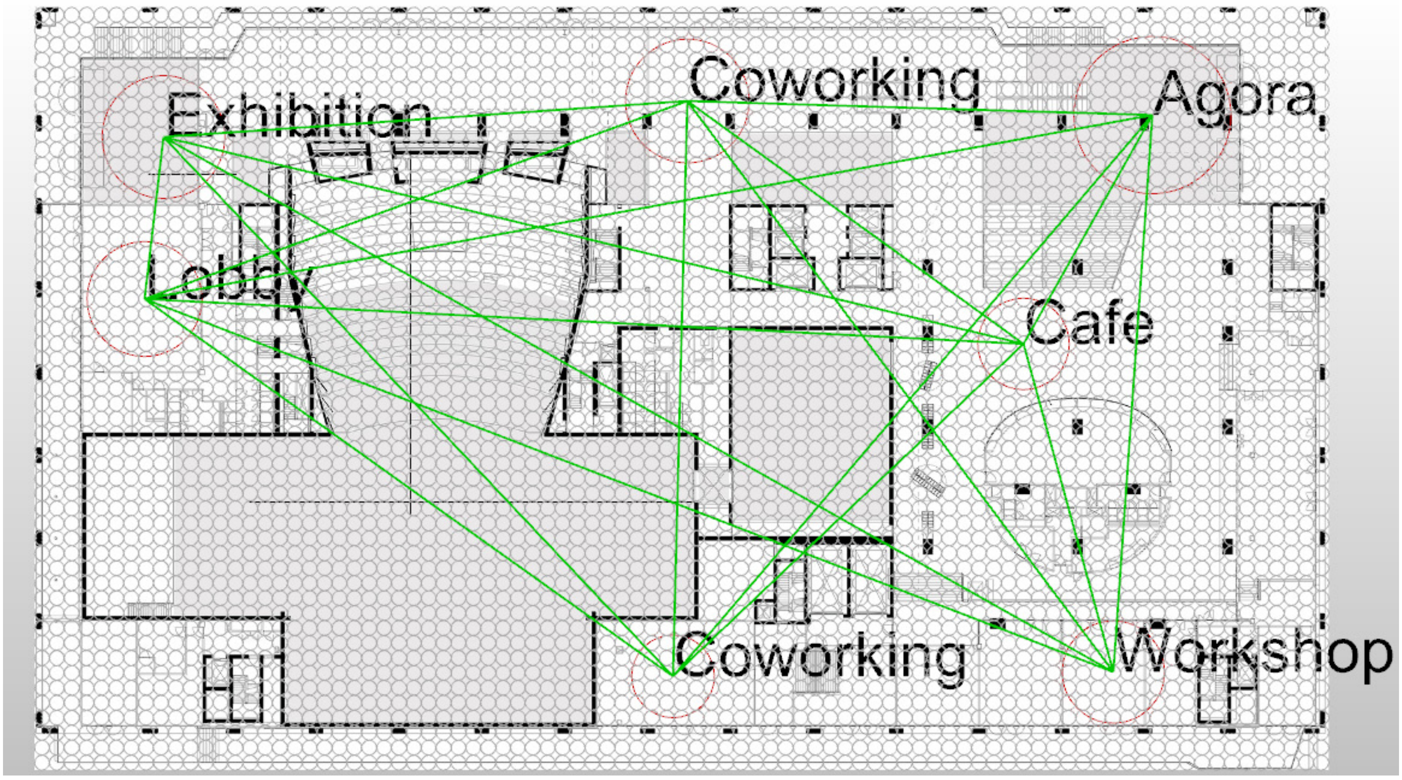


Figure 149.The connection between the zones are defined with lines shown in green. As seen in the image, the lobby was ideally defined to be connected to all the other zones. However, given the limitations of the floor plan it is now detached from almost all the other zones. The idea of space analysis introduced in the next step is to give the architects the chance to review and update design options based on spatial relationship as well.

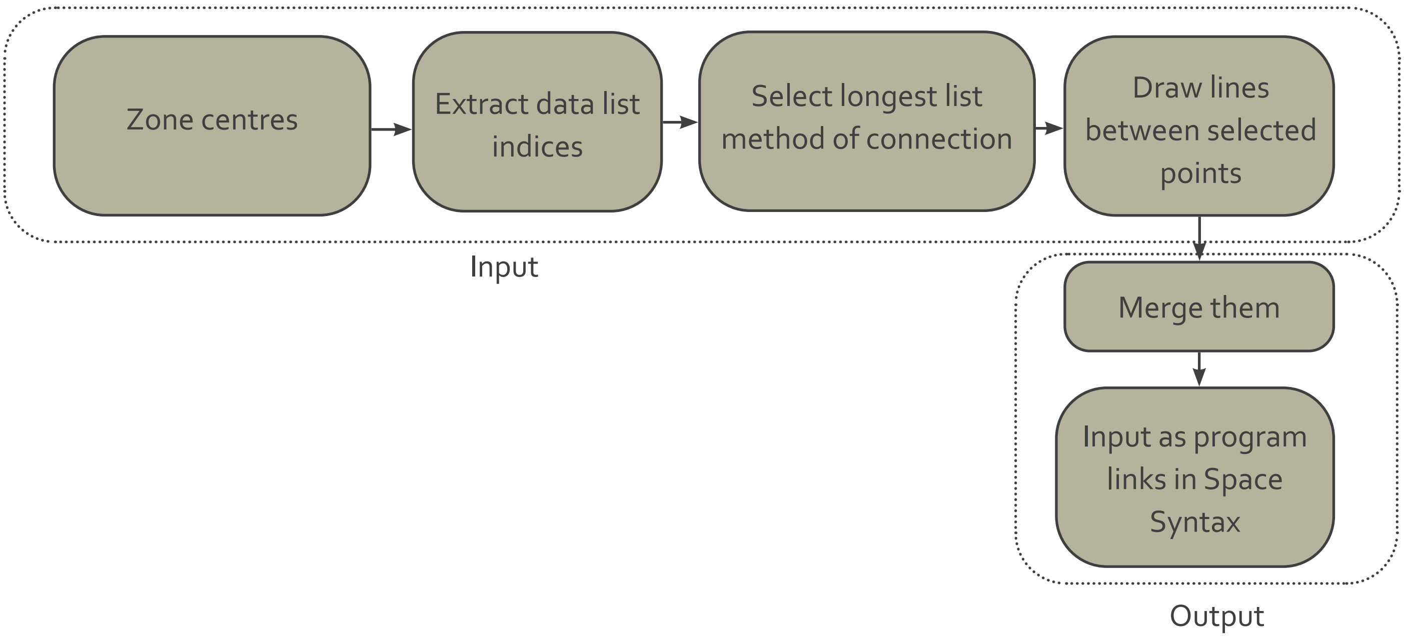


Figure 150.Diagram explaining the logic of grasshopper shown in figure 151 to create links between programs based on the ideal location and relationship between them.

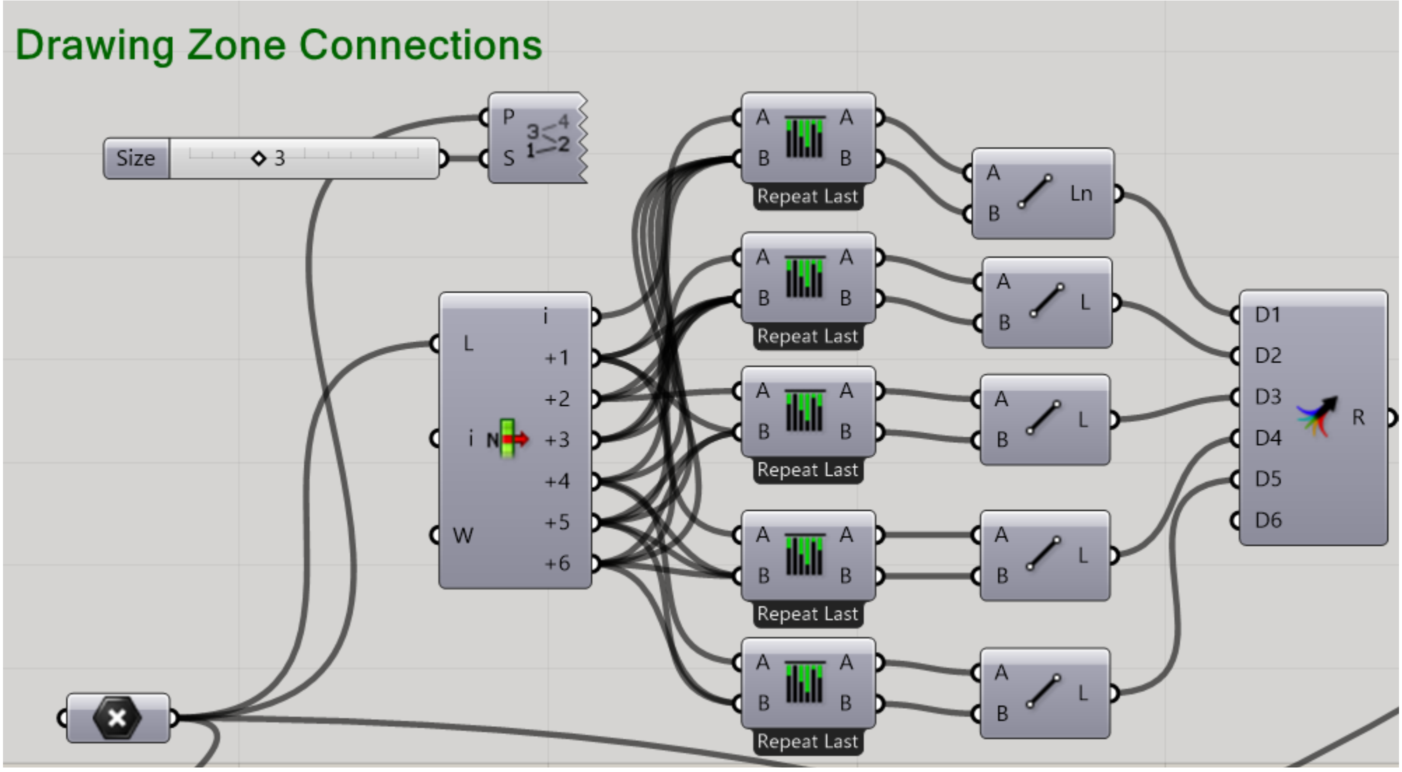


Figure 151.Creating links represented as lines to show the relationship between programs.

1.2. Spatial Analysis with Space Syntax

After the zones and programs were defined, in this step, the space syntax method was used to analyze different spatial configurations using bubble diagrams and the justified graph. As mentioned earlier, the depth steps in the justified graphs measure the number of steps required to reach all the other rooms in the building. It also represents different depth options and possible clustering of rooms/ zones. The nodes in each graph represent a room/zone/program and the links between them indicate doorways or the possible connections between programs.

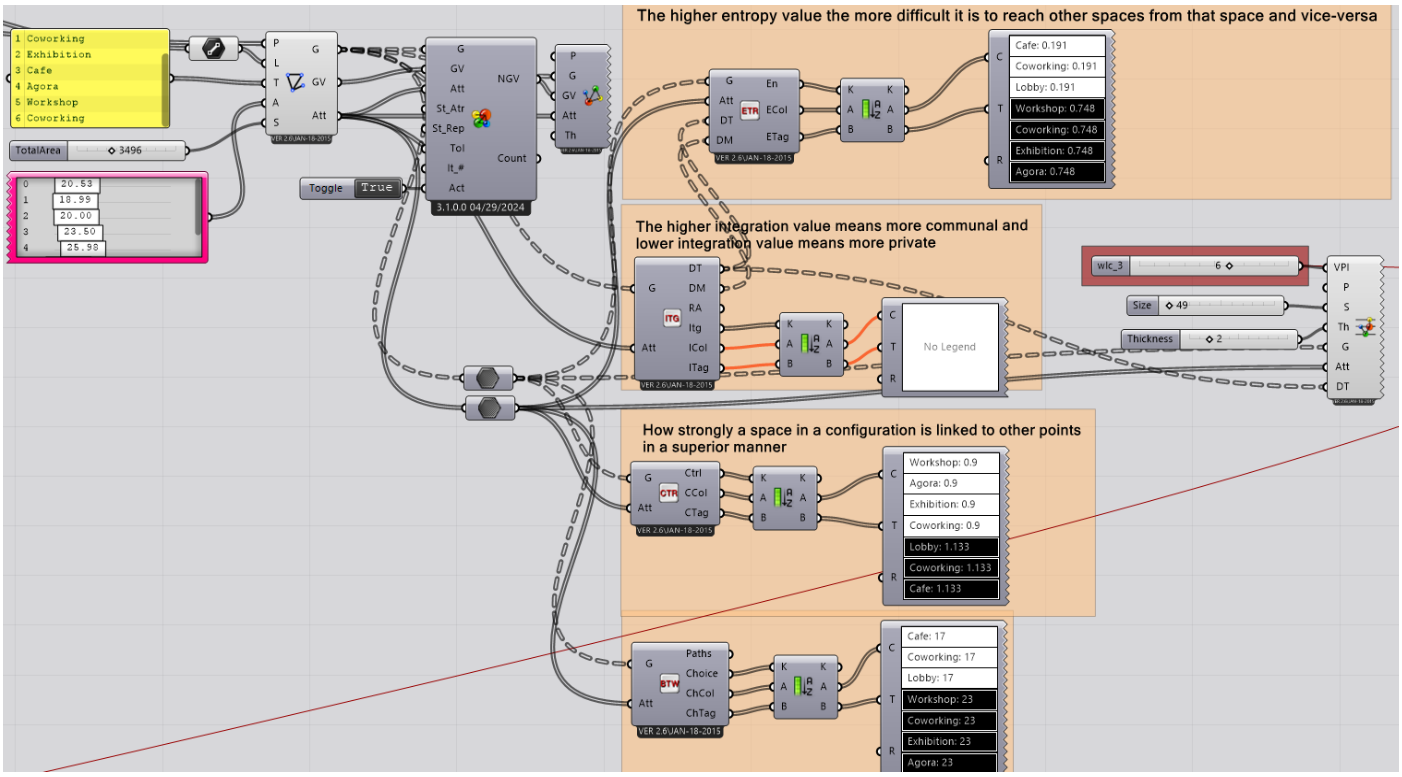


Figure 152. Using the Space Syntax method to analyze different spatial configurations

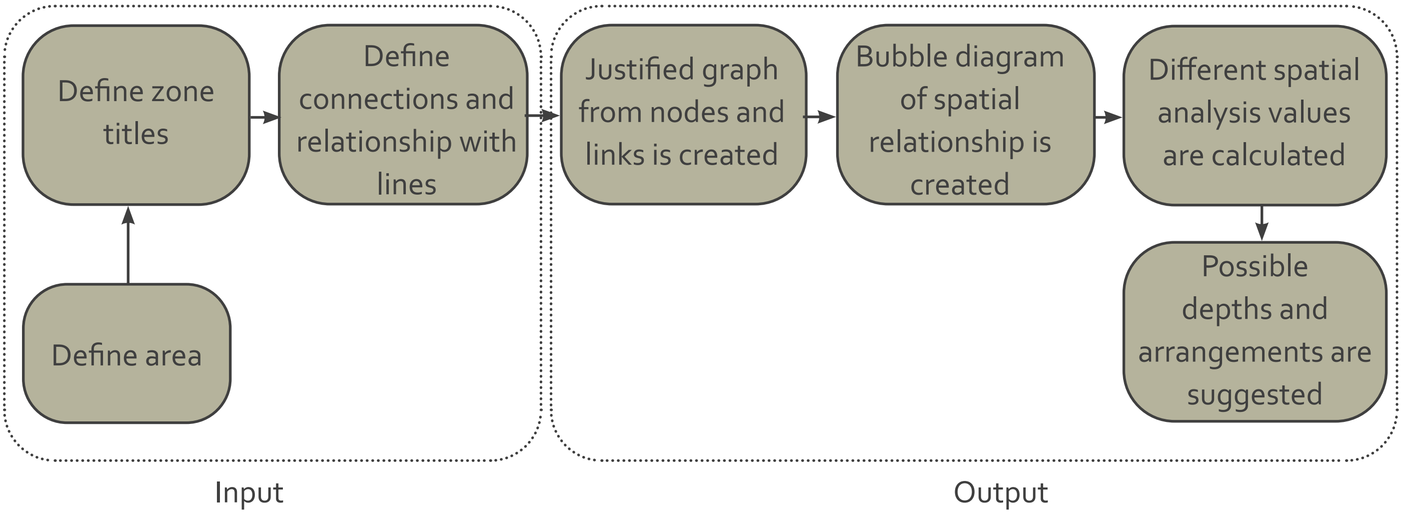


Figure 153. Diagram explaining the logic of the space syntax analysis shown in figure 152

Based on the total area defined, options are provided through the method to control each program's area in relation to other programs. The connections between the programs are defined by the user/architect. Any change in the location of these programs does not affect the provided options. The various options the method provides for the defined programs with depths and connections are shown in the following images.

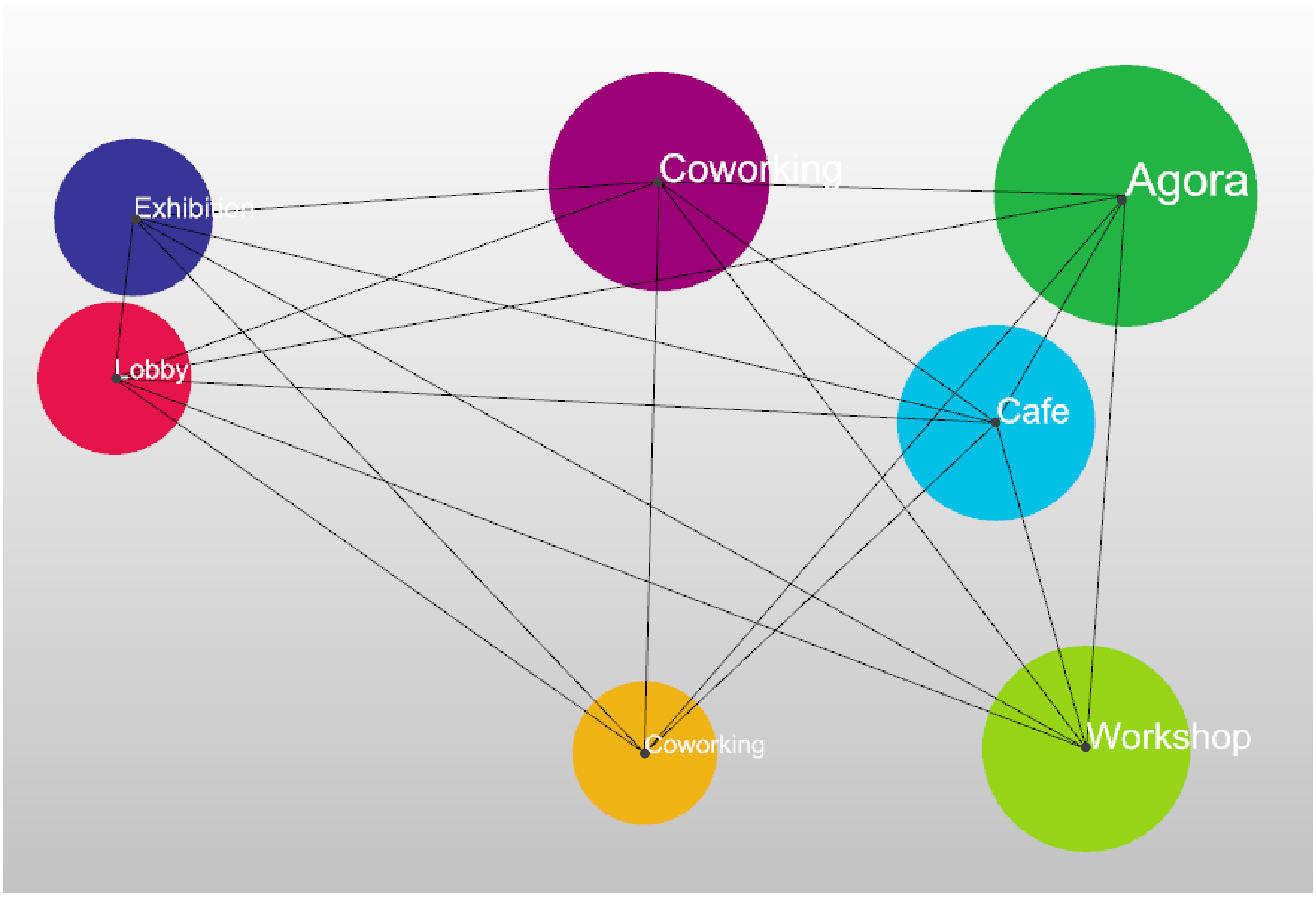


Figure 154. Space Syntax nodes and connections. The nodes in each graph represent a room/zone/program and the links between them indicate doorways or the possible connections between programs.

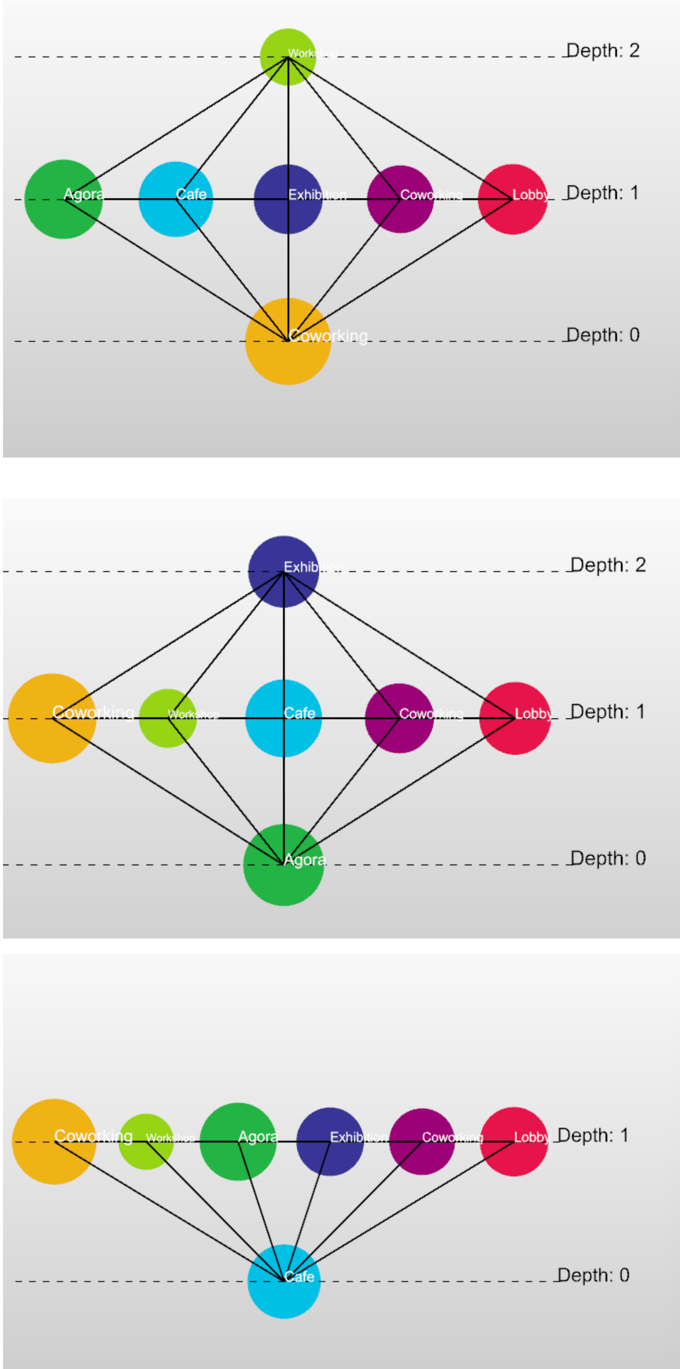


Figure 155-157.Possible depth options and clustering of programs are suggested in multiple diagrams by the Space Syntax method.

The method also shows different values for different rooms which are as follows:

1- The Entropy Value: The higher entropy value, the more difficult it is to reach other spaces from that space and vice-versa.

2-The Control Analysis value: Nourian et.al.,(2013), state that "control value intuitively indicates how strongly a vertex in a graph (a space in a configuration) is linked to other points in a superior manner. It is computed by in which Di is the degree of a 'neighbor' node, and n is the number of all neighbor nodes." In other words how strongly a space in a configuration is linked to other points in a superior manner.

$$Control = \sum_{i=1}^{n} \frac{1}{D_i}$$

3-The Choice Analysis Value: Nourian et. al., defines choice as "(Originally introduced as Betweenness by Freeman (1977)) Choice or Betweenness is a measure of importance of a node within a configuration.

That literally tells how many times a node happens to be in the shortest paths between all other nodes. It can also be computed for the links connecting the nodes in a similar way. It is computed by the formula below in which where σjk (Pi) is the number of shortest paths between node Pj and Pk which contain node Pi, and σjk the number of all geodesics between Pj and Pk." In simpler words it is the degree a space is being passed through.

$$C_B(P_i) = \sum_j \sum_k \frac{\sigma_{jk}(P_i)}{\sigma_{jk}} (j <$$

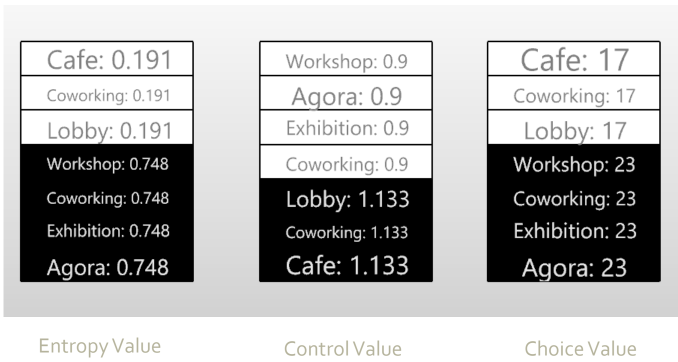


Figure 158.Space Syntax Analyses

The entropy values retrieved from the analysis indicate that the zones with more specialized programs are less reachable from other rooms. This is what the ideal design should look like, as rooms for specific tasks would ideally have less distraction from other rooms.

The control values show that the cafe, one of the co-working zones, and the lobby are well-linked to other rooms with the defined links as it was initially intended. However the lobby as shown in figure 149 , stays at another part of the building and seems to be detached from the rest of the programs. In an

ideal case then, the lobby could be possibly relocated.
The choice value shows the cafe, one of the co-working zones which is adjacent to the cafe & lobby, and the lobby are the spaces with the highest degree of being passed through.

Due to the limitations of Rhino Grasshopper for simulation of the robot movement, to optimally build up the spaces that were defined in this section, the next phases of this research were carried on Python using Matloplib Library and Animation functions and Pygame. These stages will be discussed in the next sections.

2.Pyhton Setup and Approaches

The approaches to creating different design options meant finding existing methods to program swarm behavior for pattern formation. As discussed earlier in Chapter II p 41 and 42, pattern formation in swarm robotics includes Biomimetics, Physicomimetics (Othman, W. a. F. W. (2019), and mimicking pheromone release of insects such as ants (Fujisawa, R., 2014). In this research, the methods used were from Biomimetics and involved flocking behavior like alignment, and cohesion. As stated in Chapter II, Reynolds (1987), defines these navigating behaviors of flocking birds based on the position and velocity of neighboring members as follows.

1. Separation: navigate to avoid local crowds
2. Alignment: navigate toward the average direction the local members are heading
3. Cohesion: navigate towards where the average position of local members is.

To control the behavior of the swarm there are two control systems: 1-centralized and 2- de-centralized which were referred to in Chapter II on page 36.
In the centralized method, a central computer controls the swarm and all the states are pre-planned. On the other hand in the de-centralized method, robots can make local decisions and this method is closely related to another vital aspect of self-organization which itself is based on four principles of, positive feedback, negative feedback, randomness, and multiple interactions.
How the robots sense their environment to make decisions, can be via an external positioning system like different navigation systems or locally. Coppola (2021), suggests that the centralized control with a navigation system has allowed for better performance and has attracted a higher industry investment too (Coppola, M, 2021).

In this research, both centralized and de-centralized approaches were used to understand the limitations and potentials of each for the design of flexible spaces. It is worth noting that this research did not tackle the problems of obstacle avoidance or path finding since those are two vast topics out of the scope of this thesis. This research only focused on how to create swarm behavior to generate room layouts for different programs. The approach was simplified in many ways to only focus on the logic of building a curvilinear space with a swarm of robots.

For simulation purposes, Matplotlib animation and Pygame were used on Python.

3. Problem Definition, Constraints, and Assumptions

For the programming of the swarm robots on Python in the decentralized methods, the following assumptions and constraints were considered and put into the code.

Constraints:

1-The robots are identical in the 2D visualization.
2-The robots are reactive and only perform an action based on the current state of the other robots
3- The number of robot leaders is equal to the number of spatial zones defined
4- The robots do not communicate with each other and can only sense the location of their imminent neighbors
5- The robots only are aware of their local position.

Assumptions:

1- All robots should know the angle of the target arc location
2-All robots should perform within the 2D grid.

Probabilistic Considerations

1- Do not overlap any other robot in the target position
2-Do not get connected to more than two robots
3- When in the target position, do not move.
4- Only select possible arcs following the rules in defined in the sequence

4. Layout Generation with a Centralized Control Method

The centralized approach started with the circular grid that was developed in the previous stages on Grasshopper. Each circle was divided into 4 arcs to create an organic transition in the space. The reason for the division of each circle into 4 equal arcs was to have smoother movement in the design and to avoid space waste that does not fit furniture or a person.
The robots are stored at one point on the grid to simplify the simulation process. More storage points can be defined as required by the architects. In the first approach, a design was proposed by giving the target indices to each robot. The leader starts the movement and moves to the target arc and the team of robots starts following it to go to their designated arcs. This results in a satisfying layout arrangement since it is pre-defined. However, there is no de-centralized local sensing for any of the robots, and thus can not be considered a swarm behavior.

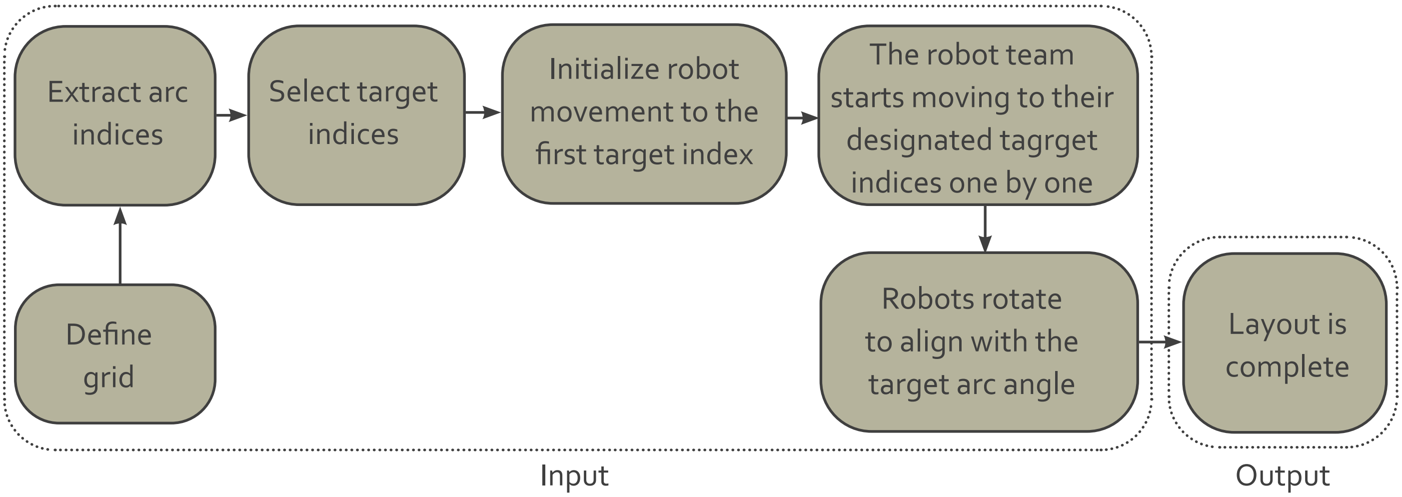


Figure 159. Diagram explaining the logic of the centralized approach in the python code shown in the following images.

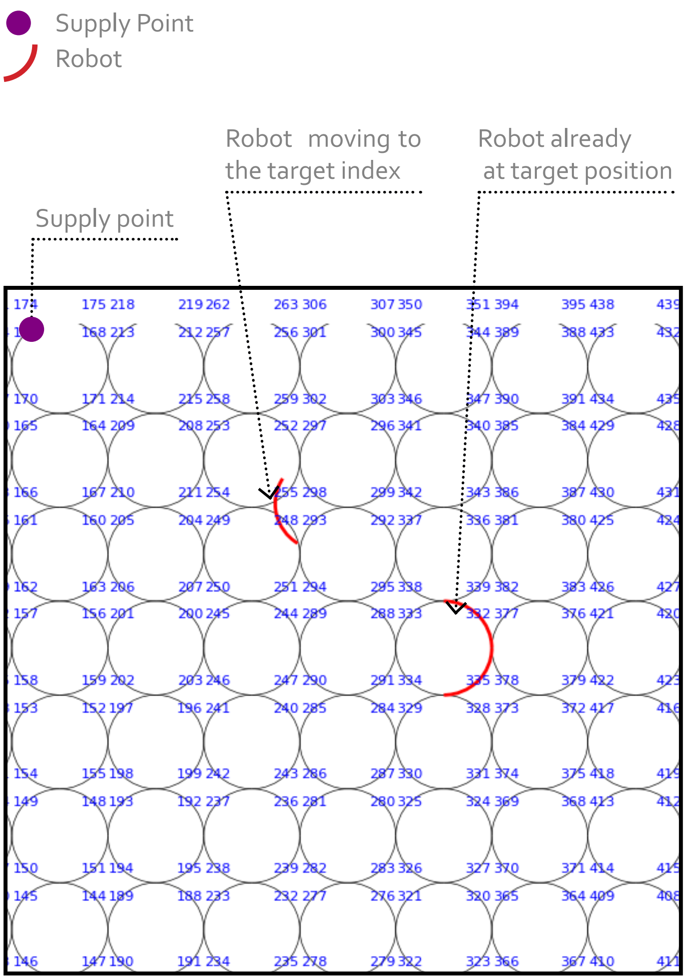


Figure 160 . Each red arc represents a robot which starts moving from the supply point (robot storage) to the designated target index on the environment grid.

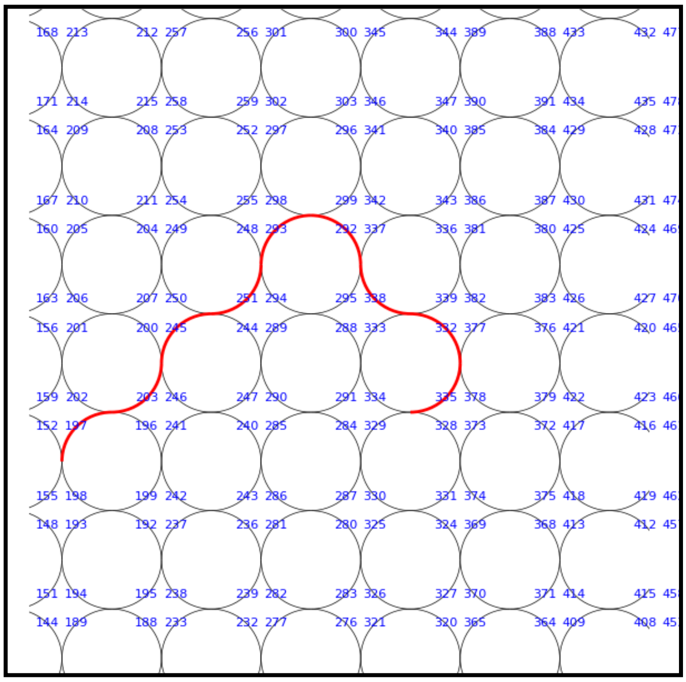


Figure 161. The robots move one by one to form the pre-planned layout.

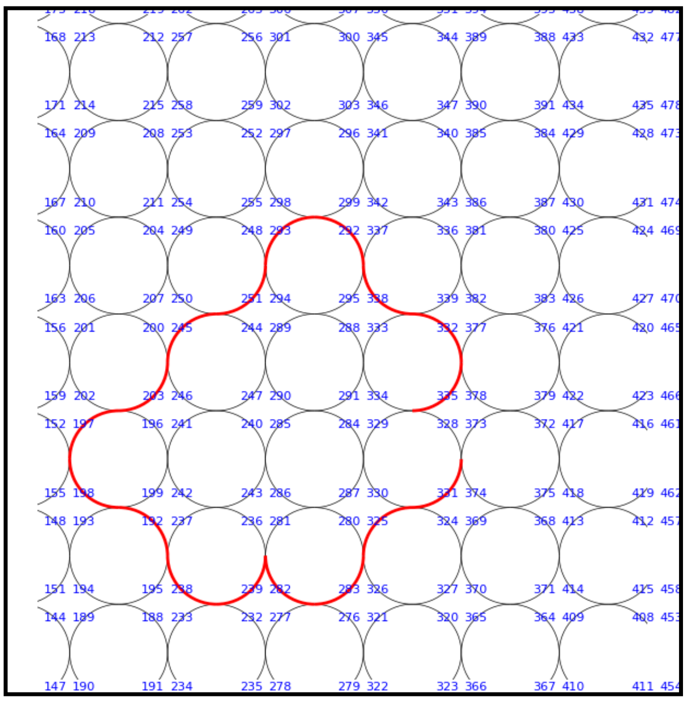


Figure 162. The final layout is achieved.

4.1. Pros and Cons of this Approach

Pros

Predictable and Precise Layouts:
The pre-defined target indices for each robot ensure that the resulting layout is precise and predictable, and allows for controlled planning and arrangement of space.

Efficient Movement Coordination:
The centralized control system facilitates efficient movement coordination among the robots, and can minimize the chances of collisions or inefficiencies in space utilization.

Simplified Simulation Process:
Storing robots at one point and programming them to move one by one to their target index can also simplify the initial setup and simulation process

Consistent Design Outcomes:
The lack of de-centralized local sensing ensures that the design outcomes are consistent with the planned layout, reducing variability and unpredictability in the final arrangement.

Cons

Limited Flexibility:
The absence of de-centralized local sensing restricts the robots' ability to adapt immediately to dynamic changes in the environment, resulting in less flexible and adaptable layouts.

Single Point of Failure:
Relying on a centralized control system introduces a single point of failure. If the central control system encounters issues, the entire layout generation process can be disrupted.

Reduced Autonomy:
Robots lack autonomy in decision-making and cannot respond to local environmental changes or obstacles, potentially leading to inefficiencies or the need for manual intervention.

Scalability Issues:
As the number of robots or the complexity of the grid increases, the centralized control system may face challenges in efficiently managing and coordinating all robots, potentially impacting performance and scalability.

Less Organic Interaction:
The pre-determined movement paths and lack of local sensing result in less organic interaction between robots, which may limit the system's ability to create truly responsive spatial configurations.

5. Layout Generation with a De-centralized Control Method 1

In the second approach, a de-centralized method was tried. Zones are drawn each time based on the architect's desired location and shape. The coordinates of these zone curves are saved in a JSON file which can be updated and used every time the design changes. Then for easier calculations in the next steps, the drawn curves are smoothed and then divided into segments. The number of segments can be changed according to preference. In the next step, the tangent of each segment is calculated and shown in red lines. The goal of this method is to let the robot team create the form of the drawn zone curve as close as they can.

Two supply points for robot storage on opposite directions of the grid are defined. The number of supply points at various locations can also be increased. Each supply point can store as many teams as are assigned to them.

Each team has a name such as Team 1 or Team 2 and several robots in the team. There is one leader robot in each team shown in black and the rest of the team are follower robots shown in red. Each robot has an ID or index. The robots have lidar sensors and are able to figure out their relative position to their immediate neighbors within a communication range that is defined in the beginning of the code and can be changed. The teams are arranged in a circular array with their leader located at the center. Every time a team is initialized, they move to the target zone which matches their number. Thus, Team 1 goes to Zone 1 and Team 2 goes to Zone 2. The leader starts the movement and the followers know they have to maintain their position with the leader so the entire team moves along with the leader to the target point while maintaining formation. This is an example of the flocking behavior of a swarm. Once the leader is at the centroid of the target zone, the team stays there for a few seconds. The leader then selects a random Zone 1 curve segment to move to it and match its tangent. The followers at this point have some local knowledge like knowing the boundary of the zone and that the leader initiated the movement so they have to move to their target position. Each follower robot starts moving to a segment of the zone 1 curve while matching its tangent. If a segment is already occupied the followers check other segments to find an empty one and match its tangent and get located on it.

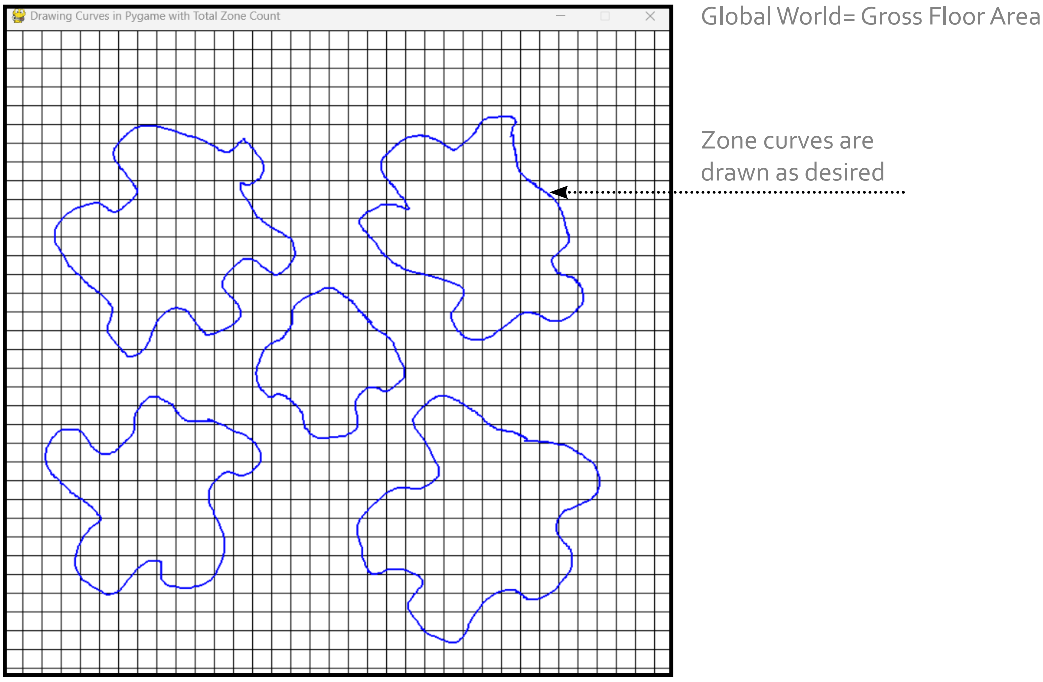


Figure 163. The zones are drawn as desired. Each blue curved line represents a zone.

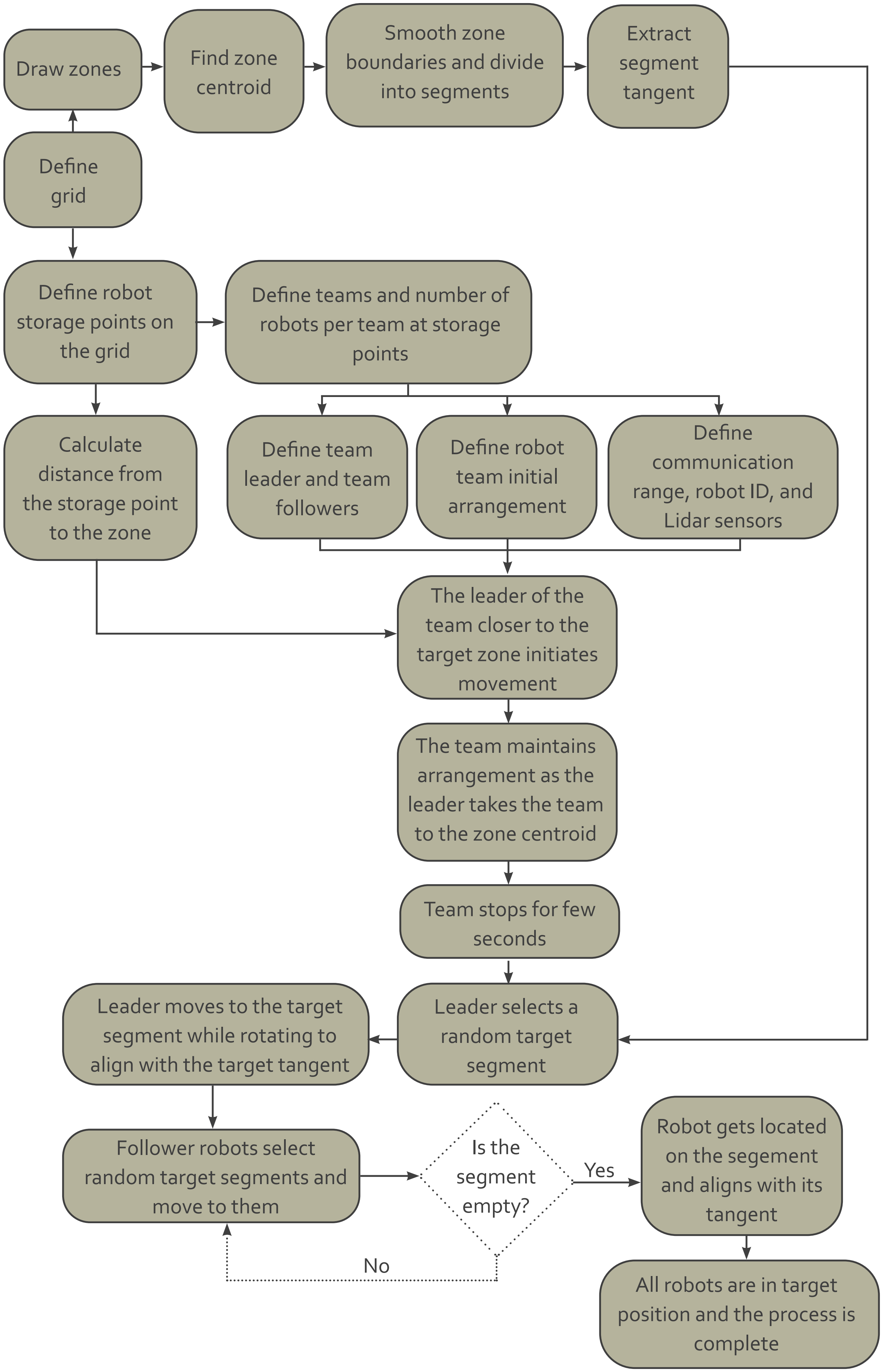


Figure 164. Diagram explaining the logic of the de-centralized approach 1 in the python code shown in the following images.

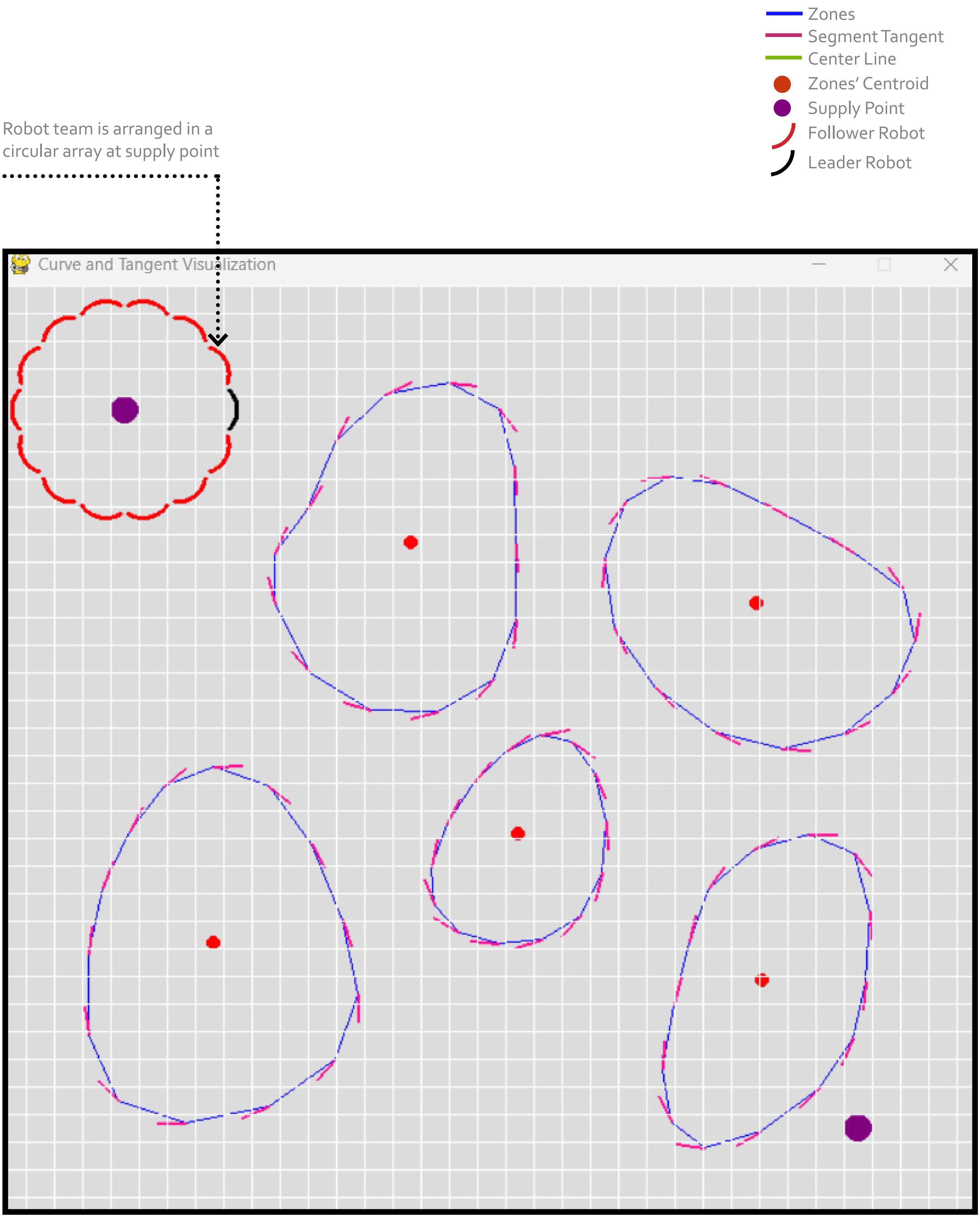


Figure 165. The zones' curves are smoothed and divided into a defined number of segments. The segments' tangents are then calculated and shown as red lines.

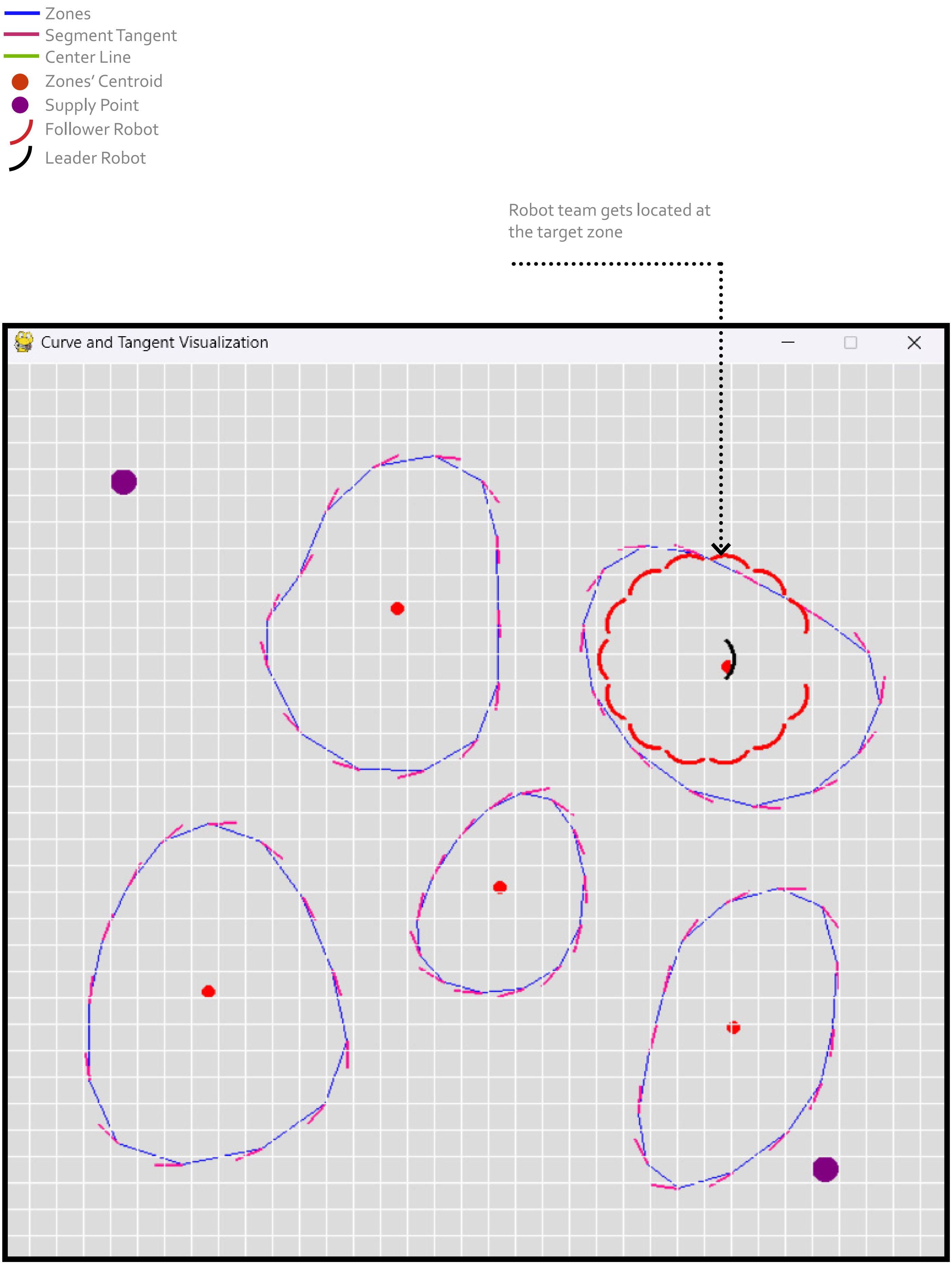


Figure 166. Robot team gets located at the target zone with the leader located at the zone's centroid.

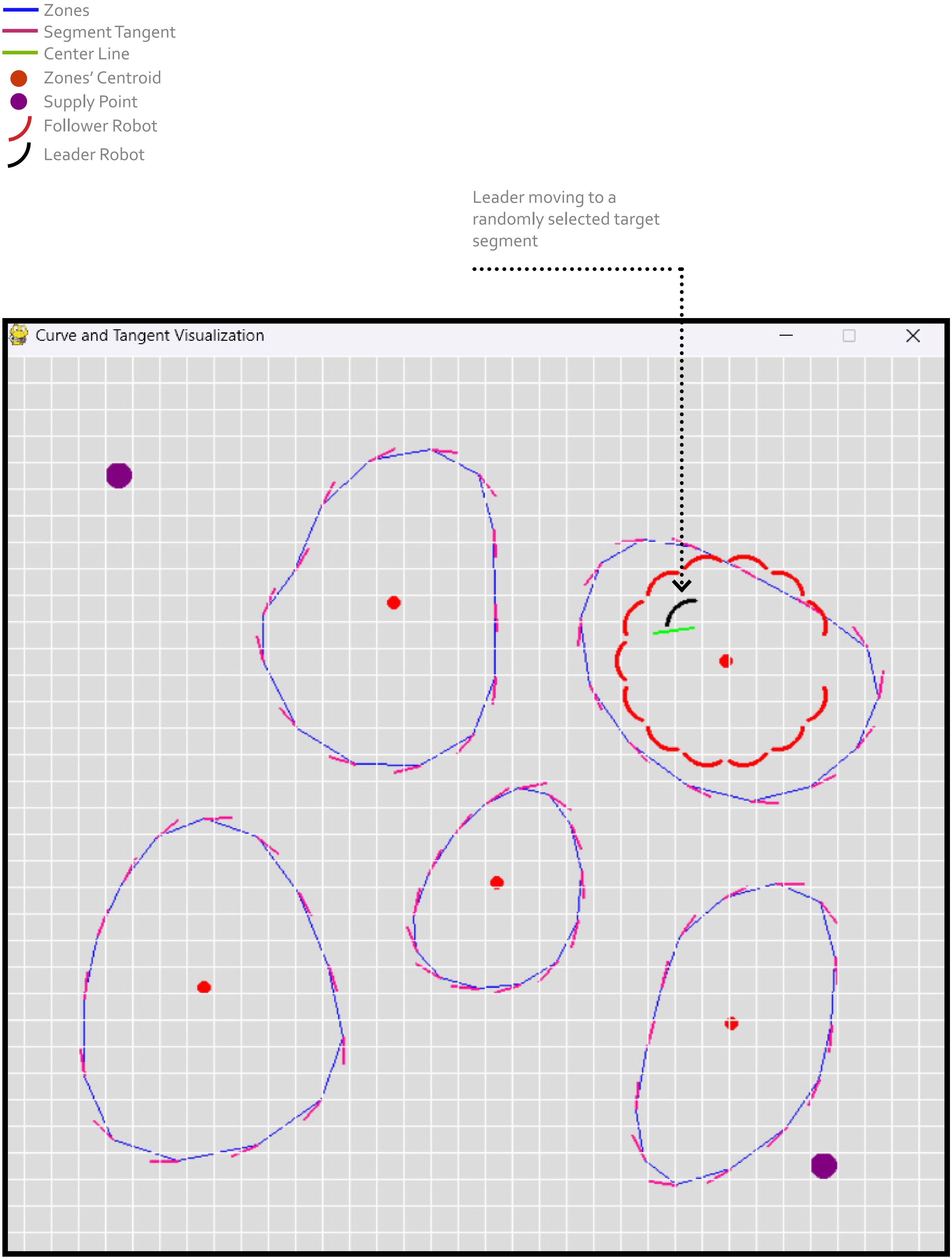


Figure 167. The leader starts moving to a segment which it randomly has selected and gets located on it while rotating to match its tangent. The green line represents the target tangent.

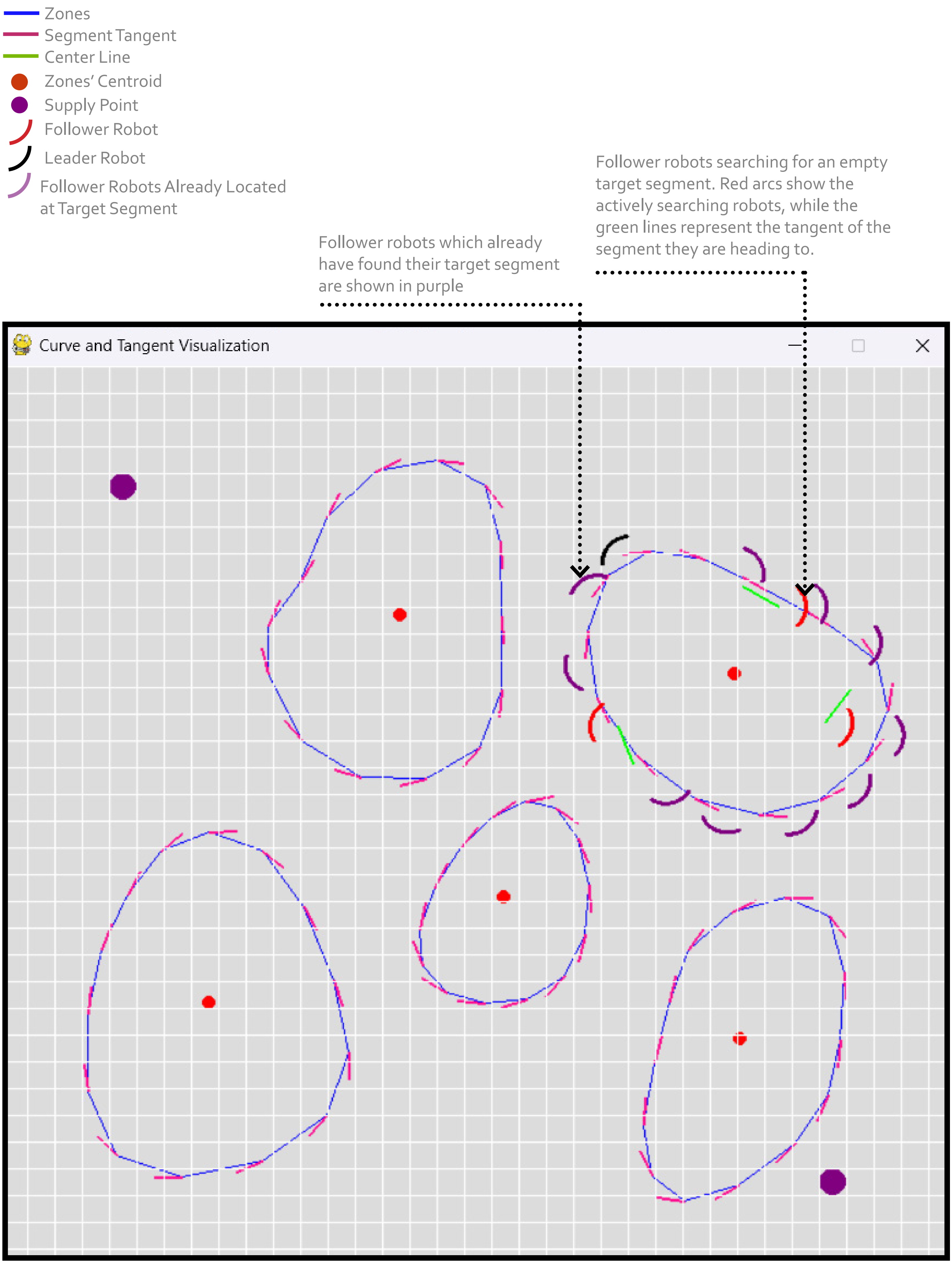


Figure 168. After the leader gets located on the target segment, each robot starts to select an empty segement to get located on, while rotating to match its tangent. If a segment is already taken, the robots go around to find another empty one.

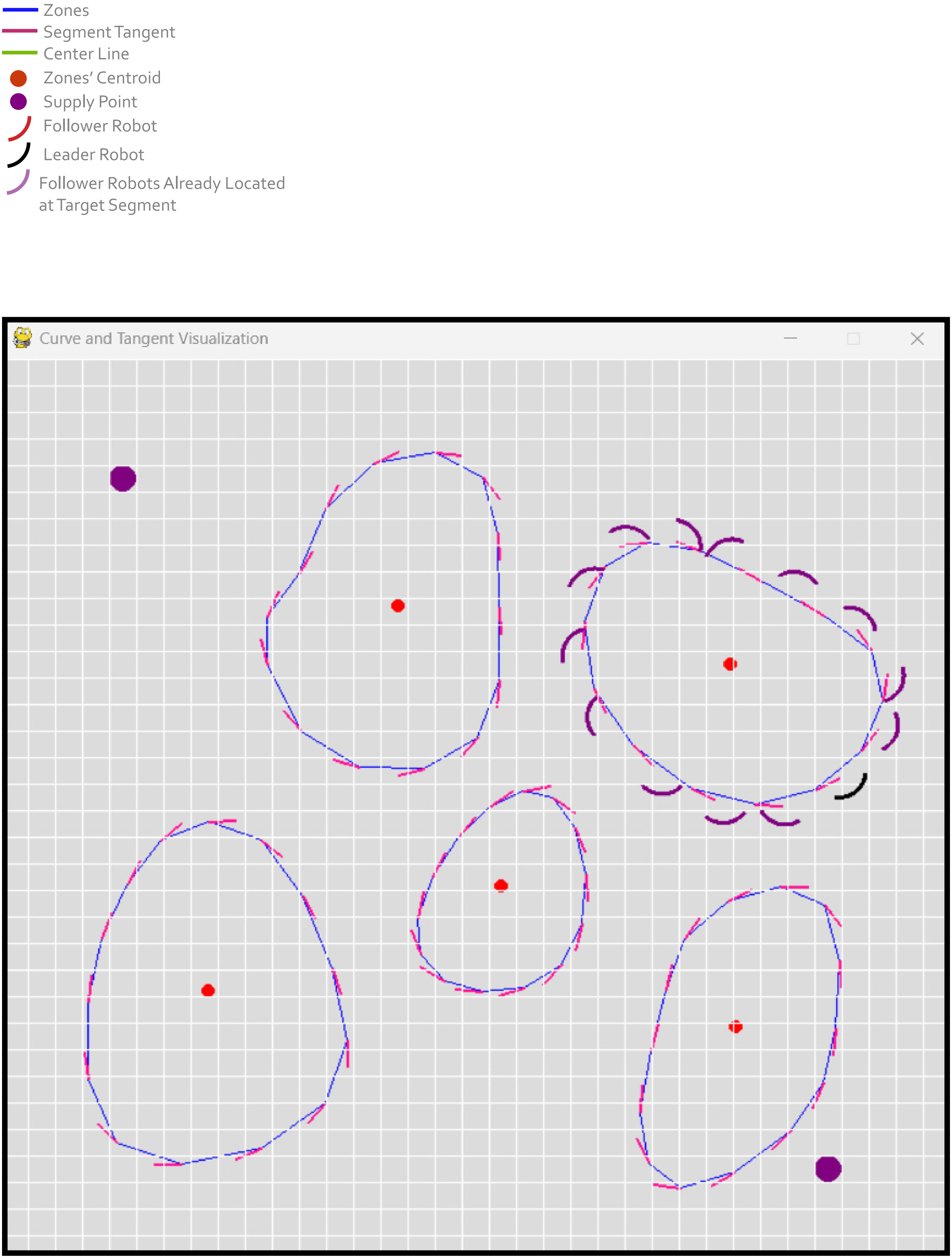


Figure 169. All the robots get located on their target segment and form the zone curve form as approximately as they can.

5.1.Pros and Cons of this Approach

Pros

Increased Flexibility and Adaptability:
The decentralized control method allows robots to adapt to changes in the environment and dynamic spatial configurations, resulting in more flexible and responsive layouts.

Resilience and Redundancy:
Decentralized systems are more resilient to failures. If one robot or team encounters a problem, others can continue functioning independently, reducing the risk of a single point of failure.

Enhanced Autonomy:
Robots make local decisions based on their immediate environment, promoting greater autonomy

Scalability:
The system can scale more effectively as more robots are added. Each robot operates semi-independently, which can handle increasing complexity without overwhelming a central controller.

Dynamic and Organic Interaction:
The use of flocking behavior and local sensing leads to more natural and dynamic interactions between robots.

Continuous Improvement:
The ability to update the JSON file with new zone curves allows for continuous improvement and iteration in the design process, enabling architects to refine and optimize spatial configurations over time.

Cons

Potential for Unpredictable Outcomes:
The decentralized nature can lead to less predictable outcomes, with some configurations potentially resulting in unpractical, less optimal or aesthetically pleasing layouts.

Complex Coordination:
Ensuring smooth coordination and interaction between multiple decentralized robots can be complex and may require sophisticated algorithms to prevent issues such as overlap, collisions, or inefficient use of space.

Initial Setup Complexity:
Setting up the initial parameters, including defining zones, calculating tangents, and segmenting curves, can be more complex and time-consuming compared to a centralized approach.

Inconsistency in Design Quality:
The variability in robot decision-making processes may result in inconsistent design quality, with some iterations producing better results than others.

Higher Computational Load:
Each robot requires its own processing capability to make local decisions, which can increase the overall computational load compared to a centralized system where a single processor handles the control logic.

Need for Sophisticated Sensing and Navigation:
The success of decentralized control relies heavily on accurate local sensing and navigation capabilities, which may require advanced sensors and algorithms, potentially increasing costs and complexity

6. Layout Generation with Decentralized Control Method 2

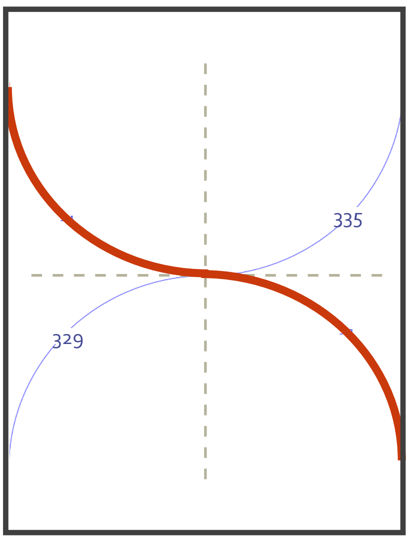
The third method used the circular grid with arc indices but in a decentralized way, through defining local rules to form global behaviors. In this method, a zone boundary was introduced on the grid. Then three angles and symmetry rules between adjacent arcs were defined as rule 1, rule 2, and rule 3. These rules were then put into different sequences like s1= [1, 2, 3, 1, 1, 1, 3, 2, 3, 3, 1, 1, 3, 2, 2]. An arc index in the boundary of the rectangle was selected as the arc initiating the next steps of the sequence. In the next step, the next robot must select from the possible arcs with spatial adjacency to the already selected arc, which also meet the symmetrical and angular conditions of rule 1 defined in the above sequence. Spatial adjacency was calculated using the Euclidean distance with the formula shown below.

$$d(\mathbf{p},\mathbf{q}) = \sqrt{\sum_{i=1}^{n}(q_i - p_i)^2}$$

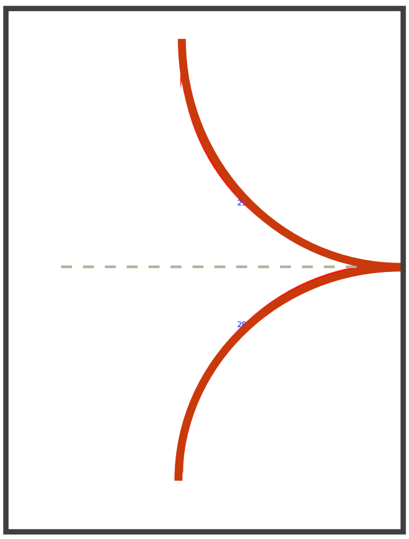
p, q = two points in Euclidean n-space
q_i, p_i = Euclidean vectors, starting from the origin of the space (initial point)
n = n-space

In the second step of the sequence, the next robot must find the possible adjacent arcs which follow the rule defined in step two of the sequence. This process goes on until the sequence steps are ended. Since the robots must only select positions within the defined boundary and might not find the arcs that follow the rule defined in that step of the sequence, a part is added to let the robots skip this step and try the next rule of the sequence. This can be done within different zones with different teams. 10 different sequences are defined for the sake of this experiment. It was noted that when the rules in all the steps of the sequence are the same, more interesting spaces are achieved.

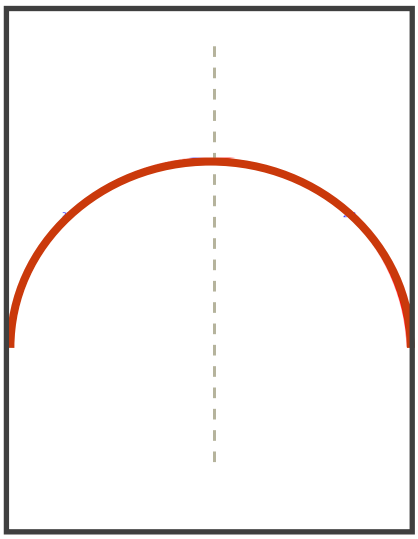
Line of symmetry



Rule1-Orthogonal Symmetry Over 2 axes



Rule2-Orthogonal Symmetry over 1 axis



Rule3-Rotational Symmetry

Figure 170, 171, 172. Different symmetry types to be input as the three rules which robot arcs have to follow to build up a layout

Rule1. Orthogonal Symmetry Over Two Axes

Movement: Moves are orthogonal, which means they can go up, down, left, or right relative to the current position.

Angle Condition: Typically associated with an angle difference of 180 degrees. This implies that the movement or symmetry is considered valid if the resulting arc is directly opposite on the coordinate system (in terms of direction).

Rule 2. Orthogonal Symmetry Over One Axis

Movement: Moves include mirroring of elements across a straight line, specifically one that intersects these elements at right angles (orthogonally).

Angle Condition: Associated with an angle difference of 90 degrees.

Rule 3. Rotational Symmetry

Movement: Rotational symmetry involves rotating an arc around its center point or a nearby central point in the grid. This rotation should position the arc in such a way that it aligns or mirrors its positioning relative to other arcs.

Angle Condition:

Rotational symmetry, typically involves rotations that result in significant shifts like 90°, 180°, or 270°, which are common in symmetrical designs because they correspond to quarter, half, and three-quarter turns, respectively.

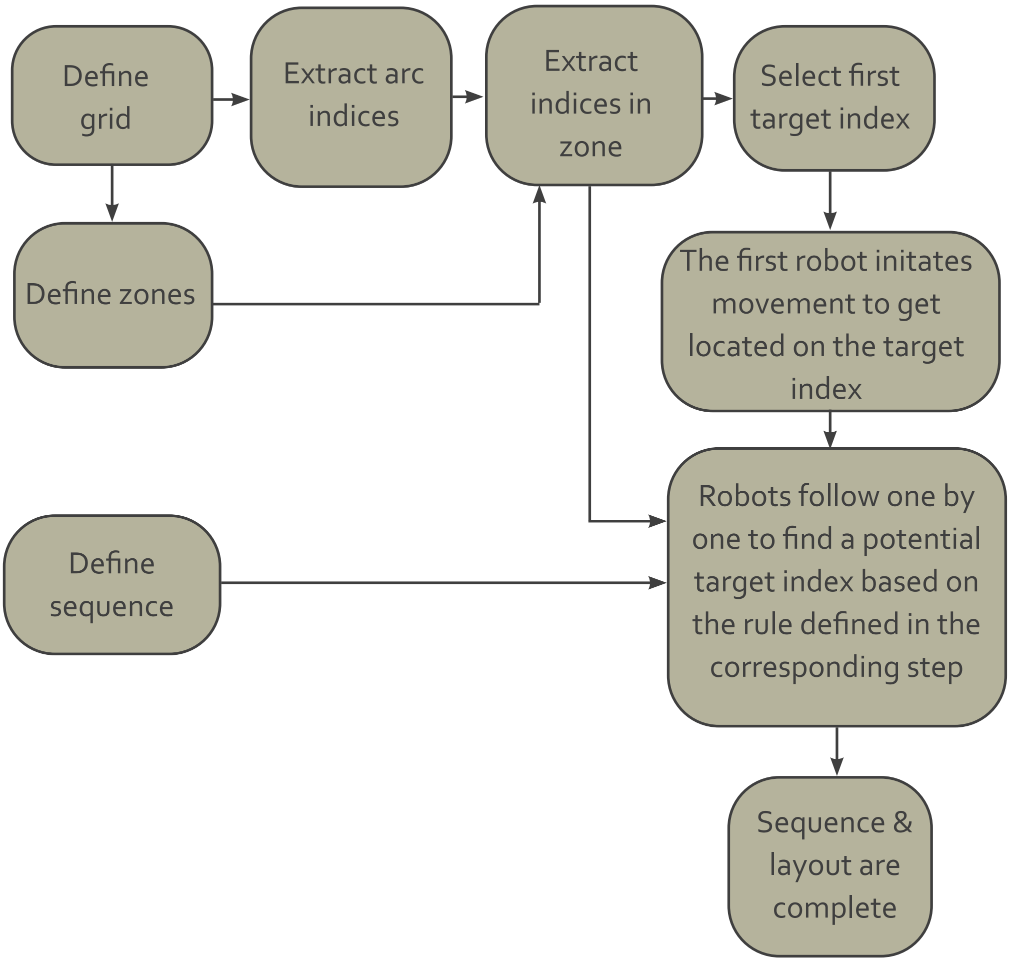


Figure 173. Diagram explaining the logic of the de-centralized approach 2 in the python code shown in the following images.

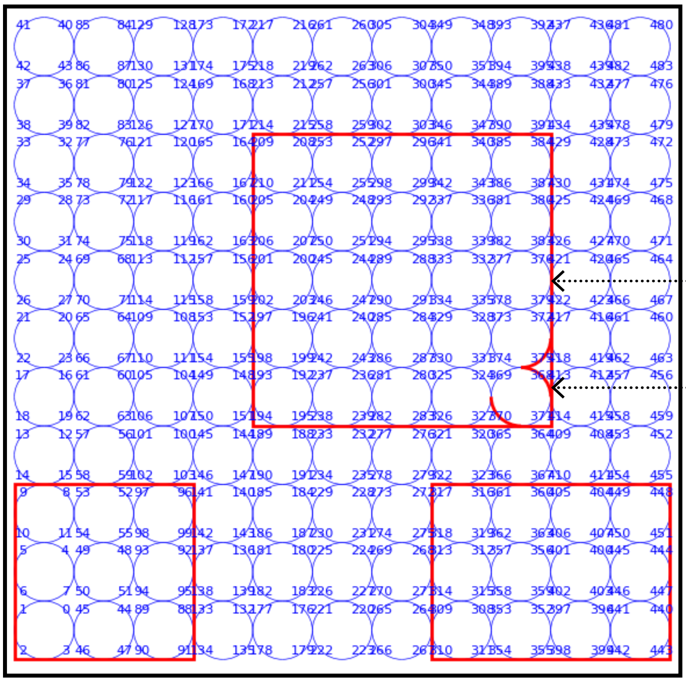
```
# Sequence of rules
s1 = [1, 1, 3, 2, 3, 1, 1, 2, 1, 1, 2, 3, 1, 1, 2, 3, 1, 1, 2, 2, 1, 1]
s2 = [2, 2, 3, 3, 1, 3, 1, 3, 1, 1, 1, 1, 1, 3, 2, 1, 1, 3, 2, 1, 1, 3]
s3 = [3, 1, 3, 1, 1, 2, 1, 3, 1, 2, 1, 2, 1, 1, 3, 1, 2, 1, 2, 3, 1, 3]
s4 = [3, 2, 2, 3, 1, 1, 1, 1, 1, 2, 3 , 2, 2, 3, 1, 1, 1, 1, 3, 1, 2, 2]
s5 = [1, 1, 1, 1, 1, 3, 1, 1, 1, 1, 1, 3, 1, 1, 1, 1, 1, 1, 1, 1, 1, 3]
s6 = [2, 2, 2, 2, 2, 2, 2, 3, 2, 2, 2, 1, 1, 2, 2, 1, 1, 2, 2, 1, 1, 2]
s7 = [3, 2, 1, 1, 2, 3, 3, 2, 1, 1, 2, 3, 3, 2, 1, 1, 2, 3, 3, 2, 1, 1]
s8 = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
s9 = [3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3]
s10 = [3, 3, 3, 3, 3, 3, 1, 1, 1, 1, 1, 1, 1, 1, 3, 1, 1, 1, 1, 3, 3, 3, 1, 1, 1, 1, 3, 3, 3, 3]
```

Figure 174. Then 10 sequences defined for this experiment, each made of the symmetry rules of the page before. The rules in each sequence were randomly selected to see how the outcome of each works. However, these rules can also be defined by the architects with regards to the specific contextual requirements and limitations.

```
# Define moves based on the rule number
rule_number = s10[frame % len(s10)]
if rule_number == 1:
    moves = [(0, 1), (0, -1), (1, 0), (-1, 0)]
elif rule_number == 2:
    moves = [(0, 1), (0, 0), (0, 0), (0, 0)]
elif rule_number == 3:
    # Adjust moves to adjacent locations only, keeping them close and aligned
    moves = [(0,-1), (0, 1), (-1, 0), (1, -0)]


next_arcs = []
x, y = arc_data[current_arc_index]['coords']
# Check adjacency and angles according to the rule
for move in moves:
    next_x = x + move[0]
    next_y = y + move[1]
    for idx, data in arc_data.items():
        if (next_x, next_y) == data['coords'] and idx in inside_arcs and idx not in selected_arcs:
            angle_diff = (arc_data[current_arc_index]['angle'] - data['angle']) % 360
            if ((rule_number == 1 and angle_diff == 180) or
                 (rule_number == 2 and angle_diff == 90) or
                 (rule_number == 3 and angle_diff == 90)):
                next_arcs.append(idx)
```

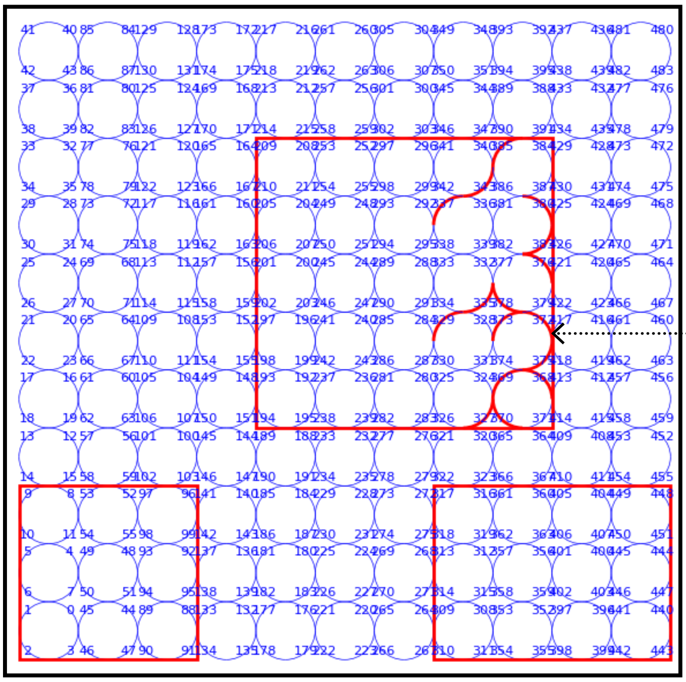
Figure 175. Part of the code that defines how the symmetry and movement on the grid should work based on each rule.



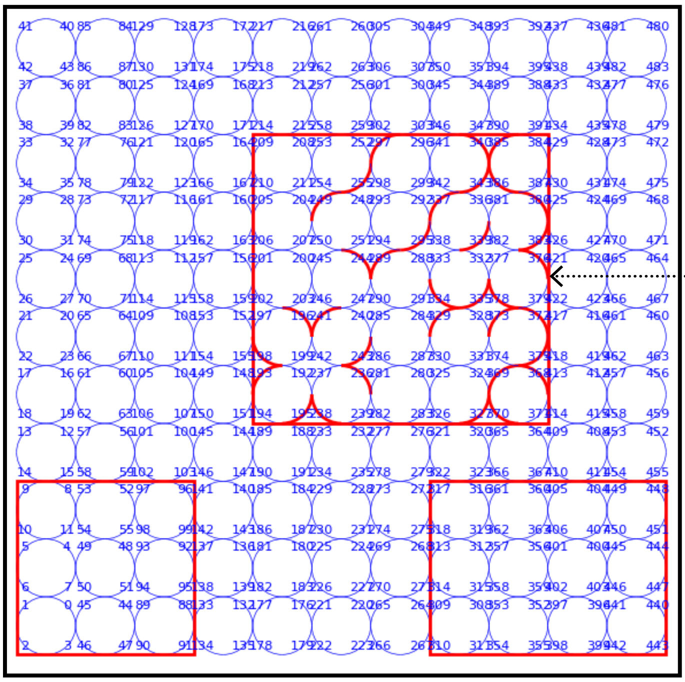
Each red arc represents a swarm robot

Different zones are defined by rectangle boundaries to control the area for layout configuration.

An arc selection, initiates the sequence



Robots go through the possibilities based on the rules defined in each step of the sequence to select the next arc



The layout configuration of the zone is complete and robots stop moving

Figure 176, 177, 178. The stages of space configuration by a team of swarm robots based on symmetry rules defined in a sequence

The following figures show the result of each sequence in one zone defined by a rectangle. The black arc shows the first arc selected after which the sequence starts.

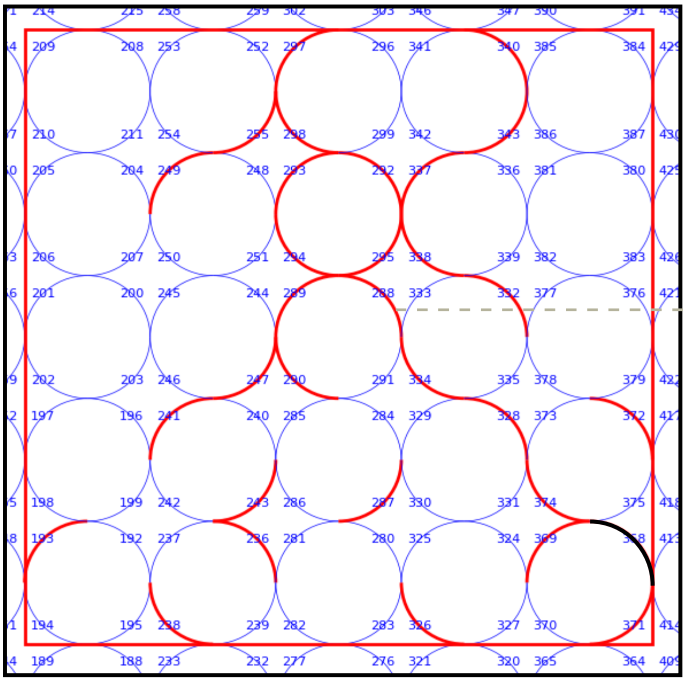


Figure 179. S1

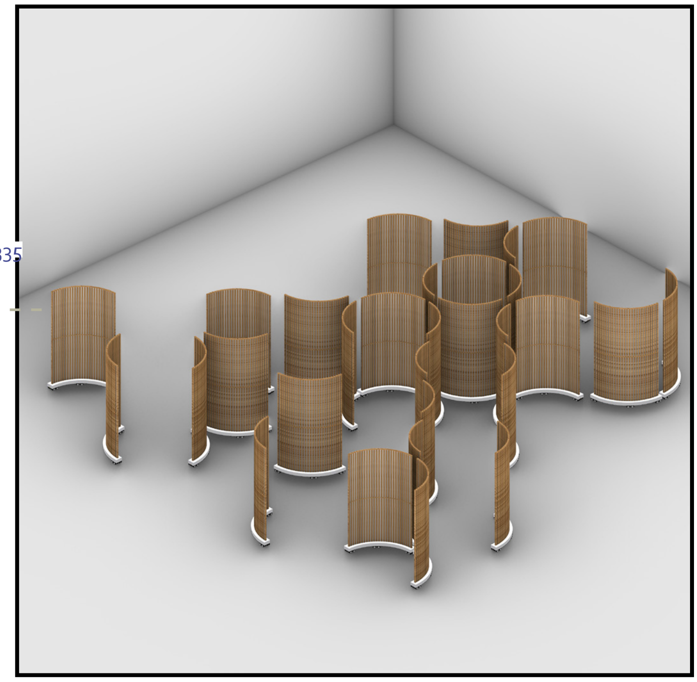


Figure 180. S1 in a 3D space.

S1 =
[1, 1, 3, 2, 3, 1, 1, 2, 1, 1, 2, 3, 1, 1, 2, 3, 1, 1, 2, 2, 1, 1]

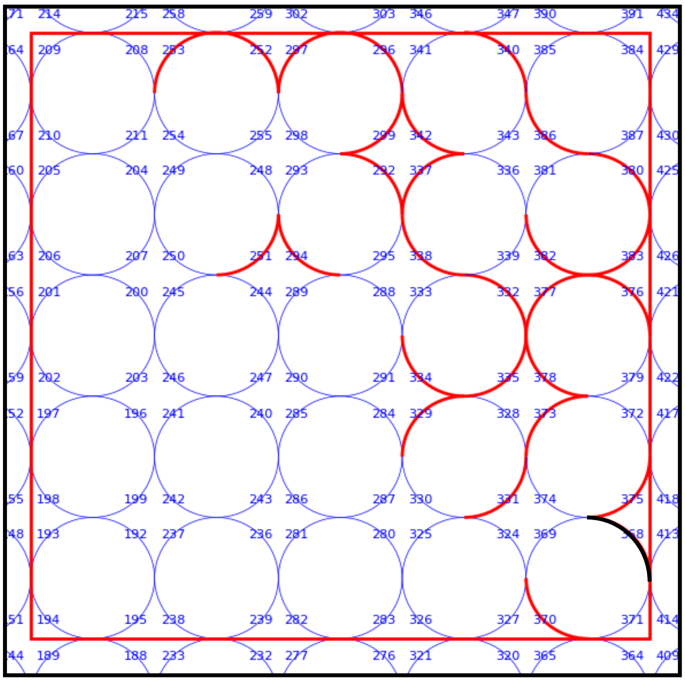


Figure 181. S2

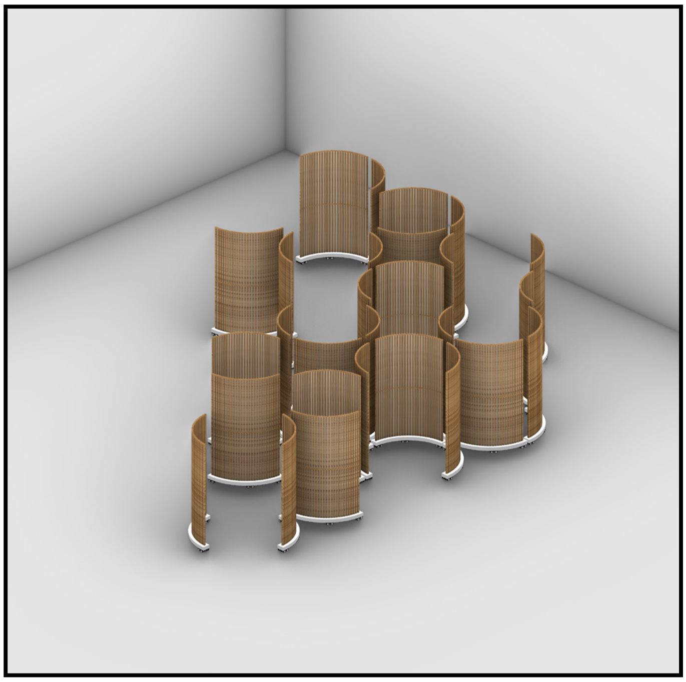


Figure 182. S2 in a 3D space.

S2 =
[2, 2, 3, 3, 1, 3, 1, 3, 1, 1, 1, 1, 1, 3, 2, 1, 1, 3, 2, 1, 1, 3]

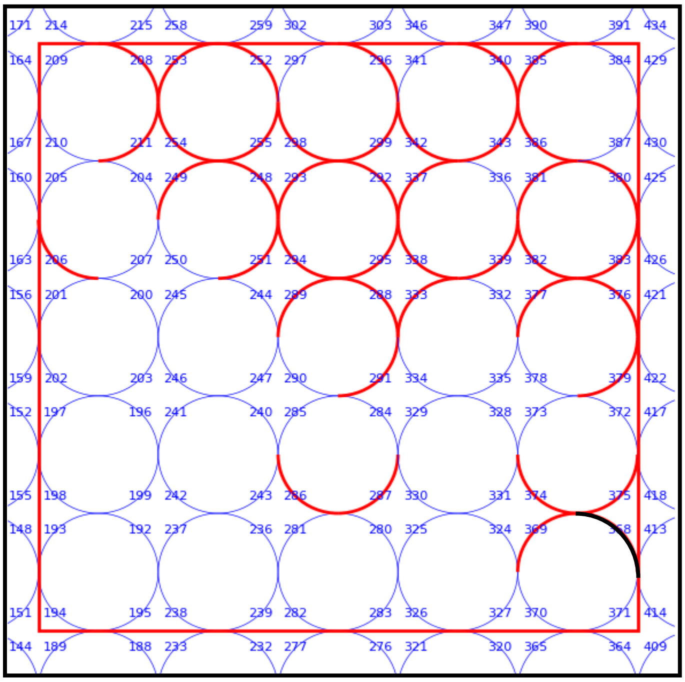


Figure 183. S3

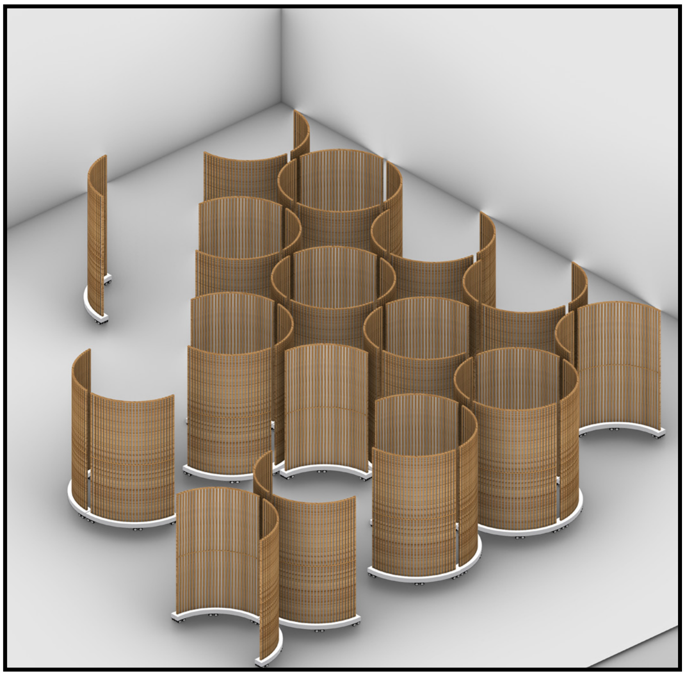


Figure 184. S3 in 3D space.

s3 =
[3, 1, 3, 1, 1, 2, 1, 3, 1, 2, 1, 2, 1, 1, 3, 1, 2, 1, 2, 3, 1, 3]

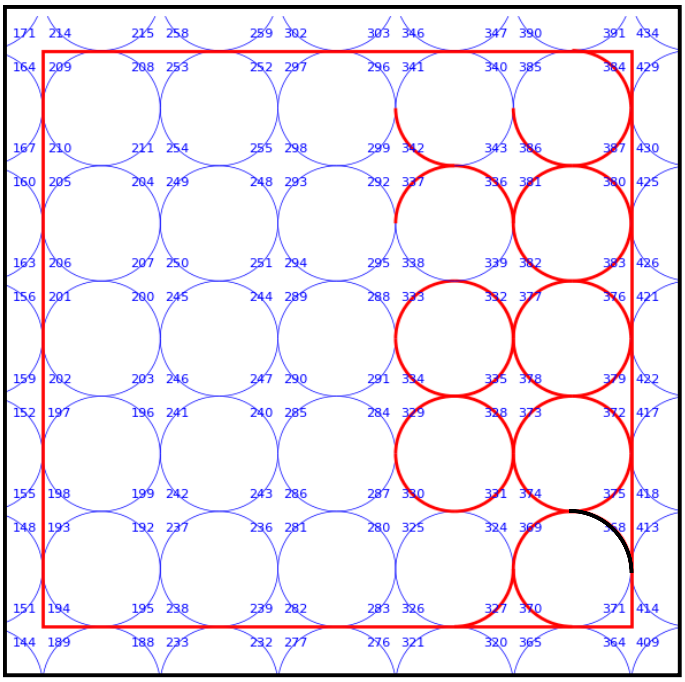


Figure 185. S4

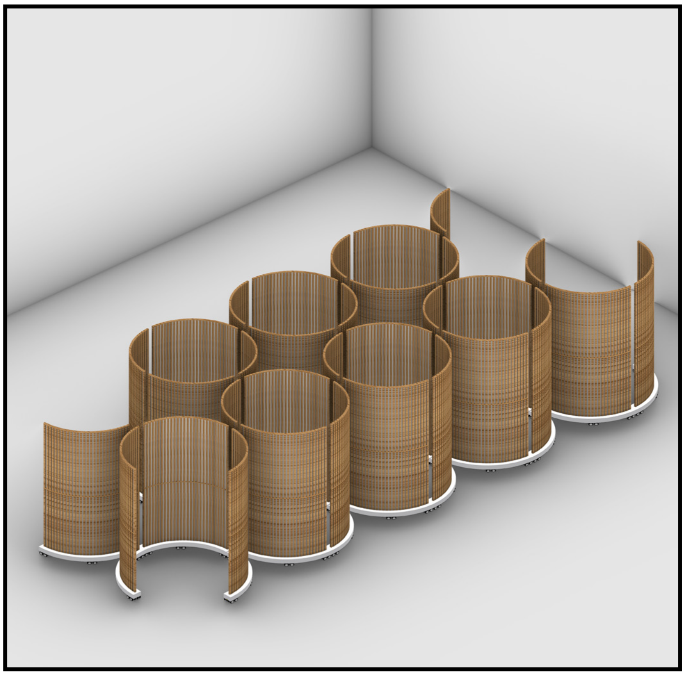


Figure 186. S4 in 3D space.

s4 =
[3, 2, 2, 3, 1, 1, 1, 1, 1, 2, 3 , 2, 2, 3, 1, 1, 1, 1, 3, 1, 2, 2]

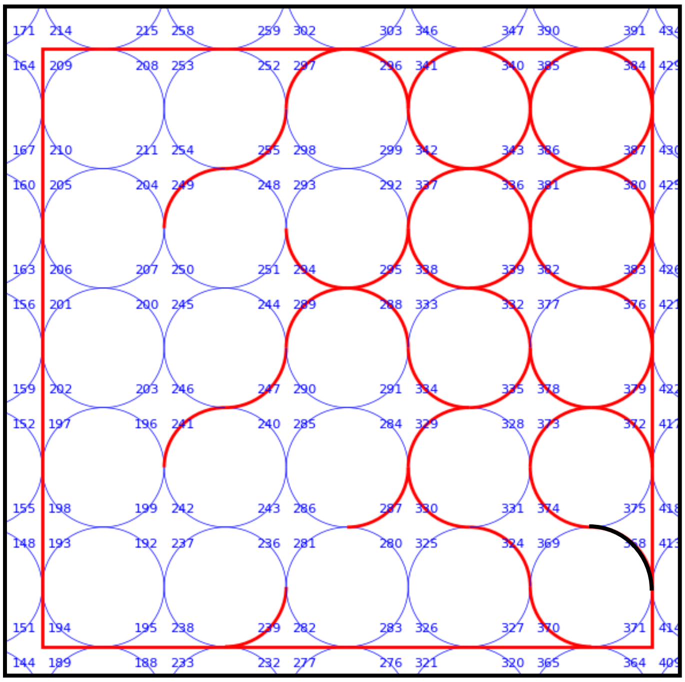


Figure 187. S5

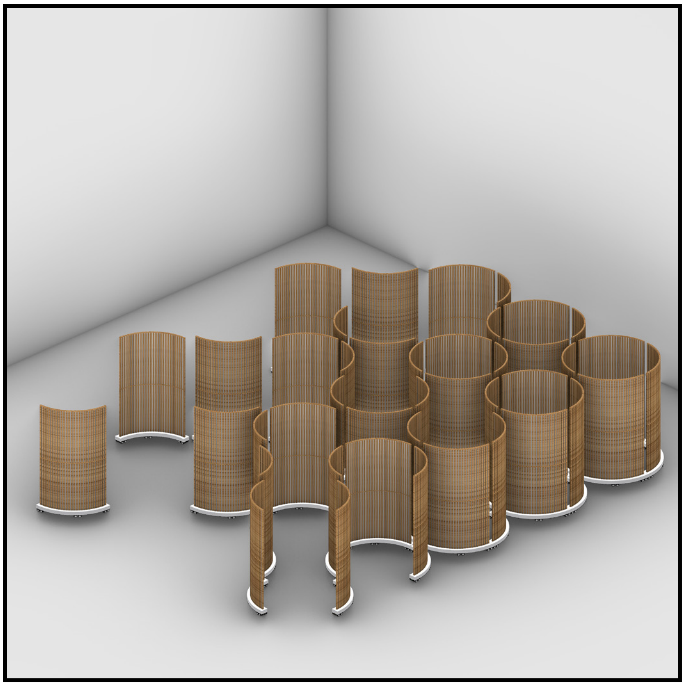


Figure 188. S5 in 3D space.

s5 =
[1, 1, 1, 1, 1, 3, 1, 1, 1, 1, 1, 3, 1, 1, 1, 1, 1, 1, 1, 1, 1, 3]

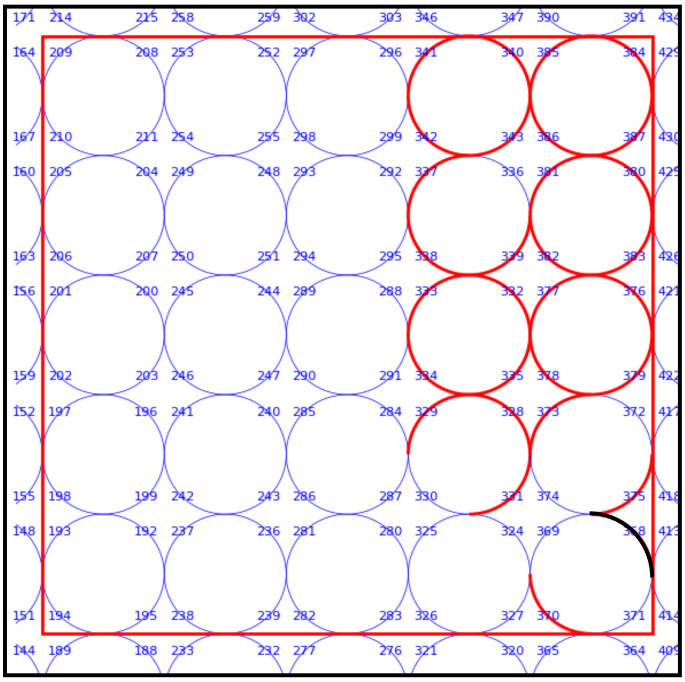


Figure 189. S6

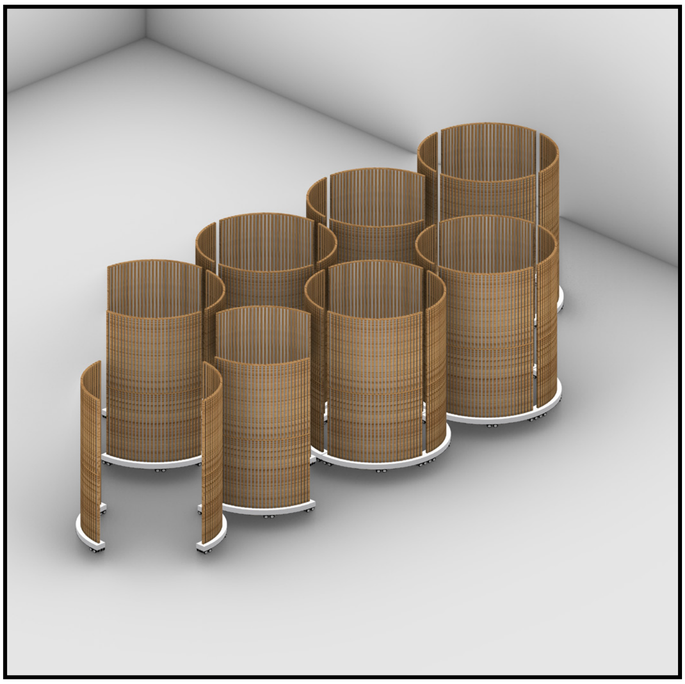
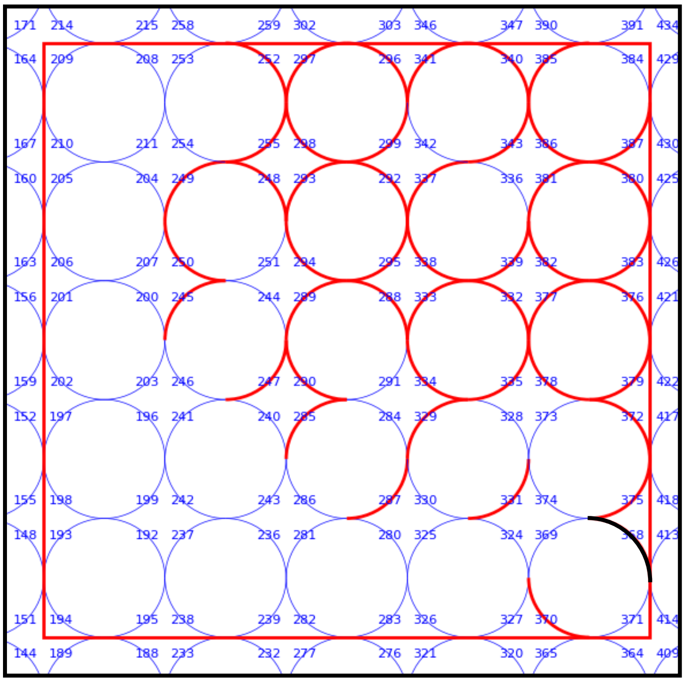


Figure 190. S6 in 3D space.

s6 =
[2, 2, 2, 2, 2, 2, 2, 3, 2, 2, 2, 1, 1, 2, 2, 1, 1, 2, 2, 1, 1, 2]



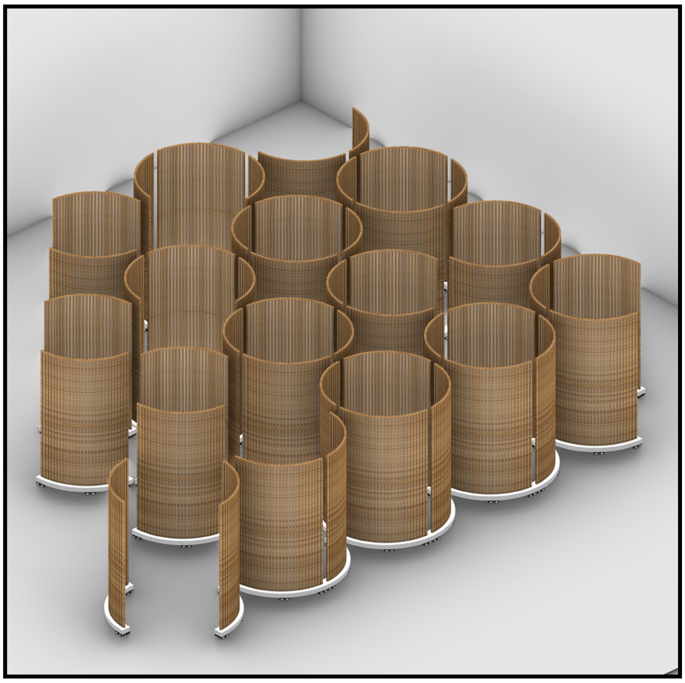
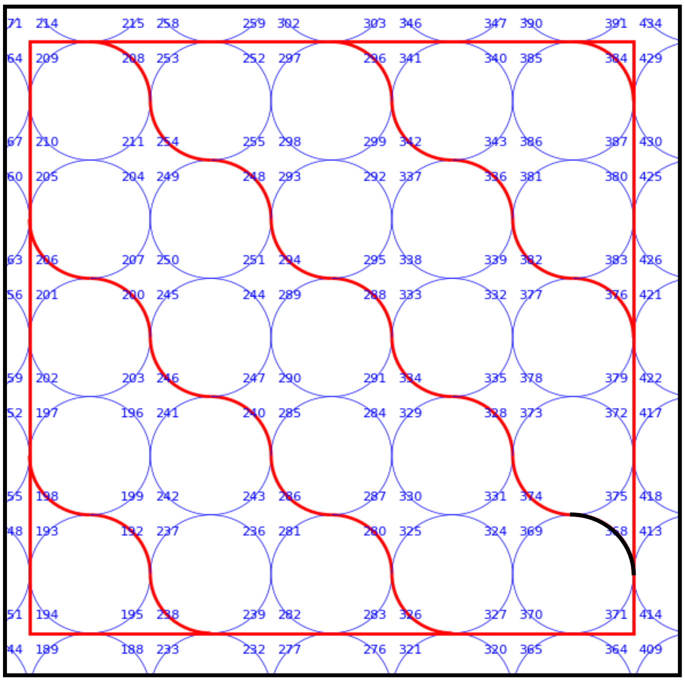


Figure 191. S7

Figure 192. S7 in 3D space.

s7 = [3, 2, 1, 1, 2, 3, 3, 2, 1, 1, 2, 3, 3, 2, 1, 1, 2, 3, 3, 2, 1, 1]



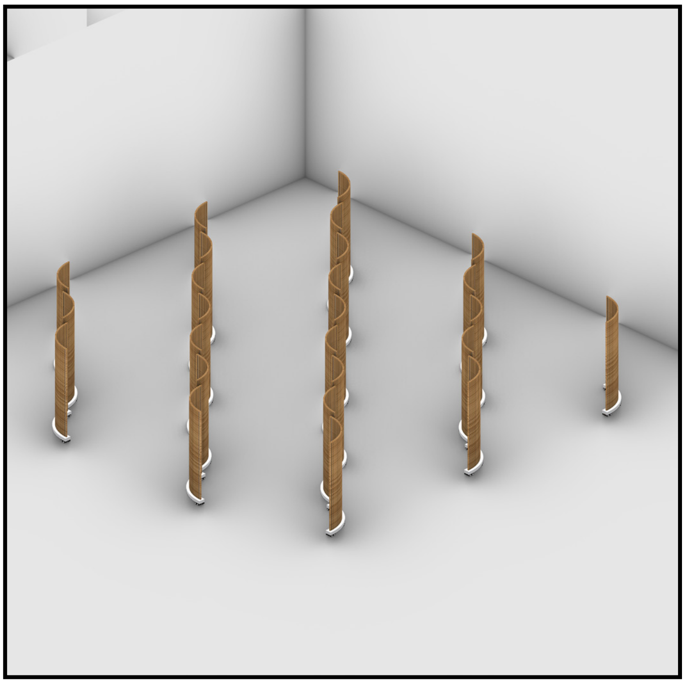


Figure 193. S8

Figure 194. S8 in 3D space.

s8 = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]

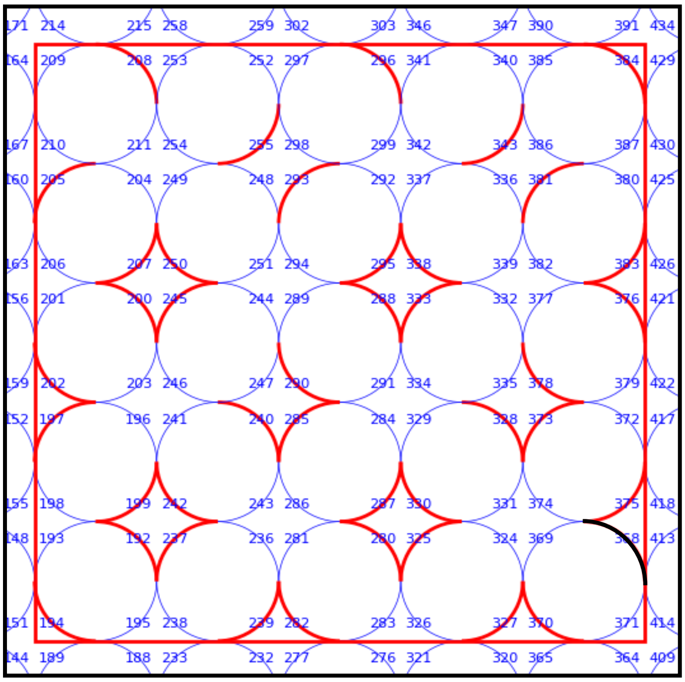


Figure 195. S9

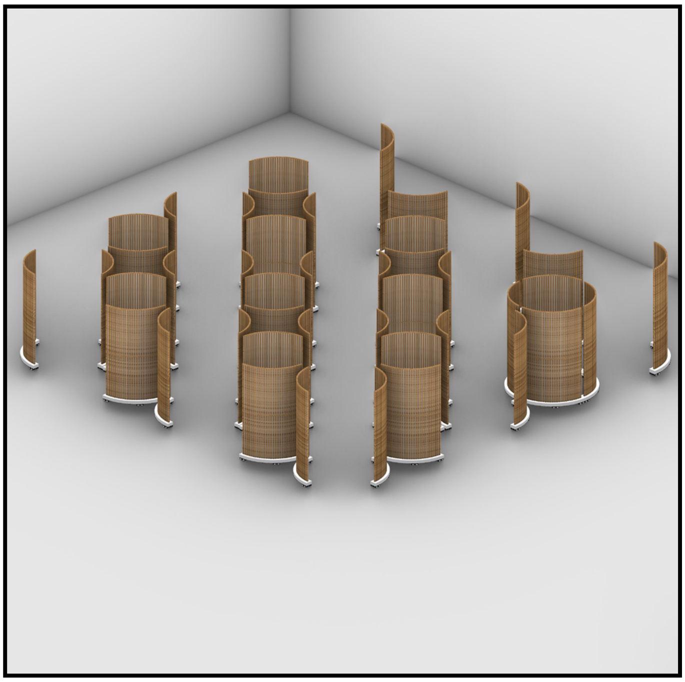


Figure 196. S9 in 3D space.

s9 = [3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3]

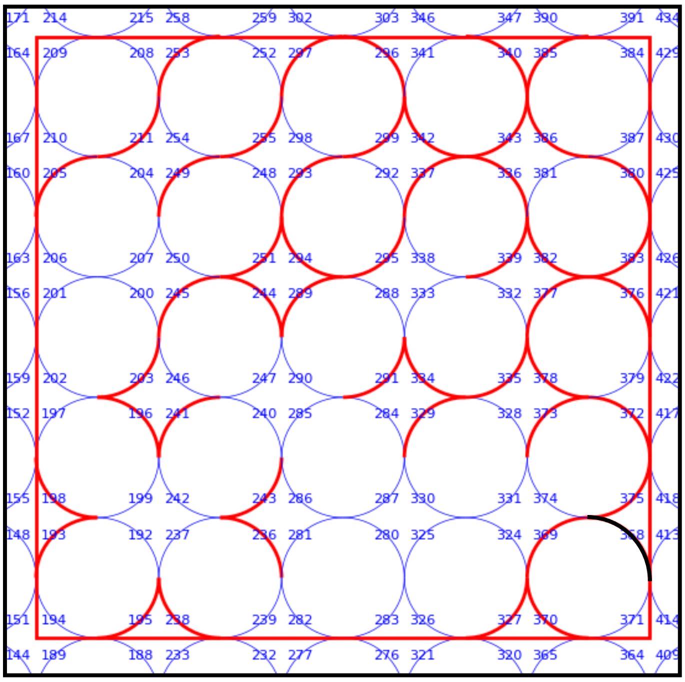


Figure 197. S10

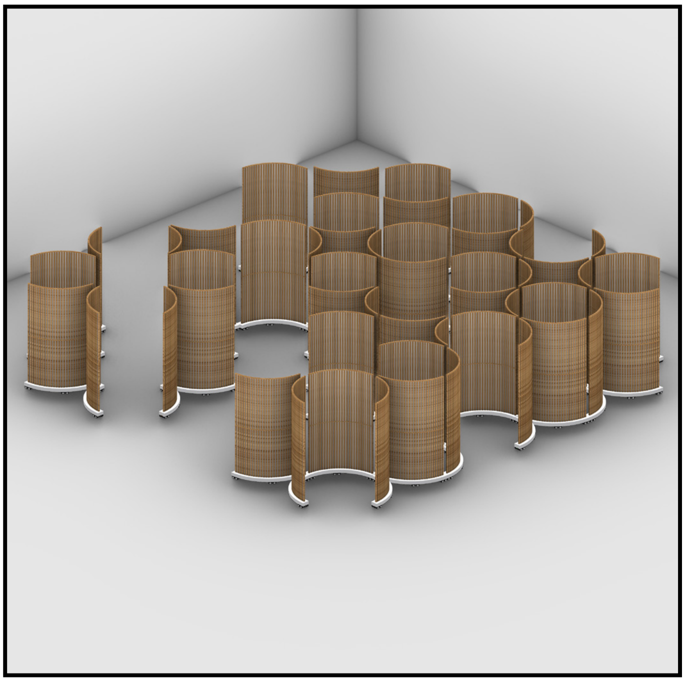


Figure 198. S10 in 3D space.

s10 = [1, 1, 3, 3, 3, 3, 1, 1, 1, 1, 1, 1, 1, 1, 3, 1, 1, 1, 1, 3, 3, 3, 1, 1, 1, 1, 3, 3, 3, 3]

6.1. Pros and Cons of this Approach:

This approach is again fully automatic and can create non-symmetrical and unique spaces, however since there is randomness in the behavior of robots, it might create small corners, closed paths, and a not an ideal layout.

Rule 1 and Rule 2 worked well together, whereas Rule 3 caused a lot of dead ends and full circles.
When only one rule was used in the entire sequence rule 1 and rule 3 could create practical layouts.

Pros

Customizable Layouts:
The method allows for a higher degree of customization through the use of local rules and sequences, enabling the creation of unique and varied spatial configurations.

Flexibility in Design:
The ability to change rules and sequences allows for flexible design iterations, making it easy to explore multiple layout options and adjust them based on specific needs or preferences.

Decentralized Control Benefits:
Similar to the other decentralized method, this approach benefits from increased resilience, as robots can operate semi-independently, reducing the impact of any single point of failure.

Potential for Innovation:
The complexity and variability inherent in this method can lead to innovative design solutions that may not be achievable through more traditional, centralized approaches.

Cons

Unpredictable Outcomes:
The reliance on local rules and sequences can lead to unpredictable outcomes, with some configurations potentially resulting in impractical or inefficient use of space.

Complex Setup and Management:
Defining and managing the rules and sequences can be complex and time-consuming, requiring a deep understanding of the spatial relationships and desired outcomes.

Risk of non Optimal Layouts:
There is a risk that the resulting layouts may not always be optimal, as the method depends on the defined rules and sequences working well with space organization.

Coordination Challenges:
Ensuring that robots follow the rules and sequences correctly can be challenging, particularly in larger or more complex zones, potentially leading to issues with coordination and overlap.

Computational Intensity:
The method may require significant computational resources to calculate spatial adjacency, manage rules, and execute sequences, especially as the number of robots and complexity of the grid increase.

Variability in Design Quality:
The quality of the resulting layouts can vary widely depending on the rules and sequences used, potentially leading to inconsistent design quality and the need for multiple iterations to achieve the desired outcome.

Difficulty in Achieving Symmetry or Attunement to the Context:
While the rules aim to incorporate symmetry, achieving consistent and aesthetically pleasing symmetrical layouts or layout that specifically fit within the conditions of the context can be difficult, particularly if the sequences are not well-defined or if the robots struggle to adhere to the rules.

C. Conclusion

This chapter started by providing a framework for understanding the design of spatial flexibility in real buildings. To do so, few case studies were selected, each exemplifying high degrees of flexibility in order to fulfill the design requirements. Two of the case studies were innovation hubs, two were educational buildings, and one was a cultural hub/ theatre. After defining the spatial qualities of innovation hubs and the design strategies used in them, all five buildings were studied in detail and their common programs which usually had to have the most spatial flexibility due to their nature, like lack of need for fixed furniture or technical equipment were identified and summarized.

Out of those programs, spaces were selected which in an architectural project can probably be built by a swarm of robots. These are: lobby, cafe, agora, co-working, workshop, and exhibition.

The case study analysis, then was combined with space syntax techniques, to set up the initial state of the design experiment, analyze and validate its accuracy. The implementation of space syntax provided valuable insights into spatial relationships and user movement, for creation of optimal configurations for different activities. The use of convex space partitioning and axial mapping enabled a detailed understanding of space connectivity and integration, essential for designing user-friendly environments.

The simulation for spatial configuration by swarm robots was set up on python using Matplotlib library animation and Pygame. To program the swarm behavior of robots one method with centralized control and two methods with de-centralized control system were used and pros and cons of each method were discussed in detail.
The centralized method offered precise and predictable layouts but lacked dynamic flexibility and scalability. In contrast, the de-centralized methods, particularly those utilizing local rules and sequences, demonstrated greater adaptability and potential for novel and dynamic spatial configuration, though they posed challenges in coordination and computational load and also with regards to the unpredictability of their outcome.

In summary, this chapter integrated theoretical insights and simulation experimentation to develop a robust methodology for designing flexible and dynamic architectural layouts by a swarm of robots. The findings were tested and compared against each other in order to understand to what degrees the results were valid and what can the future direction of similar research be.

IV

Conclusion

This thesis started by noting problems related to spatial inflexibility in architectural layouts, and the challenges they pose on user preferences and the ongoing need for change in architecture. Various issues related to the constraints of inflexibility in architecture with regards to space utilization, energy efficiency, high refurbishment and renovation costs, and integration of new technology were discussed in chapter 1. Then, the potential of swarm robots in making flexible spatial design was discussed and their collaborative nature which can increase dynamic design flexibility in architecture was mentioned. The objective of this thesis was then introduced as "Utilizing swarm robotics for spatial flexiblilty in architectural design", and the research questions that this thesis aimed to answer were:

1- What are the key design parameters to achieve spatial flexibility in architectural layout design?

2- What are the most optimal strategies and technological frameworks to efficiently integrate swarm robotics into architectural workflows, which allows for the creation of autonomous layouts that continuously respond to user preferences and evolving spatial requirements?

3- What are the necessary steps to prototype a sample scenario of a robotic swarm configuring a flexible architectural layout?

In the second chapter and the beginning section of the third chapter (Methodology), the answer to the first question was thoroughly discussed. Some of the strategies to achieve spatial flexibility in architecture which were shown in chapter 2 (Literature Review), were the use of operational elements, modular systems, arrangement of spaces, and erasing of programs. The methodology chapter with this project's particular design of robots in fact, used the same strategy of creating the robots as similar building modules which can dynamically move around and perform similar to how operational elements in literature have been performing. Their dynamic nature and movement to design spaces, can eventually lead to the erasing of programs in a space, and also to updating to new functions and needs every time.
In the studied projects in chapter three, one of the main strategies to achieve flexibility in architecture was the use of open plans which are also transparent and again polyvalent. This was also achieved within the dynamic design and nature of the swarm robots creating dynamic architectural layouts.

In the third chapter, in addition to the information gained from strategies to achieve architectural flexibility and the most flexible rooms/ spaces (often called programs in this study), the space syntax method was used to better understand the possible relationships between the spaces through various values, convex mapping, and justified graphs shown in chapter three.

Moreover, the selection of a circular grid for the creation of curvilinear spaces and the design of robots as quarter circle arcs was justified.

The rest of the experiment, for the purpose of better simulation was done on Python and different methods with centralized and de-centralized control systems were used to see which ones can create better architectural layouts. Here, the second research question was answered, which can be explained as follows:
The most optimal strategies to efficiently integrate swarm robots into the creation of dynamic architectural layouts have to involve a hybrid control system where the architect can design a desired layout on an already established grid in a pre-defined boundary with taking into account the existing space limitations, and then the robots should be able to build that design, and they can change it dynamically as occupancy increases.
The ideal method therefore, can not be fully autonomous considering the confinements of architecture.

The third question of this thesis, which considers prototyping a sample scenario of swarm robots building the architectural layout, could not be achieved in reality due to time limitations of the Graduation Studio. Moreover, due to cost efficiency, simulation on Pyhton was deemed a better solution.

Lastly, to sum up, this thesis aimed to illustrate a higher potential of the use of robotics in architecture than what is currently being used in the industry. With more autonoumous robots, architecture can solve many issued related to the inflexibility of architectural floor plans.

V

Discussion

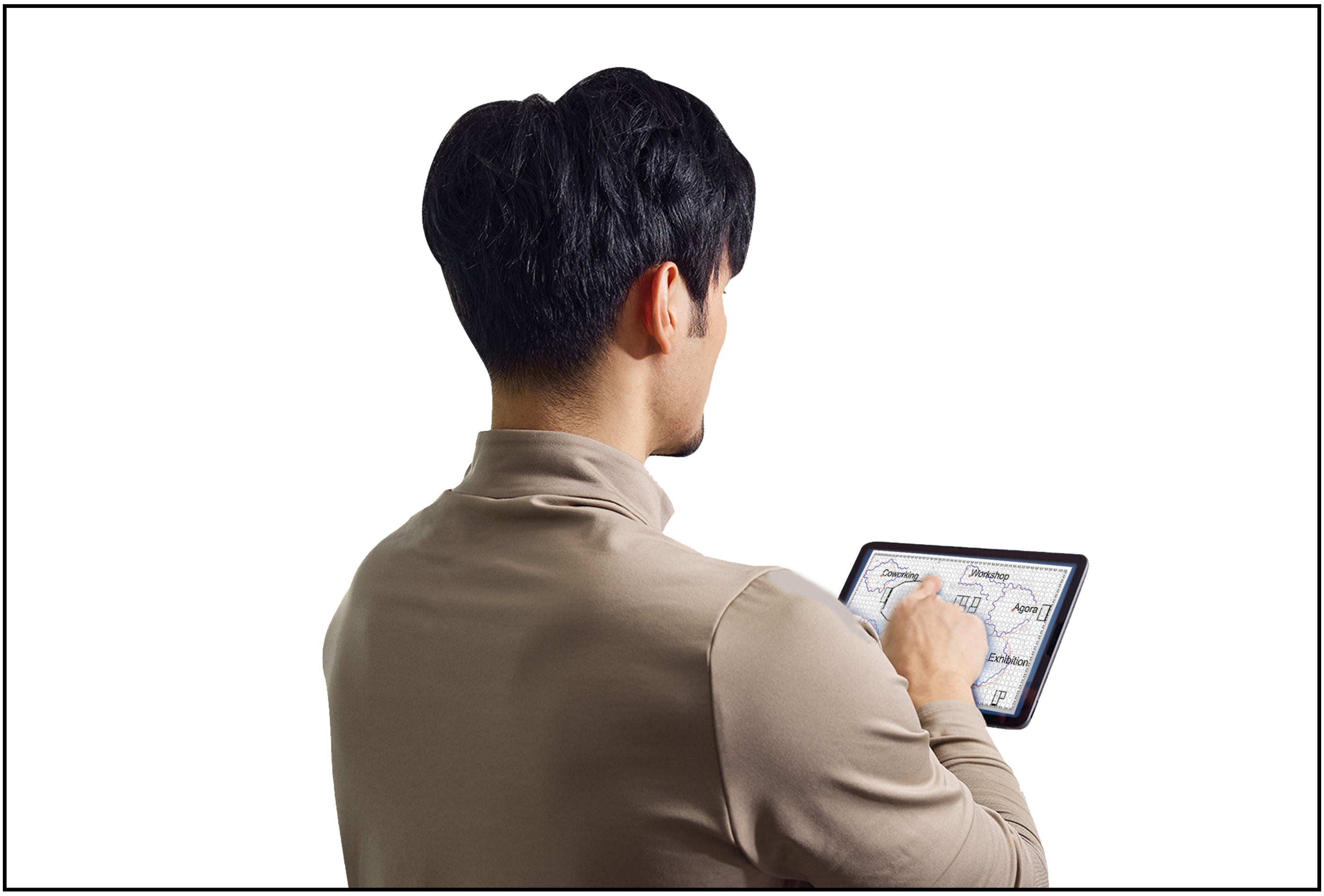
The idea of using swarm robots to increase architectural flexibility, in its nature is a vast realm of possibilities still not recognized in the industry. This thesis aimed to explore some of the very first possible usages of swarm robots to create flexible spatial configurations in architecture. The lack of similar typologies in the existing literature made the discovery of many new and unfolded aspects of every step, more difficult for this research, which of course otherwise would have affected the advancing of this thesis much smoother and probably yielded more precise and defined outcomes, had more similar research existed in literature.

In order to better design a workflow, which could enhance the performance of robots and render their behavior as close to the reality as possible, more knowledge of computer science and to a higher degree of robotics, would definitely help in the process. Therefore, in reality, in an actual architectural project, architects and computer scientists must definitely work together to achieve the most optimal results.

Although, this research attempted to define a new path for this novel topic in architecture, and was able to achieve and offer a fair understanding of the possible directions that using swarm robots as building blocks in architecture can take, there are still many aspects that could be considered to enhance the end product of such a research. Examples include the design of a dynamic interface where architects or users can draw the desired plans, or imagine a mock-up model of a central system which could control everything at the same time, or actively measure the impact this approach and usage of swarm robots has on the environment, and whether it has reduced this impact as was assumed in the process of this research.

Hence, some suggestions, for future research would be:
1- Prototyping a team of robots who dynamically build the spaces we design or instruct them to build.
2- Developing a user interface to make the use of the system easy and accessible for users.
3- To study the environmental impact of using such robots in designing for architectural flexibility.
4- To study how this system could be improved to help people with limited mobility.
5- Enhancing the accuracy of robotic behavior simulations in architecture to closely match real-world scenarios, by using advanced algorithms and machine learning techniques.
6- Establishing more frameworks for effective collaboration between architects, roboticists, and computer scientists.
7- To study the impact of the presence of swarm robots on human interaction with and perception of the flexible architectural spaces.
8- To study the methods for long term maintenance an reliability of such systems.

Figure 199. Render showing one possible spatial arrangement by swarm robots.



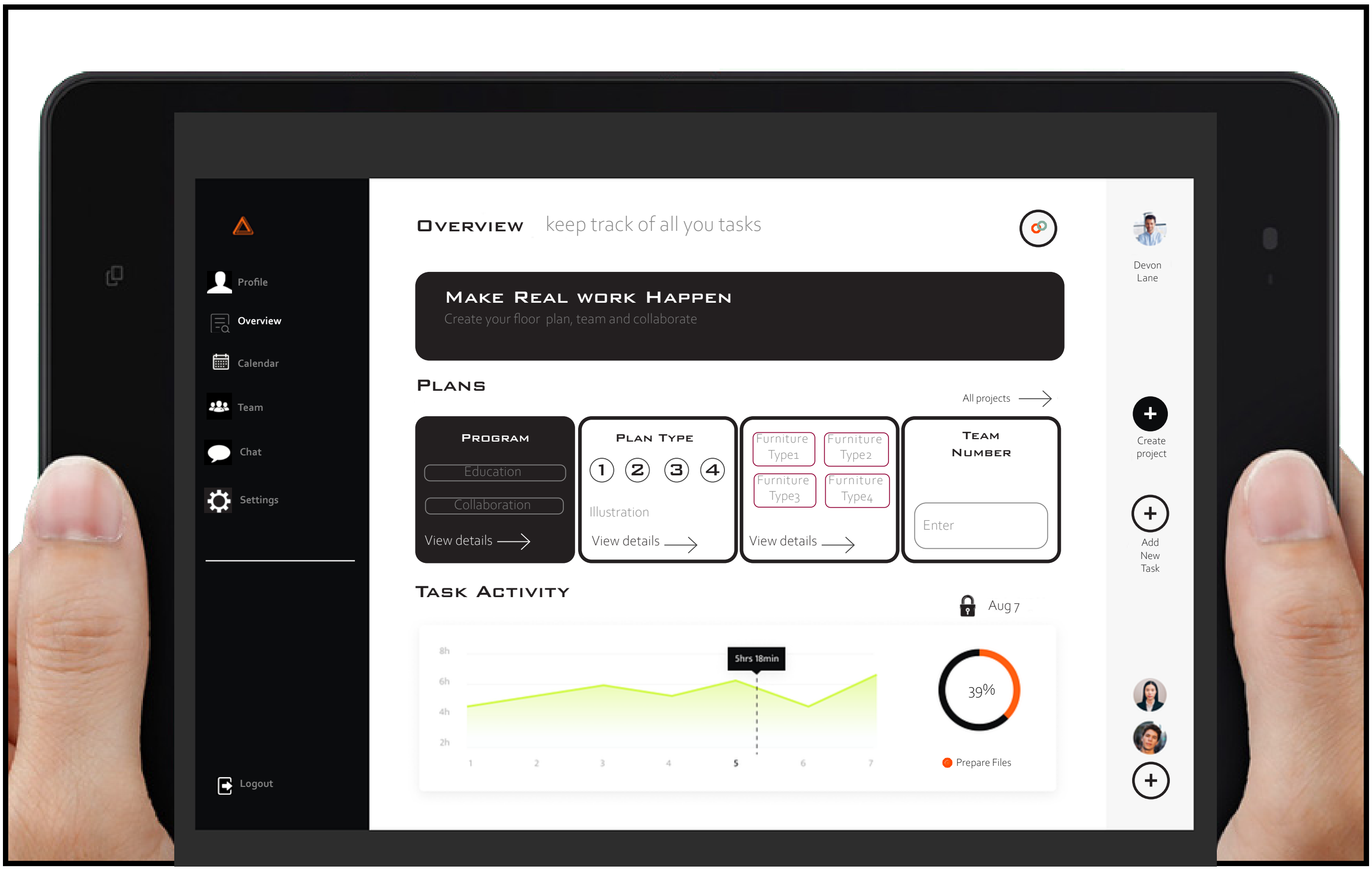
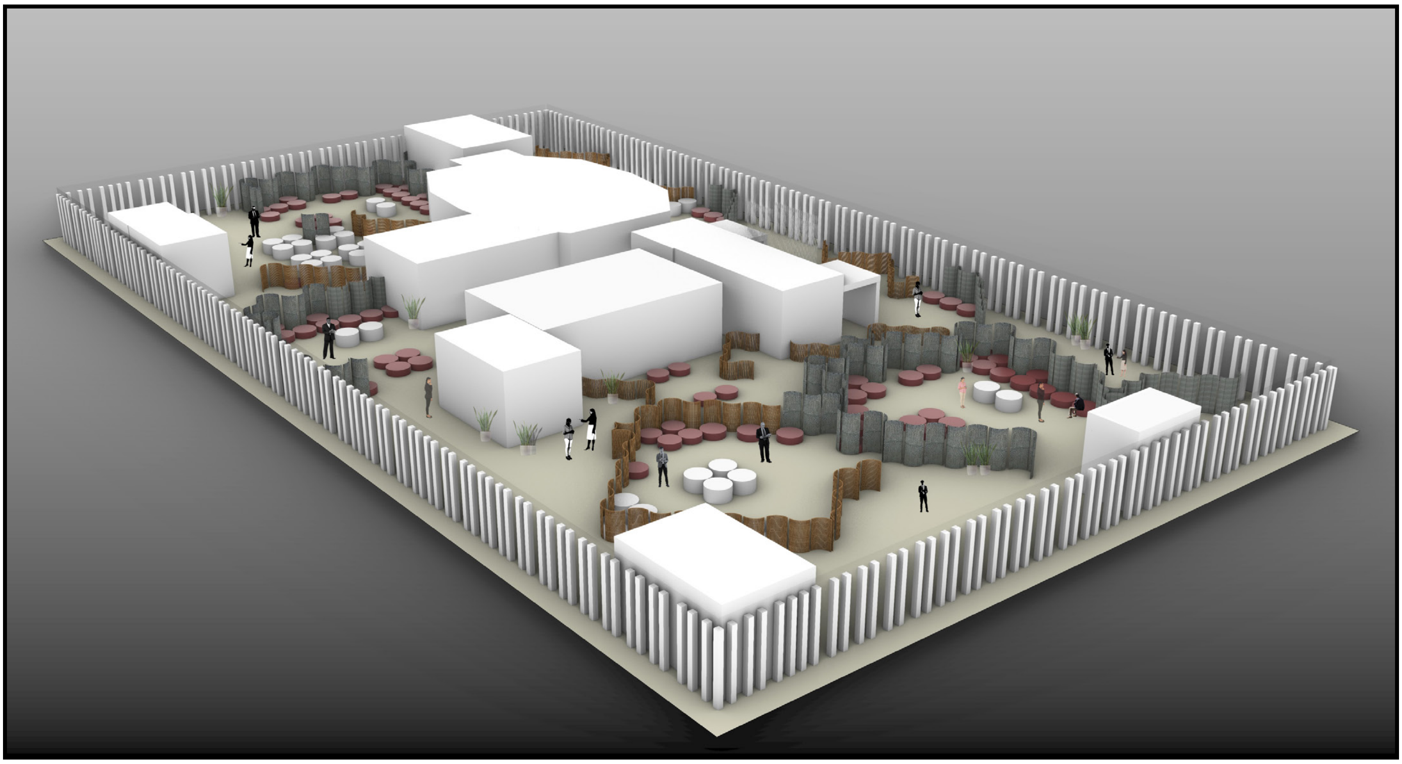


Figure 200, 201. Future implications of this research can be programmed and used on digital interfaces like tablets and mobile phones. The user can select between floor plan options or furniture layout designed by the architect which are based on user needs.



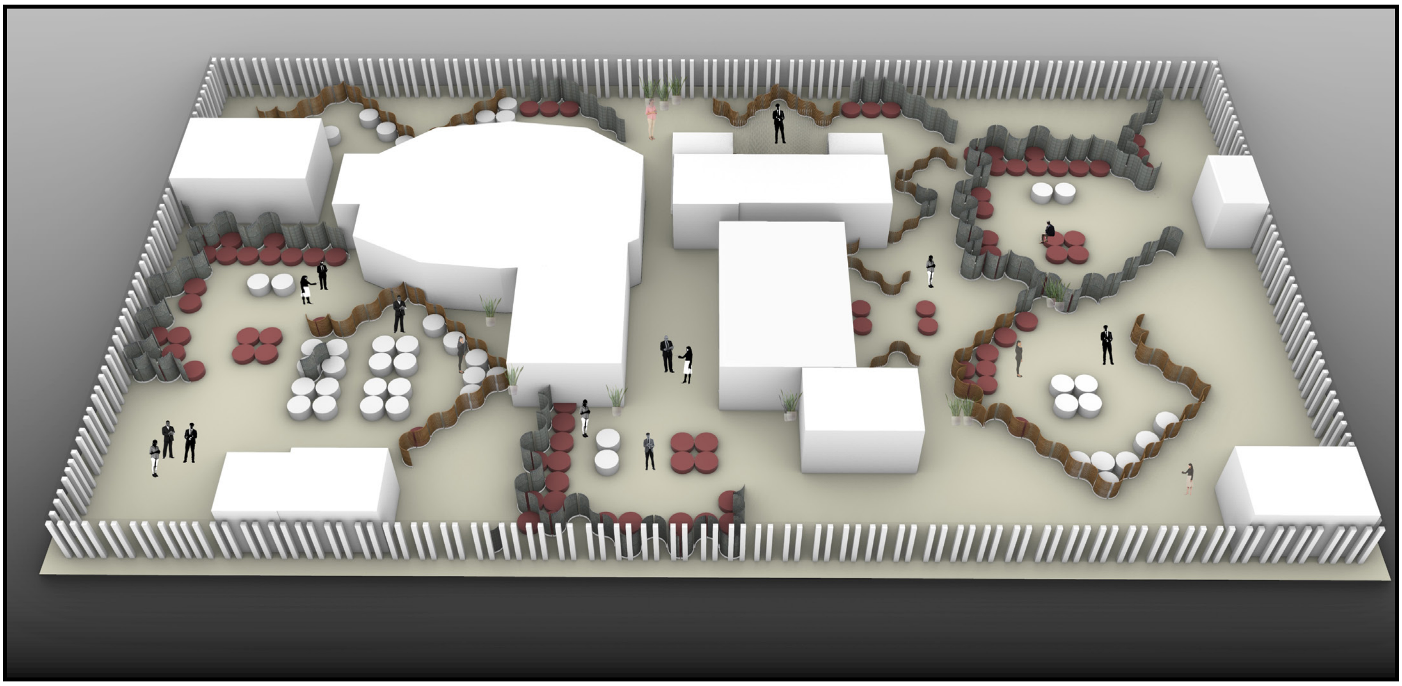
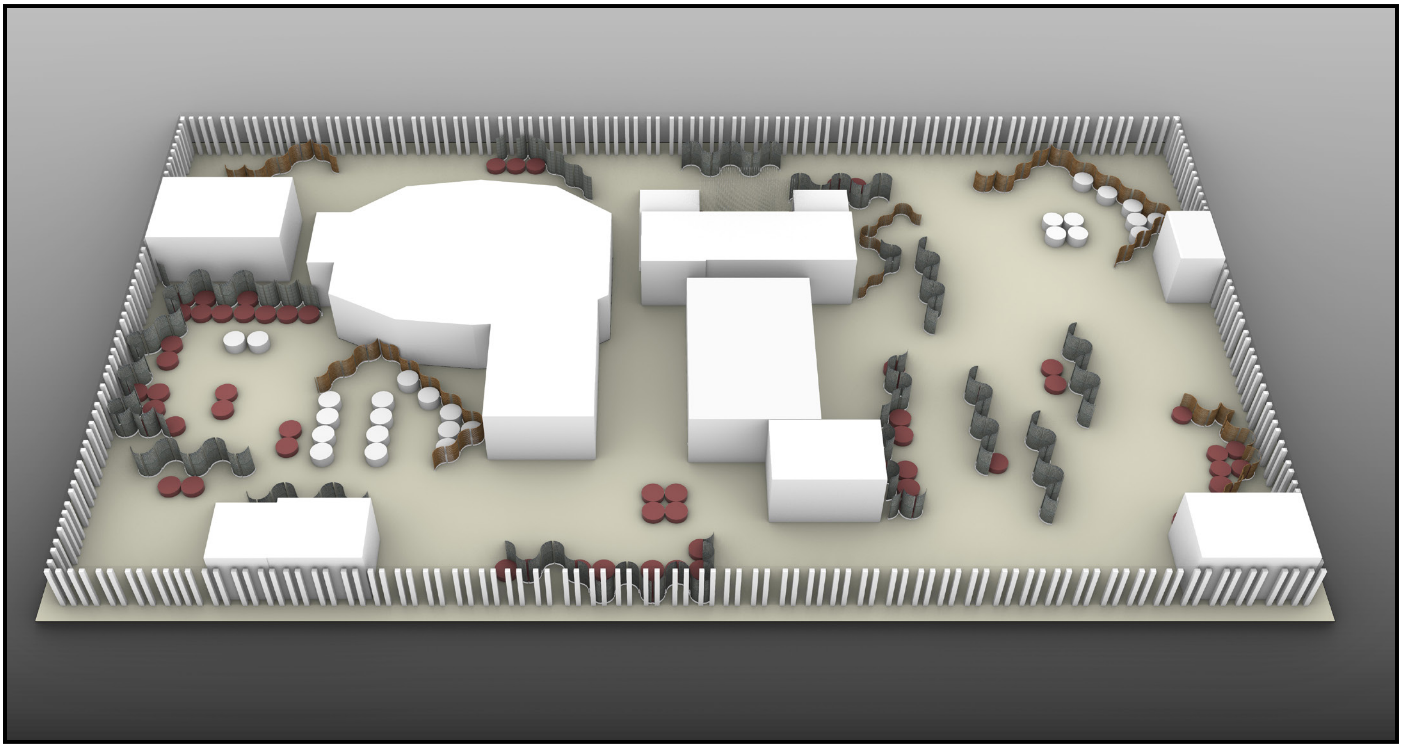


Figure 202, 203. A sample spatial arrangement with the swarm panels in the Amare Ground Floor. Images are own work.



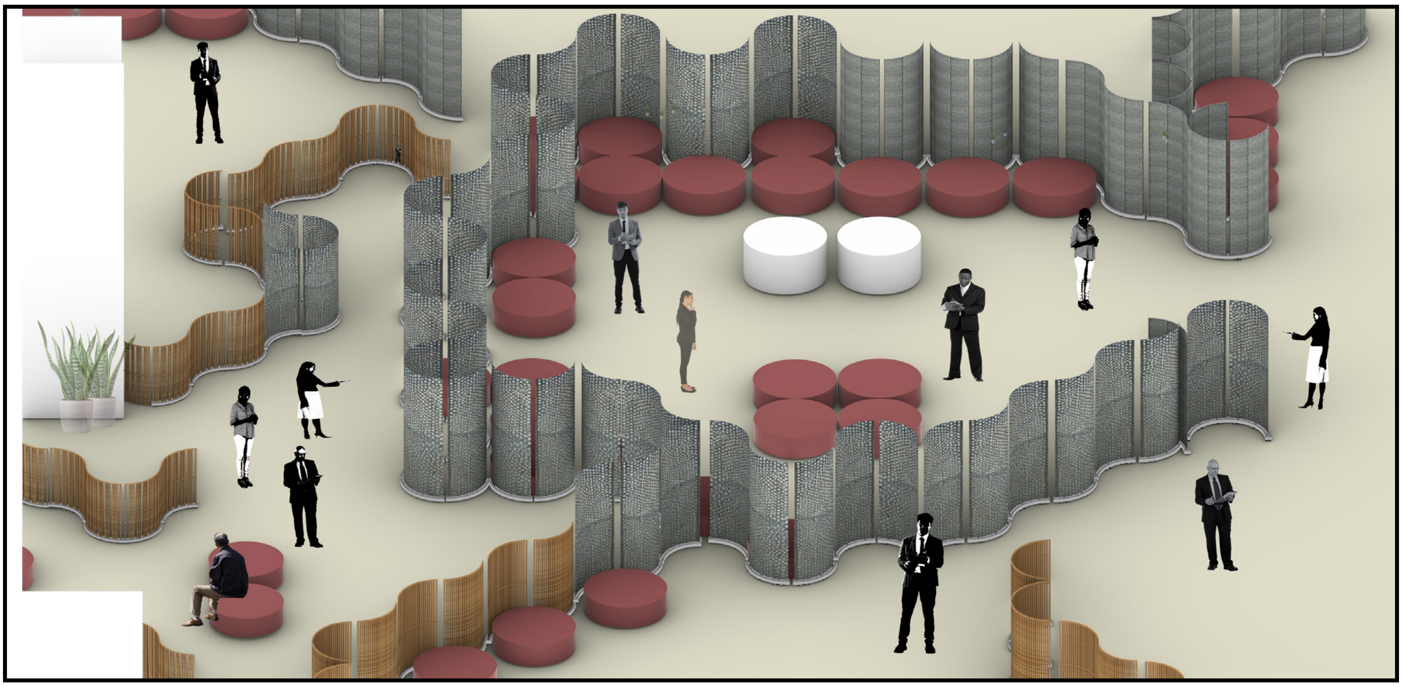


Figure 204, 205. A sample spatial arrangement with the swarm panels in the Amare Ground Floor. Images are own work.

Figure 206, 207. Future design and material of the swarm robots' panels which act as wall systems can be adjusted based on various needs and performance requirements, like acoustic panels, panles for certain lighting and ventilation conditons or climatic control. Images are own work produced using DALL-E.

VI Reflection

This thesis began with noticing the need for more flexible architectural layouts that can better meet the user's needs and enhance their spatial experience. The issues that arise from rigid architectural layouts leave little chance for quick upgrades and pose limitations on user comfort. This becomes very important, particularly for people with restricted physical mobility. Many of them experience psychological regression, and mental, cognitive, and emotional decline in environments that remain constantly the same.

On the other hand, the architectural industry has lagged behind others when it comes to using various robot types for building. Robots to this day have been only used as fabricators for 3D printing or pick and place or building assembly. However, robots can be smart and programmed to perform a wide range of tasks automatically. This makes them a good candidate to create environments that need to be able to change. To use the potential of robots to create flexible architectural layouts, this thesis in particular focused on using swarm robots that act as building blocks that can be installed, dismantled, updated, refurbished, and partially recycled. The use of wood and shoji paper for making 90% of the robot block panels, adds value to the design for circularity purposes. This, in addition to the fact that there will be no need for heavy construction, building destruction, and renovation can potentially reduce carbon footprint and the environmental impact of the design in the building industry to a large degree. The creation of architectural layouts with fully or partially automated robot teams like swarm robots, can solve the problem of inflexibility and its influence on the well-being of users. By providing the user with a layout generation map, the user can select between design options for their specific needs of the time and the robot teams can build up that space for them automatically from that point on. The social impact of this thesis is, related to its consideration of:

1-User well-being
2-Circularity of the design
3- Reducing environmental impact

The challenges of this study mainly came from its innovative nature which meant the lack of any similar research in the field of architecture. The problem of pattern formation with a swarm of robots is still a hot topic in the field of robotics and it majorly has yielded the forming of simple graphical or geometrical patterns, line formation, and clustering. The swarm robot types that have been used in the literature are all small circular robots that act like points in a space which makes building different shapes with them a lot easier. In addition to the challenge of changing the design of the swarm to fit into the creation of practical architectural layouts, a multitude of other challenges like considerations about the area, spatial adjacency, spatial relationship, circulation and flow of space users, the timing of task initiation, the transition states between each new robot state and task, task division, the degree of local and global knowledge of each robot, space navigation, and navigation system had to be taken care of.

The current study, analyzed different existing methods to create flexibility in architecture and tried to implement them in the methodology process. As explained in the previous chapters, the outcome of the experiments suggests that using a fully autonomous swarm robotic system in architecture to build various spatial configuration is neither ideal nor efficient. Therefore, use of a hybrid system with some degree of human control is suggested to achieve more optimal outcomes.

This study, was able to setup and run simulations for possible architectural layout configurations by the designed swarm robots, on Python, on an abstract level. However, the research aims to now contextualize the findings of the previous steps in real life scenarios, which will be the focus of this thesis from p4 to p5.
The process will start by giving an architectural plan to multiple architects and ask them to draw hand sketches of their desired spatial configuration within the given floorplan. The floorplan, is then given to the algorithm which programs the robots to build that particular configuration automatically everytime without the need to change the setup for each drawing.

VII

References

-Adnan, F., & Yunus, R. M. (2012). The influence of curvilinear architectural forms on Environment-Behaviour. Procedia: Social & Behavioral Sciences, 49, 341–349. https://doi.org/10.1016/j.sbspro.2012.07.032

-Alexander, C., Ishikawa, S., Silverstein, M., Jacobson, M., Fiksdahl-King, I., & Angel, S. (1977). A Pattern Language. Oxford University Press.

-Askar, R., Bragança, L., & Gervásio, H. (2021). Adaptability of Buildings: A critical review on the concept evolution. Applied Sciences, 11(10), 4483. https://doi.org/10.3390/app11104483

-Banerjee, Priyom & Goel, Manika. (2023). Flexible architecture: rethinking the indoor built environment. Urbanism. Architecture. Constructions. 14. 183-192.

-Bollnow, Otto F. 2011 [1963]. Human space. Tr. by G. Shuttleworth, ed. By J. Kohlmaier. London: Hyphen Press.

-Bognar, B. (1985). A phenomenological approach to architecture and its teaching in the design studio. In: Seamon, D., Mugerauer, R. (eds) Dwelling, Place and Environment. Springer, Dordrecht.

-Bonabeau, E.; Dorigo, M.; Theraulaz, G.; Theraulaz, G. Swarm Intelligence: From Natural to Artificial Systems; Oxford University Press: New York, NY, USA, 1999.

-Bowley, S.J.; Merrick, K. A 'Breadcrumbs' Model for Controlling an Intrinsically Motivated Swarm Using a Handheld Device. In Proceedings of the AI 2017: Advances in Artificial Intelligence, Melbourne, Australia, 19–20 August 2017; pp. 157–168.;

-Calderón-Arce, C., Brenes-Torres, J. C., & Solis-Ortega, R. (2022). Swarm Robotics: Simulators, Platforms and Applications review. Computation (Basel), 10(6), 80. https://doi.org/10.3390/computation10060080

-Colomina, B. & Wigley, M., 2018. are we human? notes on an archaeology of design. Zürich: Lars Müller Publishers.

-Corbusier L. (1923), Vers une Architecture, G. Crès publisher, Paris, France

-Coppola, M. (2021). Automatic Design of Verifiable Robot Swarms. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:b6ad7ddd-c660-4aab-8277-65f7a22a4a52

-Dawes, M., & Ostwald, M. J. (2013). Precise Locations in Space: An Alternative Approach to Space Syntax Analysis using Intersection Points. Architecture Research, 3(1), 1–11. http://article.sapub.org/pdf/10.5923.j.arch.20130301.01.pdf

-De Paris, S. R., & Lopes, C. N. L. (2018). Housing flexibility problem: Review of recent limitations and solutions. Frontiers of Architectural Research, 7(1), 80–91. https://doi.org/10.1016/j.foar.2017.11.004

-Dias, P. G. F., Silva, M. C., Filho, G. P. R., Vargas, P. A., Cota, L. P., & Pessin, G. (2021). Swarm Robotics: A perspective on the latest reviewed concepts and applications. Sensors, 21(6), 2062. https://doi.org/10.3390/s21062062

-Dorigo, M.; Birattari, M.; Stutzle, T. Ant colony optimization. IEEE Comput. Intell. Mag. 2006, 1, 28–39.

-Dutta, T., Bhattacharyya, S., Dey, S., & Platoš, J. (2020). Border Collie optimization. IEEE Access, 8, 109177–109197. https://doi.org/10.1109/access.2020.2999540

-Eberhard, John P. 2009. Brain landscape: the coexistence of neuroscience and architecture. New York, NY: Oxford University

-Elmoghazy, Z. (2014). Neo-Organic Architecture: The latest trend in Architecture. ResearchGate. https://www.researchgate.net/publication/299281607_Neo-Organic_Architecture_The_latest_trend_in_Architecture

-Estaji, H. (2017). A review of flexibility and adaptability in housing design. International Journal of Contemporary Architecture, 4(2), 37-49.

-FarokhiFirouzi, H. (2019). A REVIEW ON FLEXIBILITY IN ARCHITECTURAL DESIGN. 9 International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 10(6).

-Faste, R.A. (1987). Perceiving Needs. Technical report. Washington, DC: Society of Automotive Engineers.

-Forty, Adrian.(2000) Words and Buildings: A Vocabulary of Modern Architecture. New York, NY: Thames & Hudson Inc

-Fujisawa, R.; Dobata, S.; Sugawara, K.; Matsuno, F. Designing pheromone communication in swarm robotics: Group foraging behavior mediated by chemical substance. Swarm Intell. 2014, 8, 227–246.

-Groák, Steven, The idea of building: thought and action in the design and production of buildings. 1992: E & FN Spon, London

-Goldhagen, S. and Lagault, R .(2000). Anxious Modernisms. Cambridge, MA: The MIT Press

-Gong, D.; Lu, L.; Li, M. Robot path planning in uncertain environments based on particle swarm optimization. In Proceedings of the 2009 IEEE Congress on Evolutionary Computation, Trondheim, Norway, 18–21 May 2009; pp. 2127–2134.

-Gordon-Spears, D. ,Spears, W. "Analysis of a PhaseTransition in a Physics-Based Multiagent System", LNCS 2699, October 2002.

-Gosling, J.; Sassi, P.; Naim, M.; Lark, R. Adaptable Buildings: A Systems Approach. Sustain. Cities Soc. 2013, 7, 44–51.

-Heidegger, M. (1977). The question concerning technology, and other essays. https://ci.nii.ac.jp/ncid/BB27055321xx

-Hertzberger, H. 1991. Lessons for students in architecture. Rotterdam: Uitgeveri 010, 134p

-Hillier, B., & Hanson, J. (1989). The social logic of space. Cambridge University Press.

-Holl Steven, 1996, Intertwining, Princeton Architectural Press, New York

-Hosseini, S.M.; Mohammadi, M.; Rosemann, A.; Schröder, T.; Lichtenberg, J. A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review. Build. Environ. 2019, 153, 186–204.

-Holubchak, K., Sleptsov, O., & Томлінс, P. (2020). Architectural and City-Planning aspects of innovation hubs formation in the context of creative urban regeneration (On the case of Ukrainian cities). IOP Conference Series: Materials Science and Engineering, 907(1), 012014. https://doi.org/10.1088/1757-899x/907/1/012014

-Iocchi, L.; Nardi, D.; Salerno, M.D. Reactivity and Deliberation: A Survey on Multi-Robot Systems. In Workshop on Balancing Reactivity and Social Deliberation in Multi-Agent Systems; Springer: Berlin/Heidelberg, Germany, 2001; pp. 9–32

-Karaboga, D.; Basturk, B. A powerful and efficient algorithm for numeric function optimization: Artificial Bee Colony (ABC) algorithm. J. Glob. Optim. 2007, 39, 459–471.

-Karimi, K. (2023). The Configurational Structures of Social Spaces: space Syntax and urban Morphology in the context of Analytical, Evidence-Based Design. Land, 12(11), 2084. https://doi.org/10.3390/land12112084

-Kendall S. (2004), Open Building: A New Paradigm in Hospital Architecture, AIA Academy of Health Journal 7:34-44.

-Kendall, S.; Ando, M. Theory and Methods in Support of Adaptable Buildings. In Proceedings of the Action for Sustainability Conference, Tokyo, Japan, 27–29 September 2005; p. 4.

-Kennedy, J.; Eberhart, R. Particle swarm optimization. In Proceedings of the ICNN'95-International Conference on Neural Networks, Perth, WA, Australia, 27 November–1 December 1995; Volume 4, pp. 1942–1948

-Kim, H., Jun, C., Cho, Y., Kim, G., & Dept. of Geoinformatics, University of Seoul. (n.d.). INDOOR SPATIAL ANALYSIS USING SPACE SYNTAX. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B2. Beijing 2008. https://www.isprs.org/proceedings/XXXVII/congress/2_pdf/11_ThS-6/07.pdf

-Kim, Y. (2013). On flexibility in architecture focused on the contradiction in designing flexible space and its design proposition. Architectural Research, 15(4), 191–200. https://doi.org/10.5659/aikar.2013.15.4.191

-Kooi, Y. K. (2022). Adaptability and Flexibility in Architecture Concepts & Theories Applied in Residential Architecture to. . . ResearchGate. https://www.researchgate.net/publication/357866253_Adaptability_and_Flexibility_in_Architecture_Concepts_Theories_Applied_in_Residential_Architecture_to_Achieve_Adaptability

-Koolhaas, R. (1995). Last Apples. Koolhaas, R. and Mau, B."S, M, L, XL, OMA". The Monacelli Press, New York.

-Kronenburg, R. (2005). Flexible architecture: the cultural impact of responsive building. Open House International, 30(2), 59–65. https://doi.org/10.1108/ohi-02-2005-b0008

-Kroner, W.M. An intelligent and responsive architecture. Autom. Constr. 1997, 6, 381–393.

-Lai, J., Honda, T., & Yang, M. C. (2010). A study of the role of user-centered design methods in design team projects. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 24(3), 303–316. https://doi.org/10.1017/s0890060410000211

-Lee, J. H., Ostwald, M. J., & Kim, M. J. (2021). Characterizing smart environments as interactive and collective platforms: A review of the key behaviors of responsive architecture. Sensors, 21(10), 3417. https://doi.org/10.3390/s21103417

-Lefebvre, H. (1992). The production of space. Wiley-Blackwell.

-Liu, H. (2016). From Nicholas Negroponte to Al Bahar Tower: The development in theory and technology of responsive architecture. In CRC Press eBooks (pp. 161–164). https://doi.org/10.1201/b19880-28

-Mallgrave, Harry F. 2013. Architecture and embodiment: the implications of the new sciences and humanities for design. London and New York: Routledge.

-Manewa, A., Siriwardena, M., Ross, A., & Madanayake, U. (2016). Adaptable Buildings for Sustainable Built Environment. Built Environment Project and Asset Management, 6, 139–158.

-Meyboom, A.; Johnson, G.; Wojtowicz, J. Architectronics: Towards a Responsive Environment. Int. J. Archit. Comput. 2011, 9, 77–98.

-McKim, R.H. (1972). Experiences in Visual Thinking. Monterey, CA: Brooks Cole

-Middendorf, J. (2019). Curvilinear form in architecture. www.academia.edu. https://www.academia.edu/41436353/Curvilinear_Form_in_Architecture

Mustafa, F. A. (2010). Using space syntax analysis in detecting privacy: a comparative study of traditional and modern house layouts in Erbil city, Iraq. Asian Social Science, 6(8). https://doi.org/10.5539/ass.v6n8p157

-Na, S., Qiu, Y., Turgut, A. E., Ulrich, J., Krajník, T., Yue, S., Lennox, B., & Arvin, F. (2020). Bio-inspired artificial pheromone system for swarm robotics applications. Adaptive Behavior, 29(4), 395–415. https://doi.org/10.1177/1059712320918936

-Negroponte, N. Toward a Theory of Architecture Machines. J. Archit. Educ. 1969

-Negroponte, N. Soft Architecture Machines; MIT Press: Cambridge, MA, USA, 1975.

-Norman, D.A., & Draper, S.W., Eds. (1986). User Centered System Design. Hillsdale, NJ: Erlbaum

-Noyes, J., & Baber, C. (1999). User-Centred Design of Systems. Springer.London, UK.

-Nourian, P., Rezvani, S., & Sarıyıldız, S. (2013). Designing with Space Syntax. eCAADe Proceedings. https://doi.org/10.52842/conf.ecaade.2013.1.357

-Nuñez, M. M. P., & Parra-González, M. E. (2023). The importance of the educational space for the use of active methodologies. International Journal of Childhood Education, 4(1), 1–11. https://doi.org/10.33422/ijce.v4i1.338

-Othman, W. a. F. W. (2019). Pattern formation and organisation in robot swarms. Usm. https://www.academia.edu/39647887/Pattern_Formation_and_Organisation_in_Robot_Swarms

-Oungrinis, K.-A.; Liapi, M. Spatial Elements Imbued with Cognition: A possible step toward the "Architecture Machine". Int. J. Archit. Comput. 2014.

-Payton, D. W., Daily, M., Estowski, R., Howard, M. D., & Lee, C. (2001). Pheromone Robotics. Autonomous Robots, 11(3), 319–324. https://doi.org/10.1023/a:1012411712038
Websites:

-Pelsmakers, S., Poutanen, J., & Saarimaa, S. (2020). (Hybrid) architecture in and over time. In M. Pedersen Zari, P. Connolly & M. Southcombe (Eds.), Ecologies design: Transforming architecture, landscape and urbanism(pp. 268–275). Routledge. DOI: https://doi.org/10.4324/9780429279904-35

-Poli, R.; Kennedy, J.; Blackwell, T. Particle swarm optimization: An overview. Swarm Intell. 2007, 1, 33–57.

-Premier, A. Solar shading devices integrating smart materials: An overview of projects, prototypes and products for advanced façade design. Archit. Sci. Rev. 2019, 62, 455–465.

-Rabeneck, A. (2021). Housing adaptability: Some past lessons [Commentary]. Buildings & Cities. https://www.buildingsandcities.org/insights/commentaries/housing-adaptability-lessons.html

-Radford, Gero (1988). Design by Optimization, in Architecture, Building, and Construction. Van Nostrand Reinhold.

-Rajan, K.; Saffiotti, A. Towards a science of integrated AI and Robotics. Artif. Intell. 2017, 247, 1–9.

-Ramzy, N.; Fayed, H. Kinetic systems in architecture: New approach for environmental control systems and context-sensitive buildings. Sustain. Cities Soc. 2011.

-Rabeneck, A., David,S., and Peter, T.,(1973) Flexible(?) housing. Architectural Design, Nov., 698-732

-Reynolds, C. ,"Flocks, Herds and Schools: A Distributed Behavioral Model", Computer Graphics, vol 21, No. 4, pp. 22-34, 1987.

-Rogers, Richard.(1998) Cities for a small planet. Westview Press.

-Rossi, Aldo.(1982) The Architecture of the City. Cambridge, MA:The MIT Press

-Saffer, D.: Designing for Interaction. New Riders, Berkeley (2010)

-ŞahïN, E. (2005). Swarm robotics: from sources of inspiration to domains of application. In Lecture Notes in Computer Science (pp. 10–20). https://doi.org/10.1007/978-3-540-30552-1_2

-Sanders, E.B.-N. (1992). Converging perspectives: product development research for the 1990s. Design Management Journal 3(4), 49–54.
-Schmidt III, Robert, et al., What is the meaning ofAdaptability in the building industry? O&SB 2010,2010: p. 233.

-Schmidt III, R. & Austin, S. (2016). Adaptable Architecture. theory and practice. Routledge.

-Schuermann, M. (2014). Coworking space: A Potent Business Model for Plug 'n Play and Indie Workers. epubli GmbH.

-Schumacher, P. (2011). The Autopoiesis of Architecture. A new framework for architecture. ResearchGate. https://www.researchgate.net/publication/303990577_The_Autopoiesis_of_Architecture_A_new_framework_for_architecture

-Shahzad, M. M., Saeed, Z., Akhtar, A., Munawar, H., Yousaf, M. H., Baloach, N. K., & Hussain, F. (2023). A review of swarm robotics in a NutShell. Drones, 7(4), 269. https://doi.org/10.3390/drones7040269

-Slaughter, E.S. Design Strategies to Increase Building Flexibility. Build. Res. Inf. 2001, 29, 208–217.

-Spears, W., Gordon, D., "Using Artificial Physics to control agents", In: IEEE Intl. Conf on Information, Intelligence, pp. 281-288, 1999.

Türkler, L., Akkan, T., & Akkan, L. Ö. (2022). Usage of evolutionary algorithms in swarm robotics and design problems. Sensors, 22(12), 4437. https://doi.org/10.3390/s22124437

-Vaidis, M., & Otis, M. J. (2021). Swarm Robotic Interactions in an open and cluttered environment: a survey. Designs, 5(2), 37. https://doi.org/10.3390/designs5020037

-Van Nes, A. (2014). Space Syntax in theory and practice. In The Geojournal library (pp. 237–257). https://doi.org/10.1007/978-3-319-08299-8_15

-Zeng, X., Yu, Y., Yang, S., Lv, Y., & Sarker, N. I. (2022). Urban Resilience for Urban Sustainability: Concepts, dimensions, and Perspectives. Sustainability, 14(5), 2481. https://doi.org/10.3390/su14052481

-Interaction Design Foundation - IxDF. https://www.interaction-design.org/literature/topics/user-centered-design
-LoopNet. https://www.loopnet.com/Listing/1-Main-St-New-York-NY/9995556/
-Cornell Tech. https://tech.cornell.edu/news/tcs-cornell-tech-inaugurate-the-tata-innovation-center/
-Noahh.NL. https://noahh.nl/portfolio_page/amare-the-hague/
-Space Syntax. https://www.spacesyntax.online/