ENHANCING AUTONOMY ON CONSTRUCTION SITES THROUGH IMPLEMENTATION OF SWARM ROBOTICS AS AN ADAPTIVE MATERIAL-HANDLING LOGISTICS SYSTEM

BT Graduation Studio Master Thesis June 2024

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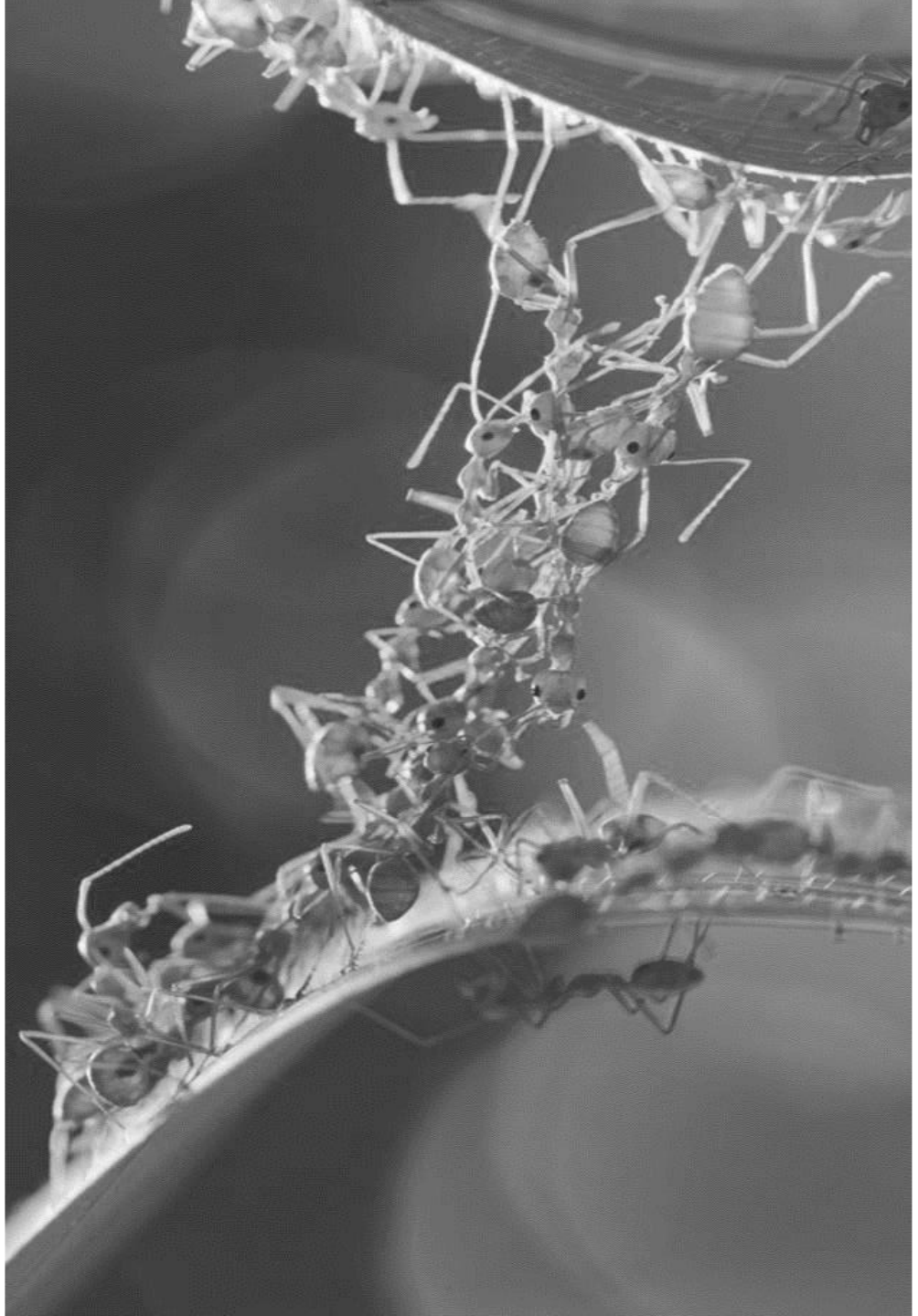
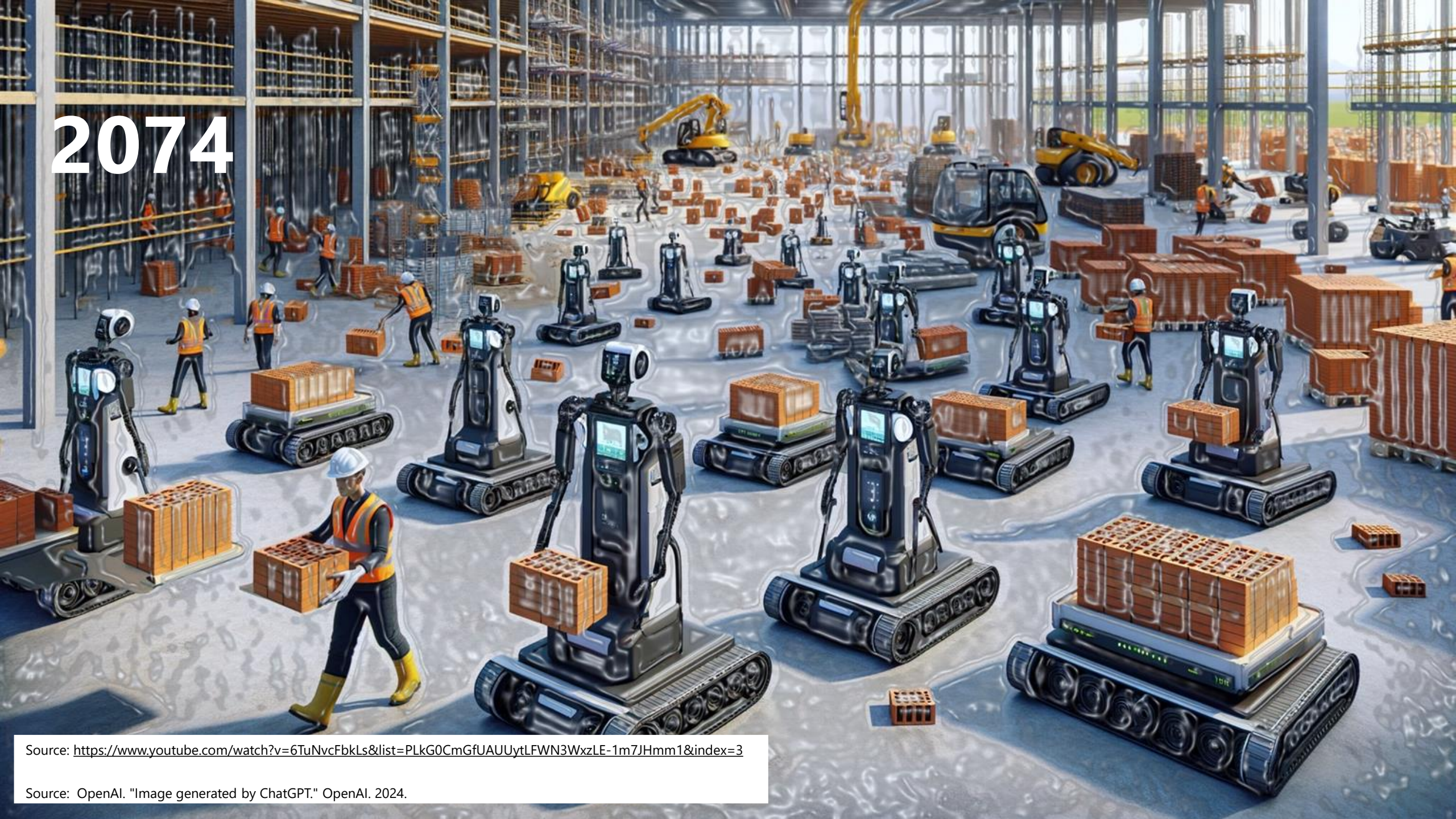
TU Delft

Source: OpenAI. "Image generated by ChatGPT." OpenAI. 2024.



CHAPTERS

1. Introduction
2. Literature Review
3. Implementation
4. Simulation
5. Experiments
6. Results
7. Conclusion
8. Discussion
9. Reflection



Source: https://www.youtube.com/watch?v=6TuNvcFbkLs&list=PLkG0CmGfUAUUytLFWN3WxzLE-1m7JHmm1&index=3

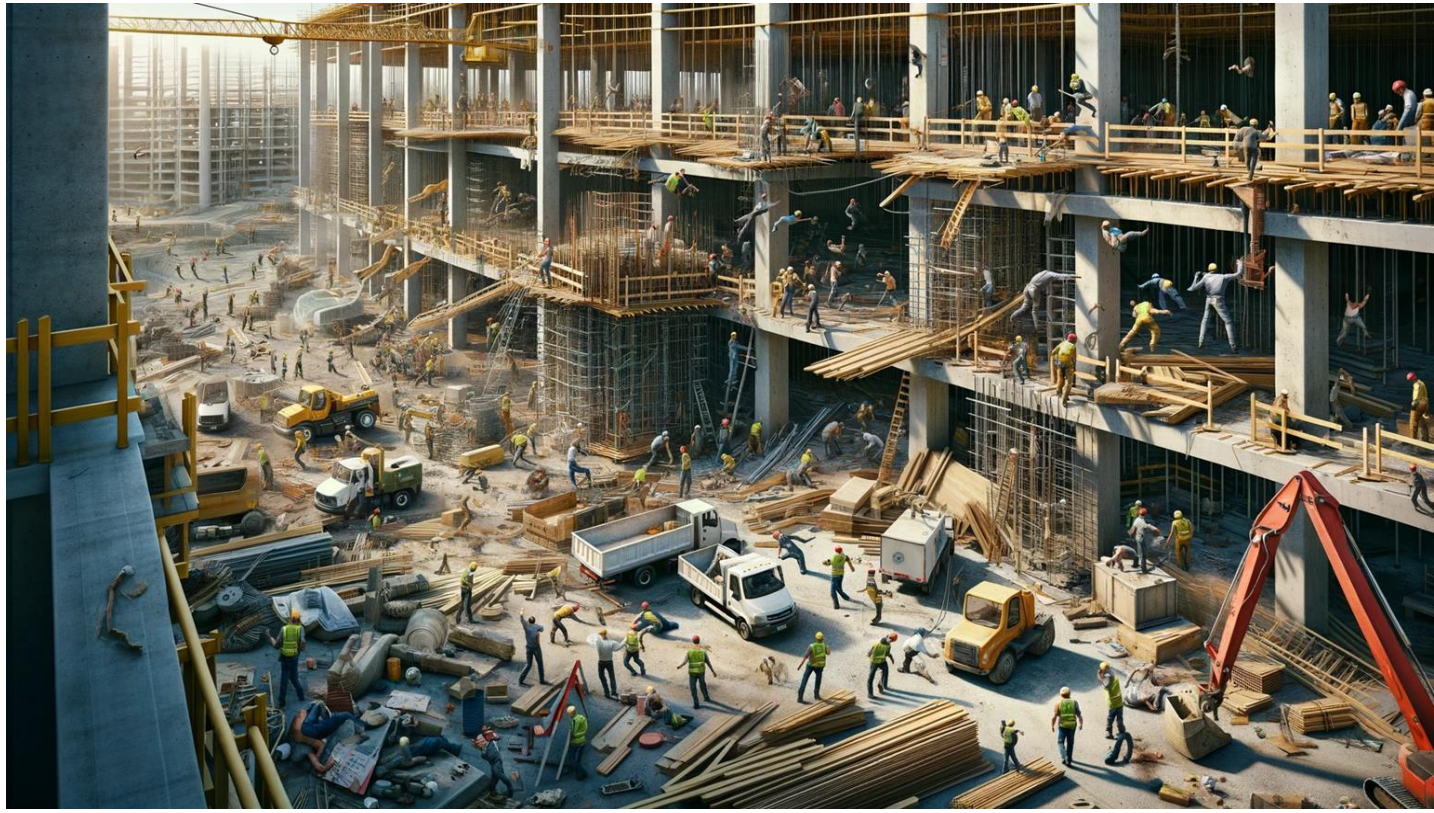
Source: OpenAI. "Image generated by ChatGPT." OpenAI. 2024.

Source: https://builtlogy.com/handling-and-storage-of-construction-materials-tips/

CONSTRUCTION INDUSTRY

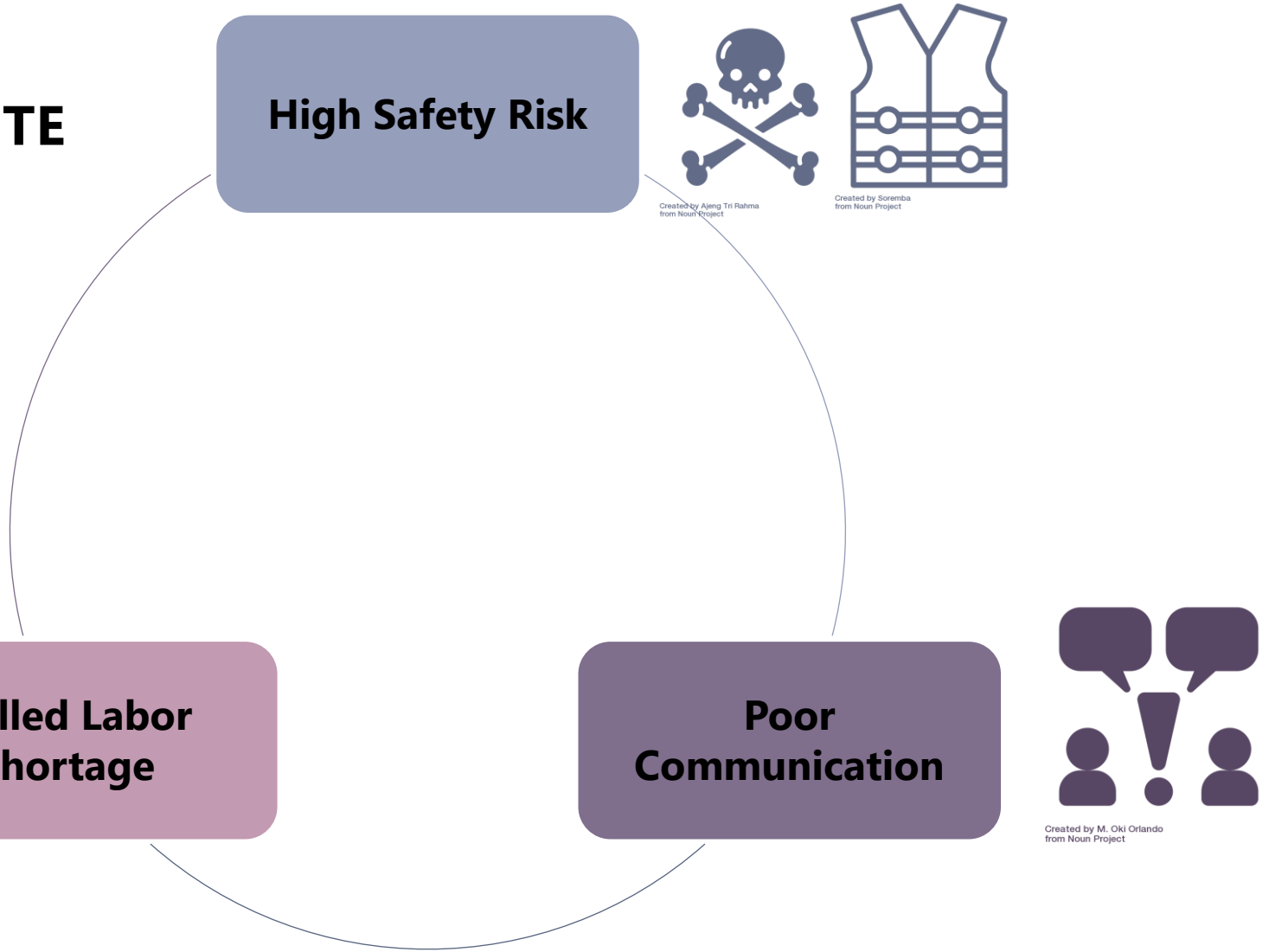
- **High dependency** of the construction industry on the human workforce

- Challenges related to their **presence** on the construction site.



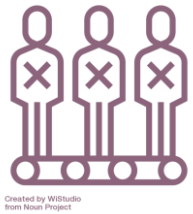
Source: OpenAI. "Image generated by ChatGPT." OpenAI. 2024.

LABOR-RELATED CONSTRUCTION SITE ISSUES



HOW TO TACKLE?

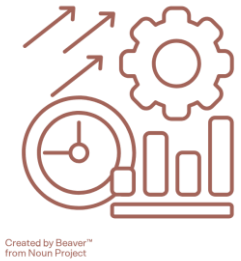
High Safety Risk



Labor Shortage

Efficiency

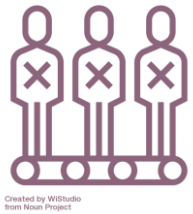
Productivity



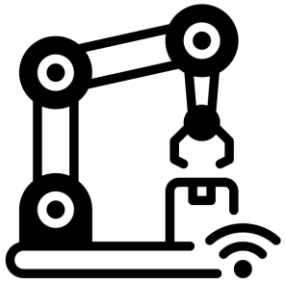
Poor Communication

HOW TO TACKLE?

High Safety Risk

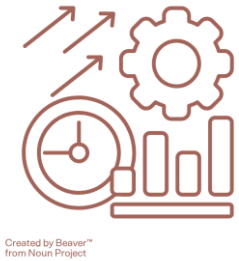


Labor Shortage



ROBOTIC CONSTRUCTION

Efficiency



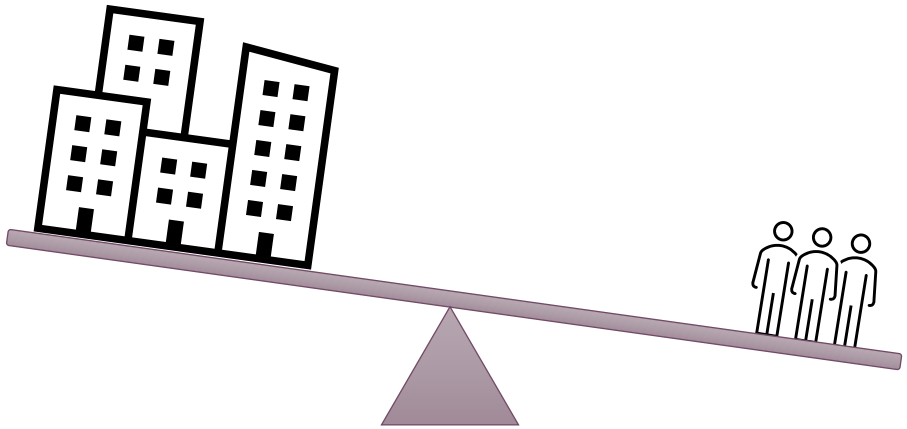
Productivity

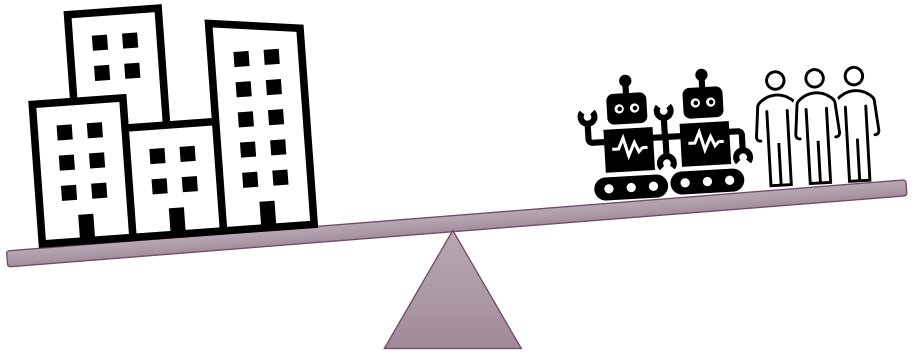
Poor Communication

LABOR-RELATED ISSUES SOLUTIONS

Skilled Labor Shortage

- Robots complement the human workforce
- Bring Back the balance to the industry

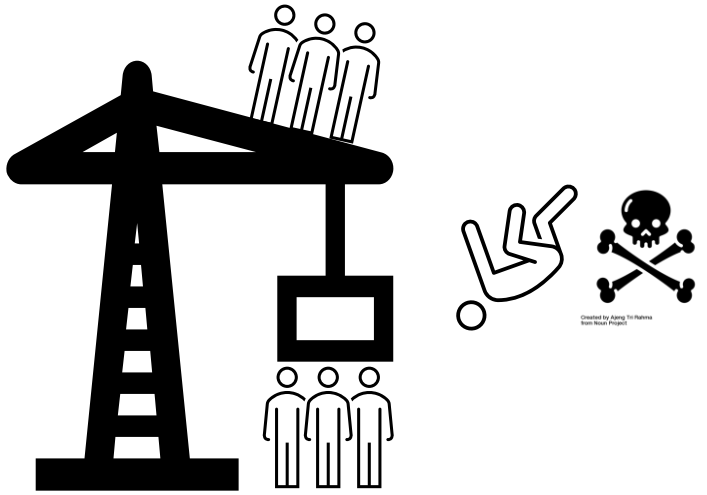


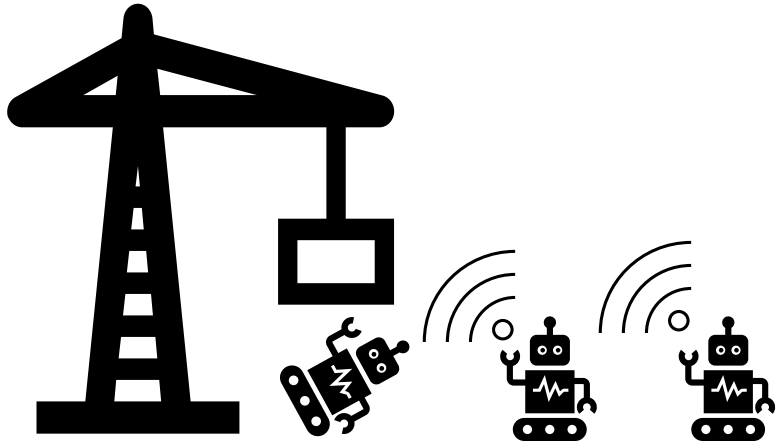


LABOR-RELATED ISSUES SOLUTIONS

High Safety Risks

- sharing tasks with robots
- workers are less exposed to safety risks.

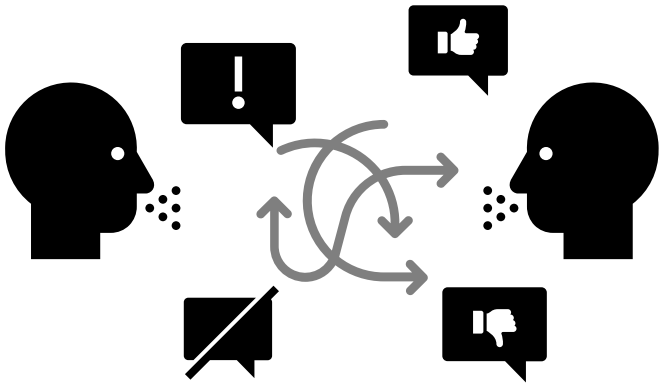


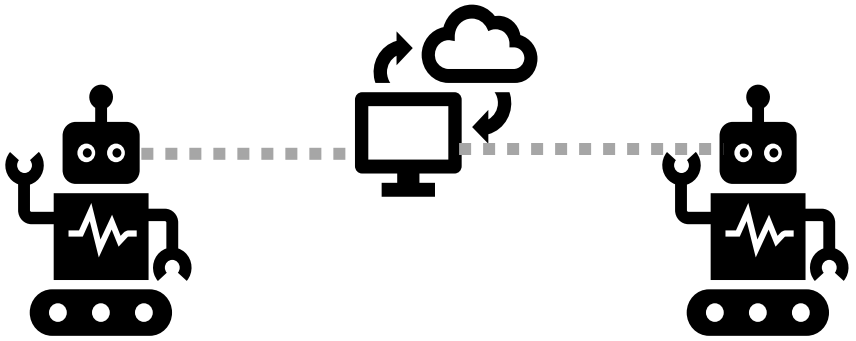


LABOR-RELATED ISSUES SOLUTIONS

Poor Communication

- Robots with built-in standard communication
- No different interpretations



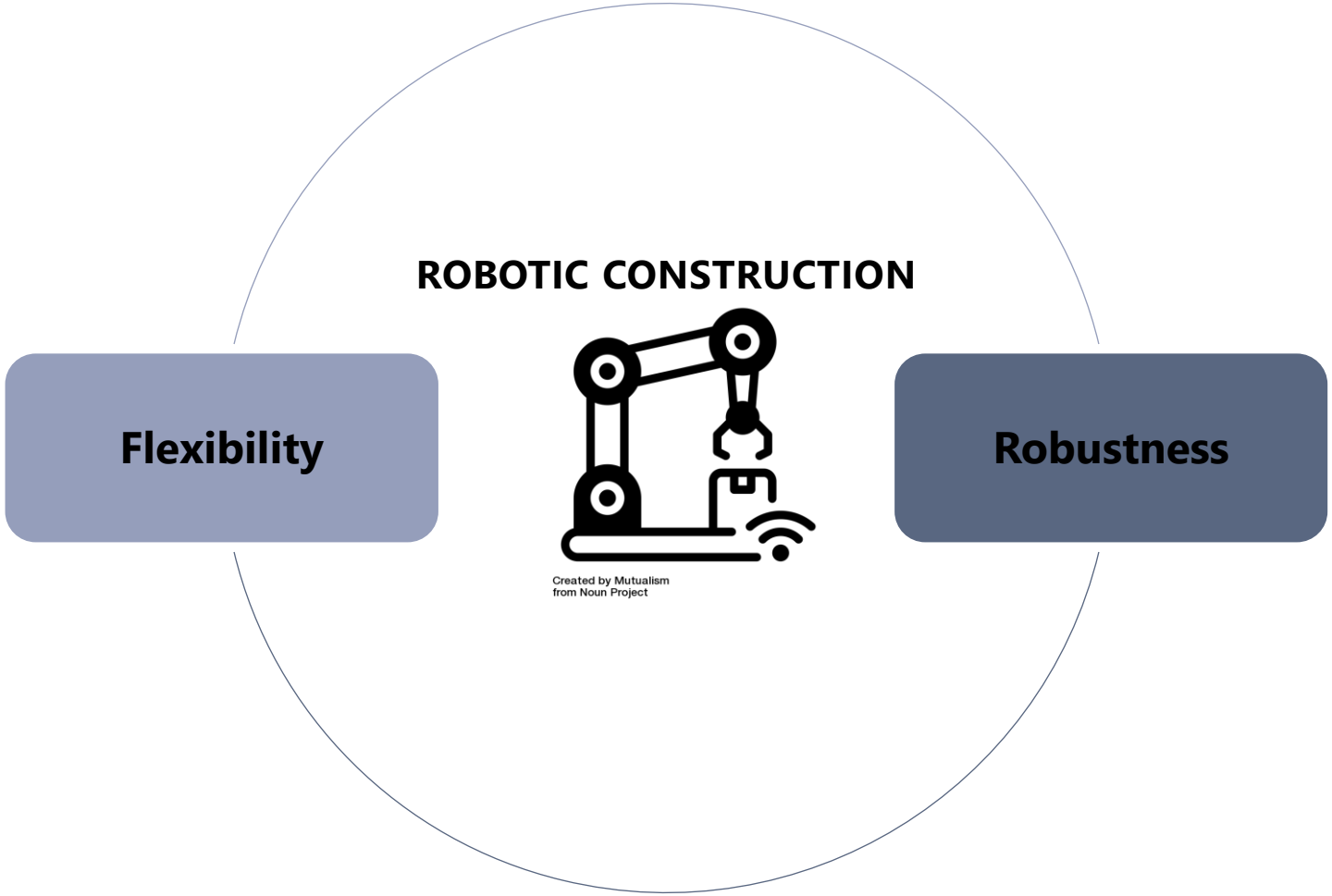


PROBLEM STATEMENT

- Construction Automation and Robotics (CAR), have **not** yet experienced widespread **real-world** implementation on a **large scale**.

BUT WHY?

CURRENT CHALLENGES IN THE CONSTRUCTION INDUSTRY

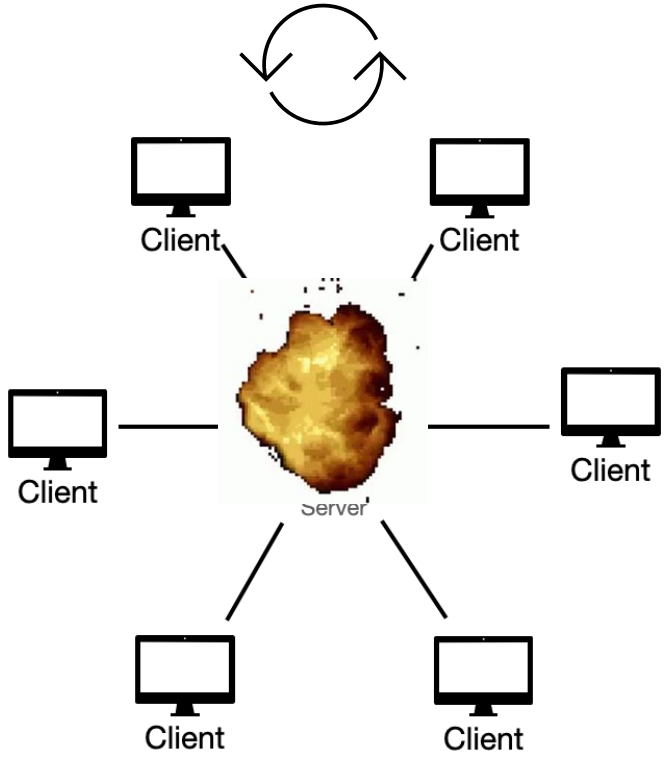


CENTRALIZED SYSTEMS

Flexibility

Existing Systems

- Costly and Hard to adapt to changes in dynamic environments.



Robustness

Existing Systems

- if one robot or the central authority malfunctions, the entire system is at risk of failure.

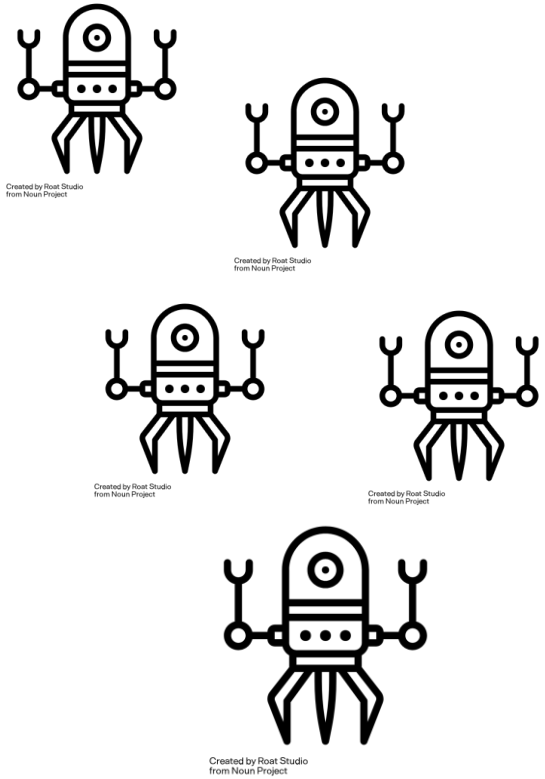
Source: https://systemdesignschool.io/blog/peer-to-peer-architecture

ADVANTAGES OF SWARM ROBOTS

Flexibility

Swarm Robots

- generate multiple solutions through coordinated robot collaboration
- adapt and act simultaneously in response to environmental changes



Robustness

Swarm Robots

- if one robot malfunctions, efficiency consists.
- In case of failure: compensated for by others

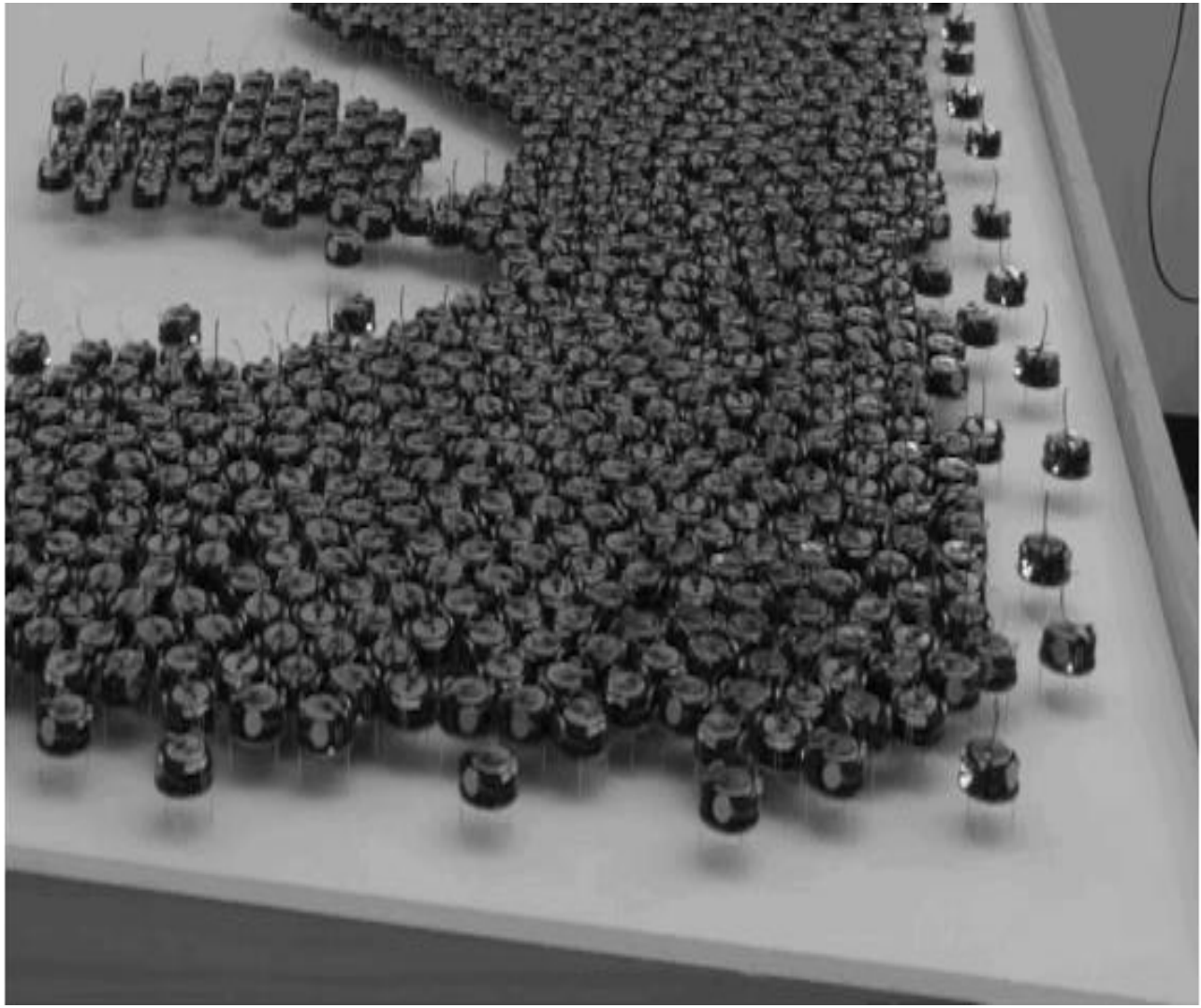
SWARM INTELLIGENCE & ALGORITHMS

- A discipline based on the **natural behavior** of Species like ants, wasps, herds, etc.
- Numerous individuals coordinating by **decentralized control**
- Simple tasks achieving more complex tasks

Source: https://medium.com/zerone-magazine/swarm-intelligence-676e40968473

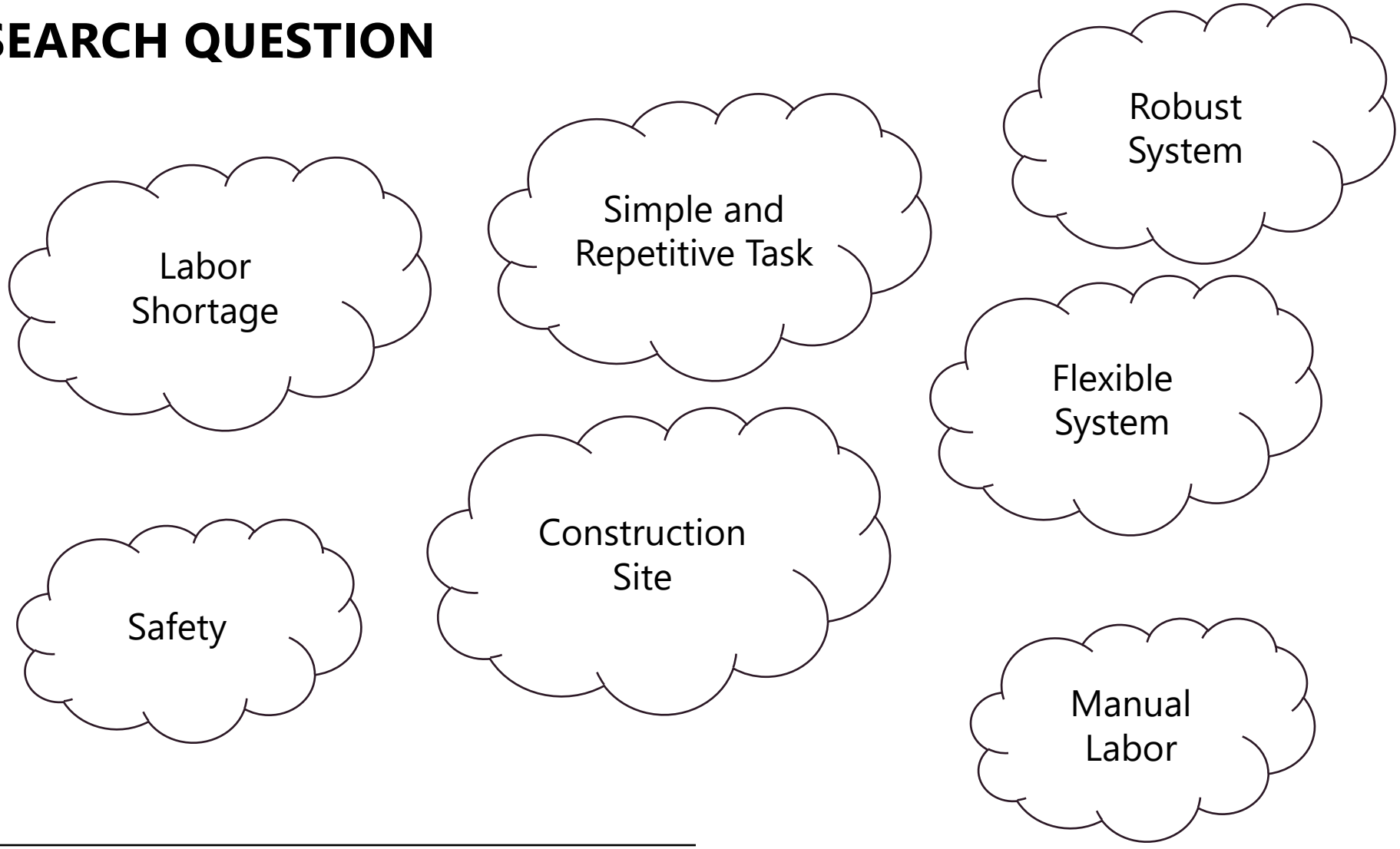
SWARM ROBOTIC

- Swarm robotics is the application of **swarm intelligence** principles to the control of swarms of robots.
- Used in other industries but not construction



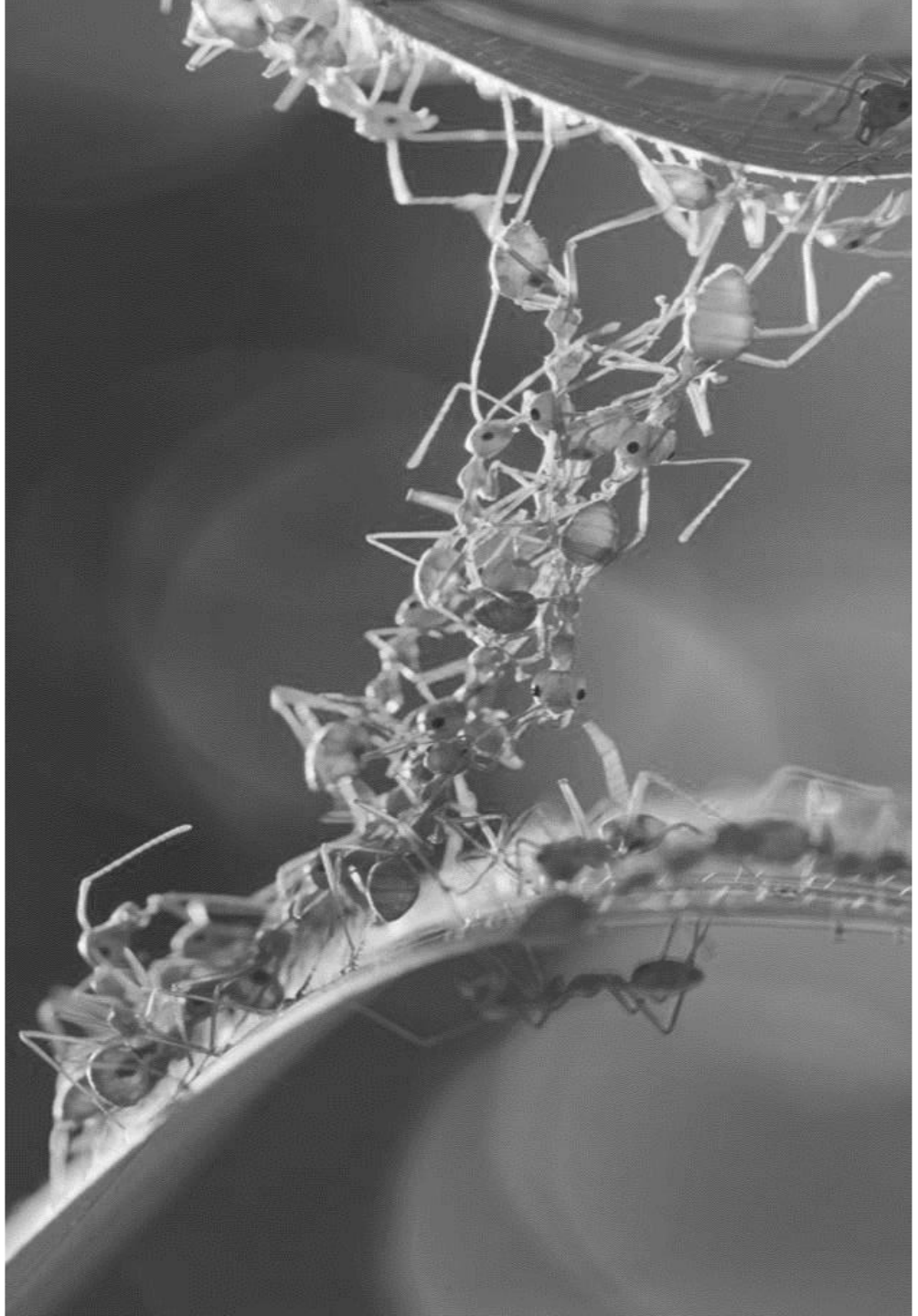
Kilobot Robot- Source: https://gifer.com/en/1Zup.

RESEARCH QUESTION



RESEARCH QUESTION

"HOW CAN SWARM ROBOTS PERFORM AS AN ON-SITE ADAPTIVE LOGISTIC SYSTEM ON A DYNAMIC CONSTRUCTION SITE?"



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1. Introduction
2. Literature Review
    - Construction Site
    - Swarm Algorithms
3. Implementation
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CONSTRUCTION SITE AS A DYNAMIC ENVIRONMENT

- Dynamic and Dangerous workplace
- unpredictable nature
- Controllable Parameters
  - Strong management
  - Well-organized logistics
- uncontrollable Parameters
  - Weather
  - Accidents

Subway connects York University-https://www.youtube.com/watch?v=gSRPcRDPy1w

CONSTRUCTION DISRUPTIONS

Source; https://creativemarket.com/Good_Studio/3174516-Construction-site-illustration?u=ohlove&epik=dj0yJnU9cHRBT0t3cGo5LWdtdFUzRFJtd1RYdDFiMnZHUUU0Q3omcD0wJm49ajRZYzNSVmY1YW5IcjFGZDBOX0hjZyZ0PUFBQUFBR1pVVERR

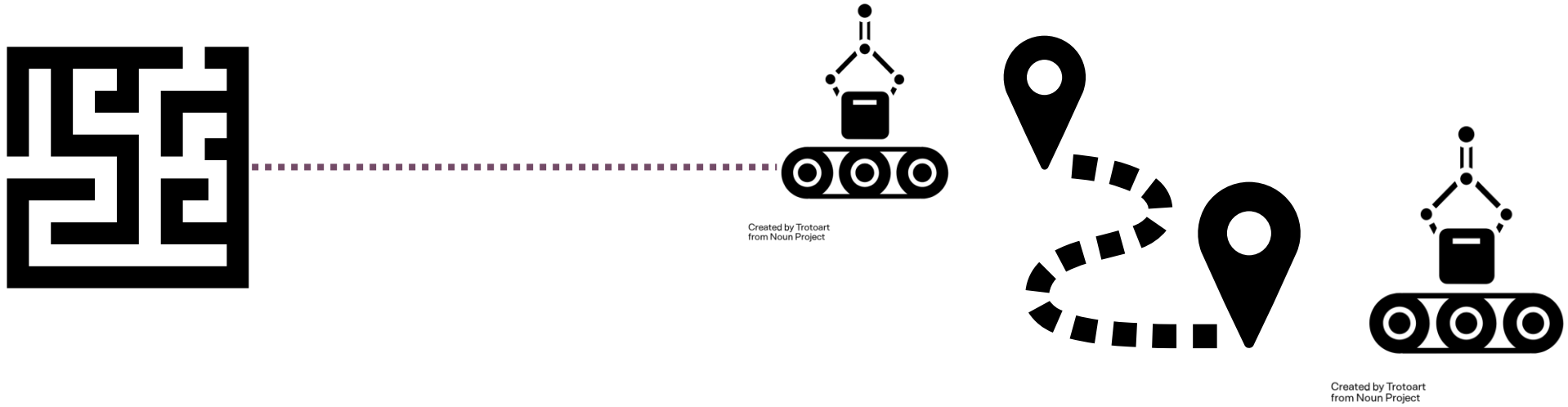
Inadequate material-handling

Inefficient site logistics

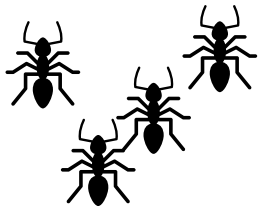
Source; https://www.levelset.com/blog/2020-report-construction-wasted-time-slow-payment/

ROBOT NAVIGATION & PATH-PLANNING

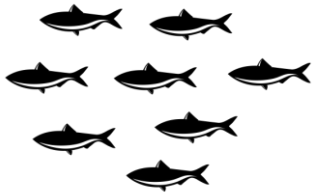
- Ability to perceive, plan and act → Path-planning
- Enhancing Efficiency and Safety



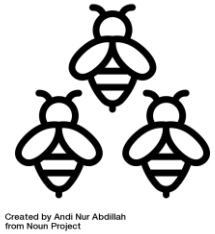
SWARM ALGORITHMS WITH NAVIGATION BEHAVIORS



Ant Colony Optimization-
artificial/engineering

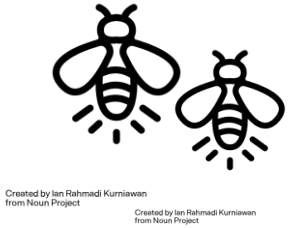


Particle Swarm Optimization-
artificial/engineering



Bee Colony Optimization (BCO)

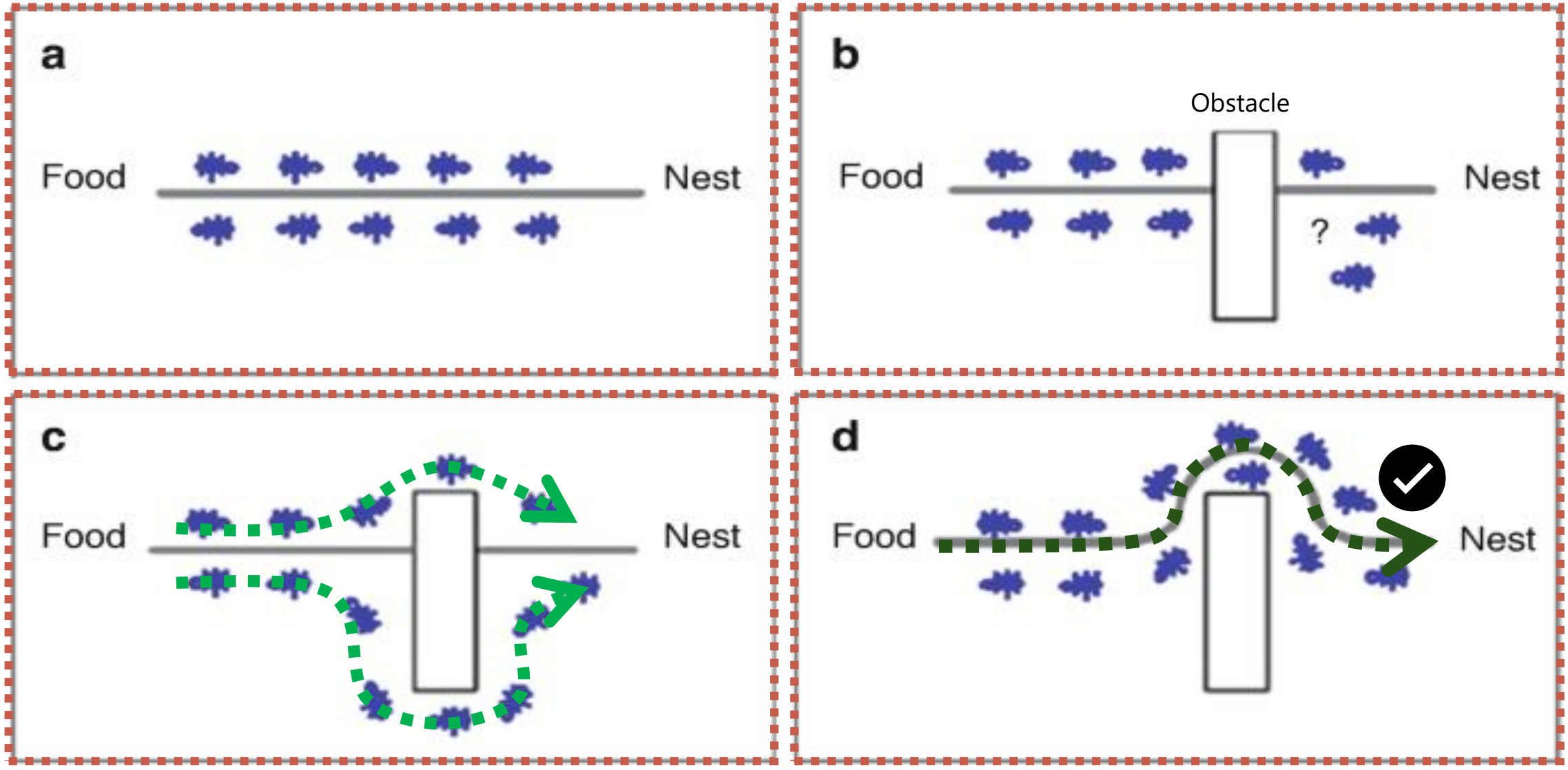
artificial/engineering



Firefly Algorithm (FA)

Natural/Scientific

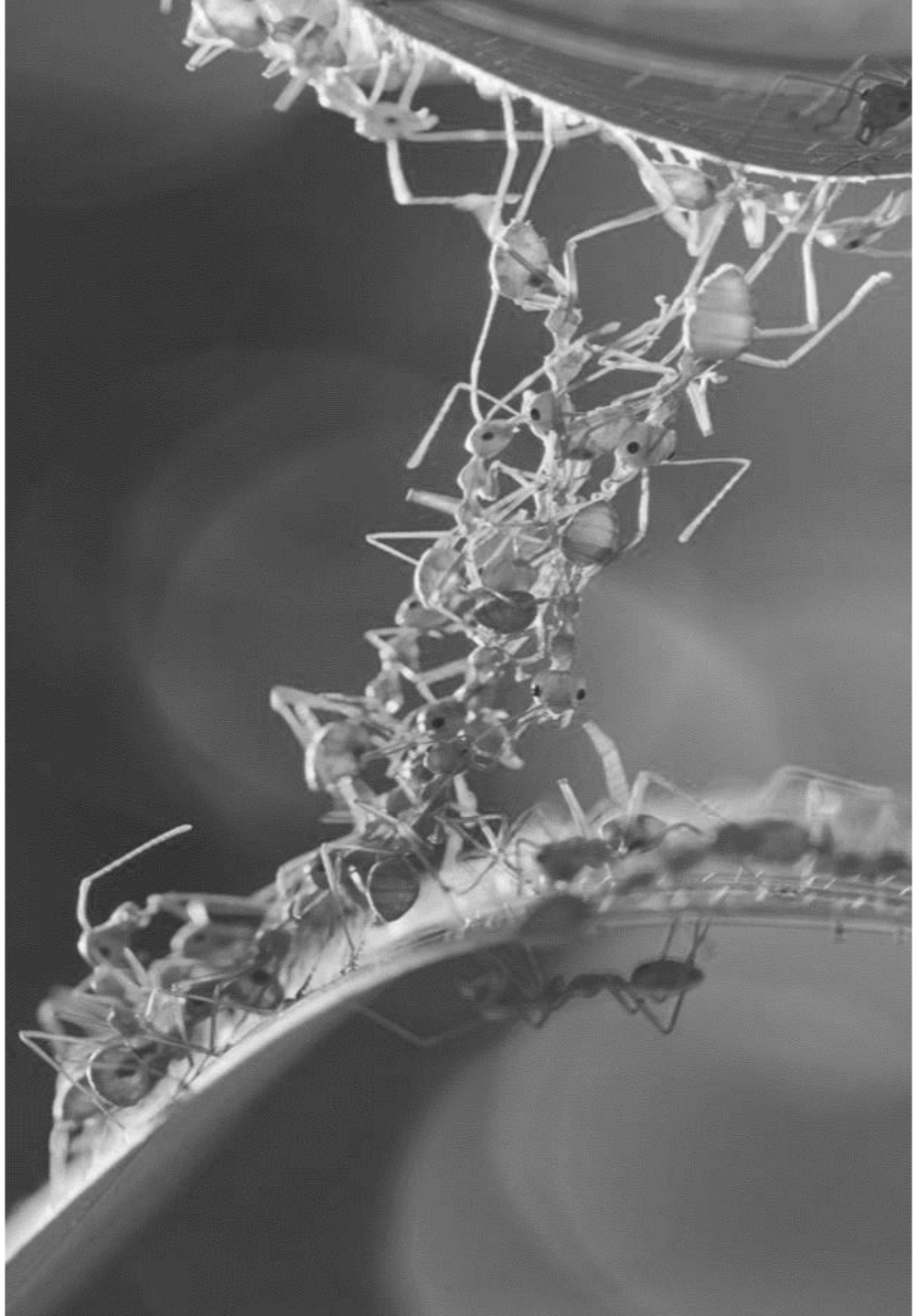
ANT COLONY OPTIMIZATION



Source: (Gupta et al., 2021)
Enhancing Construction Autonomy on Dynamic Building Sites Through Implementation of Swarm Robotics

LET’S SEE IF WE CAN TRANSFORM THE ANTS TO ROBOTS!

Source: https://www.youtube.com/watch?v=mgCIKGIYJ1A



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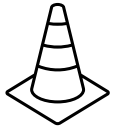
HOW TO CREATE A FRAMEWORK?

Design Essentials Steps

1- Architectural scenario and function of it



2- Construction site’s condition and layout

3- Structure type creating the layout and the used material

4- Operating robotic system and its technical features

What has been Studied?

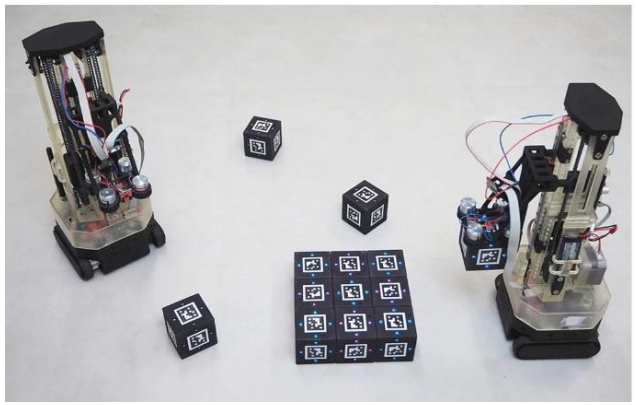
Architectural and construction site Layout

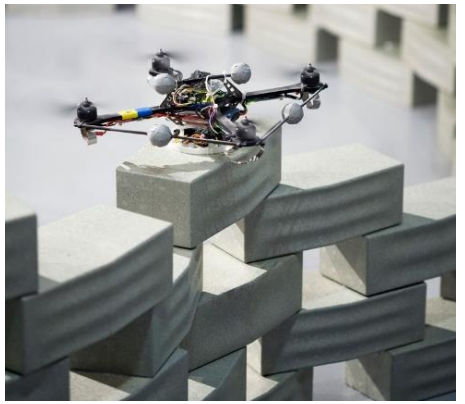
Structural and Material Selection

Current Robots in the Industry

CAPABILITIES AND APPLICATIONS OF SWARM ROBOTS

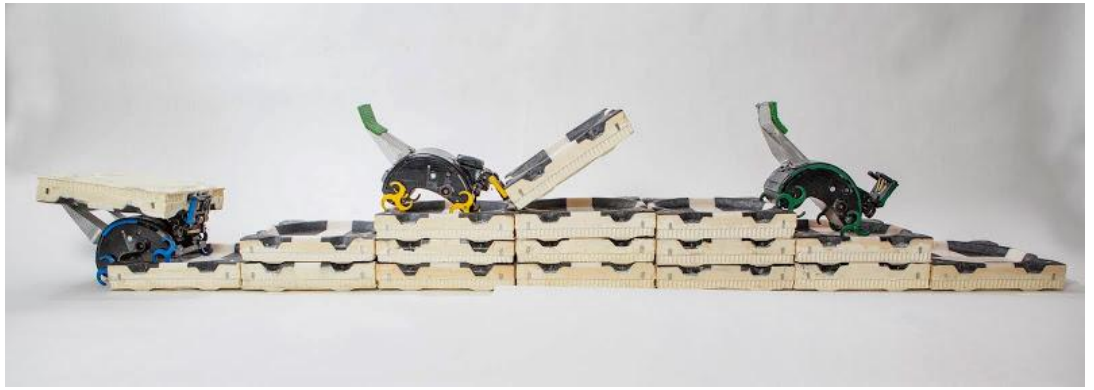
- Mostly used for stacking lightweight discrete material
- Practical limitations in large-scale projects with conventional heavy material
- Material handling as a primary task focus





Source: https://gramaziokohler.arch.ethz.ch/web/e/projekte/209

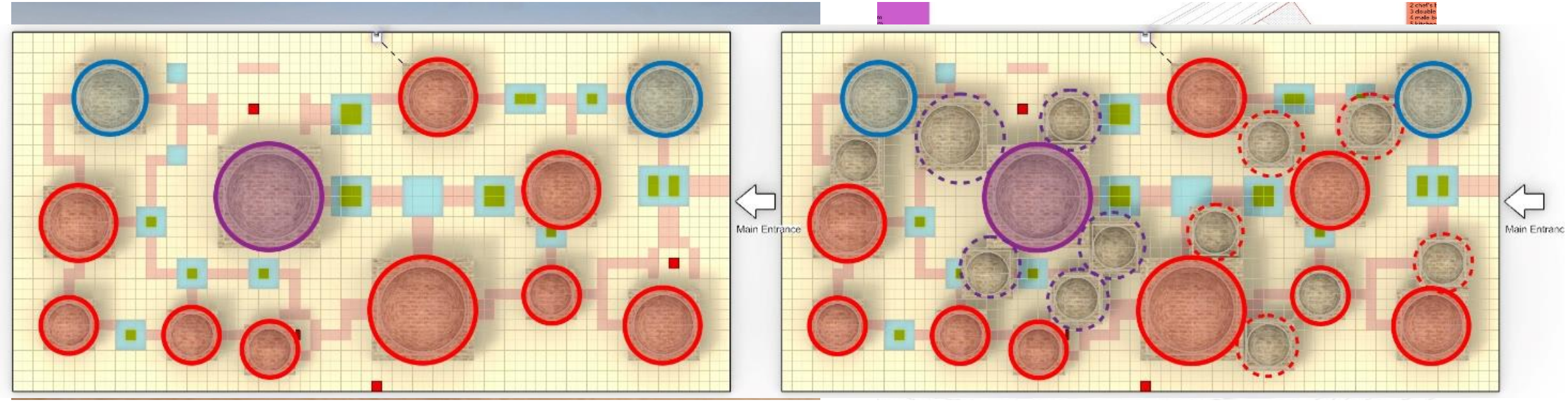
Source: (Khaluf et al., 2020)



Source: https://ssr.seas.harvard.edu/termes

ARCHITECTURAL LAYOUT

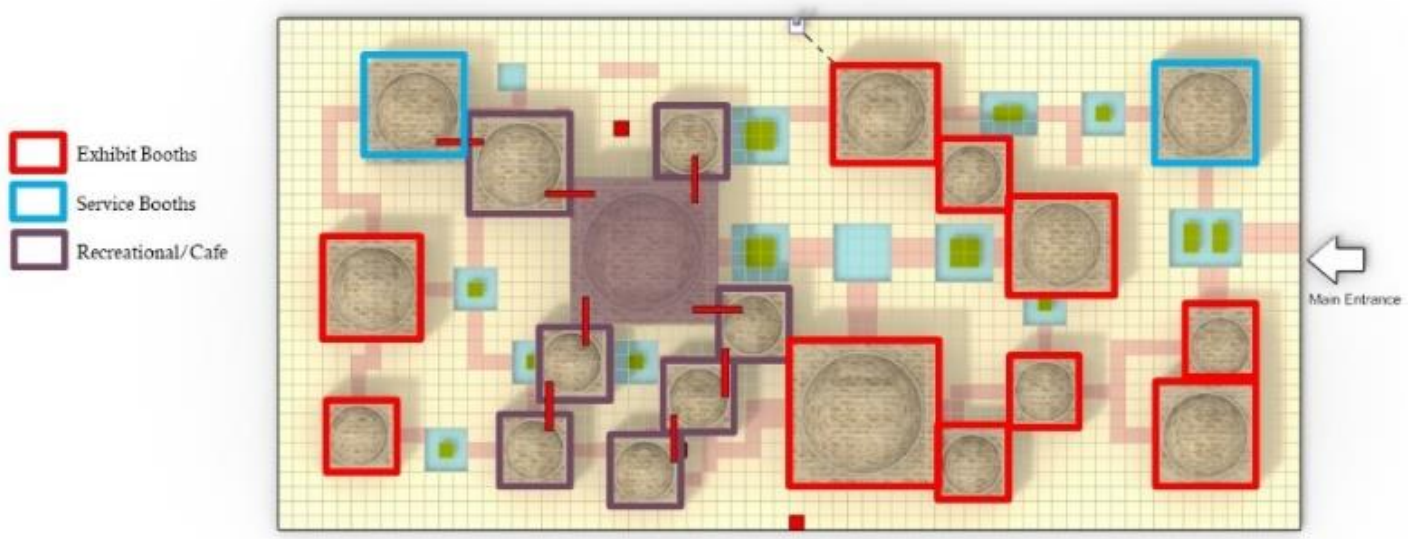
- Inspired by Riadh Houses, Multiple scattered points, functioning as the main cores
- Enhances the ease of robot movement around the site
- Allowing different levels of compactness and design flexibility on the site



Source: Riyadh Dream Villas | Collarch

ARCHITECTURAL LAYOUT

- Architectural Function: Temporary Exhibition consisting of multiple booths
- Multiple assembly and disassembly
- Suitable for customization by Architect
- Three types of booths
- Ponds & Walking Path



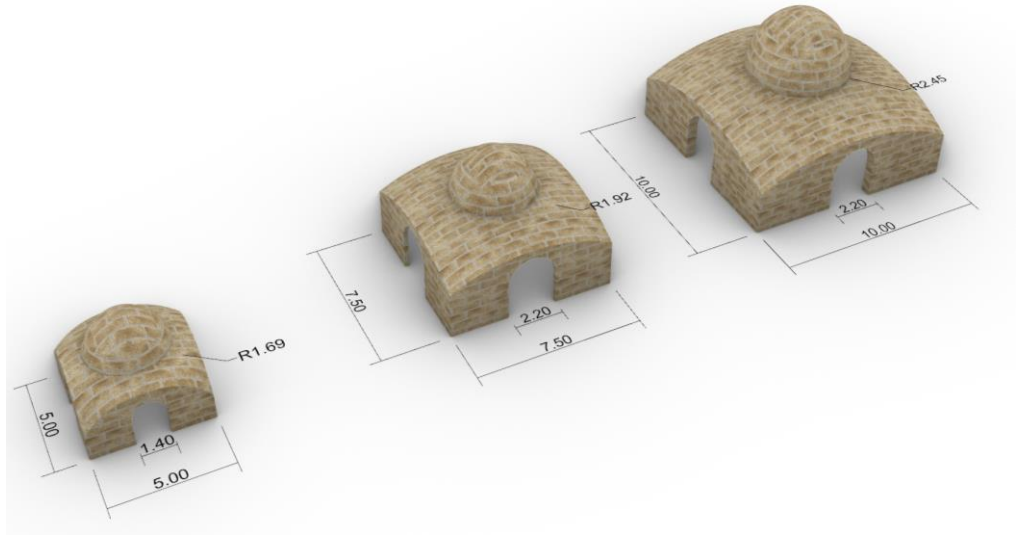
BOOTH DESIGN

- Compression-only structures
- Architectural inspiration from Atashkade, a term in Persian architecture
- The booths are designed in three sizes:

5m x 5m, 7.5m x 7.5m, and 10m x 10m, each requiring a different volume of materials.

Source: https://www.3dwasp.com/en/3d-printed-house-tecla/

Source: https://memarifa.ir/what-is-atashkade/

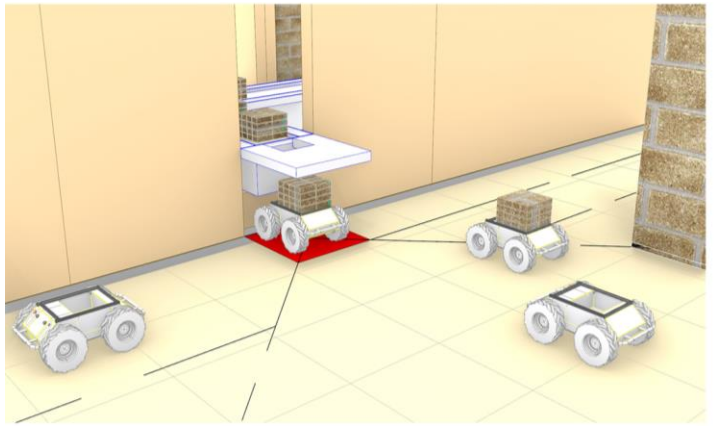


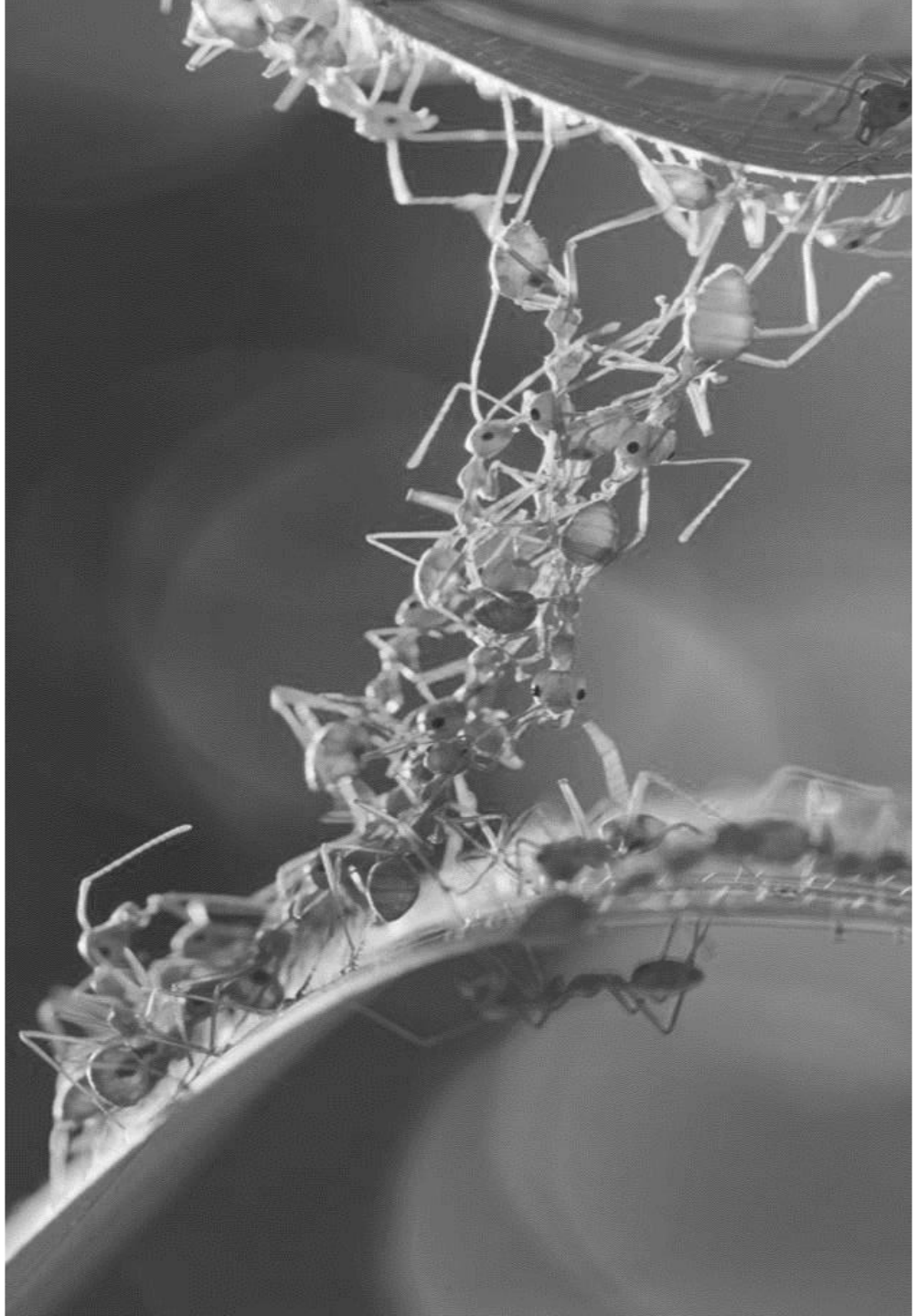
ROBOT SELECTION

- Autonomous mobile robots in industrial projects With larger sizes

- Husky a UGV robot for construction sites, 75 kg payload and 1m/s

Source: https://clearpathrobotics.com/husky-3d-model/





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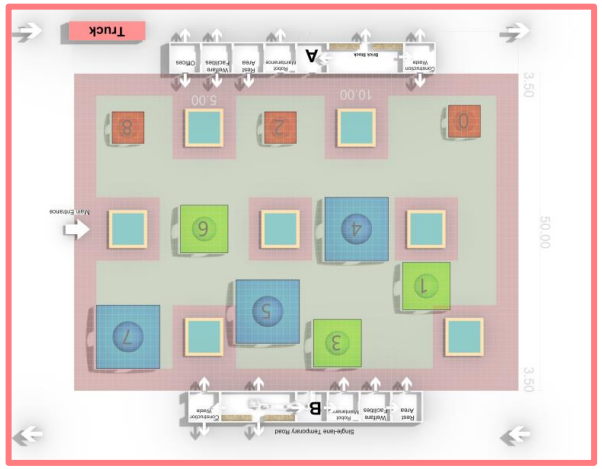
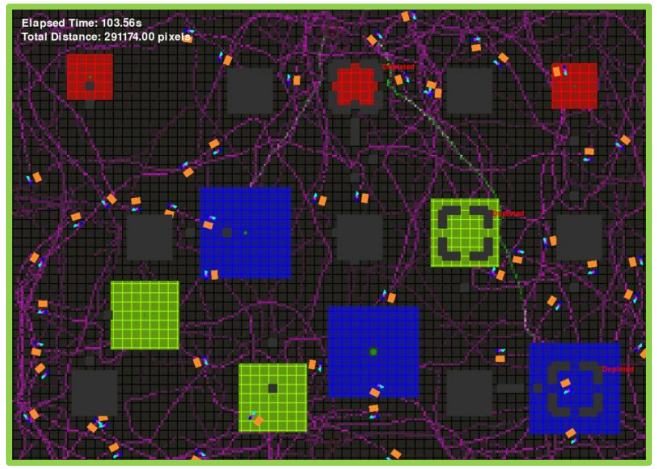
WORKFLOW

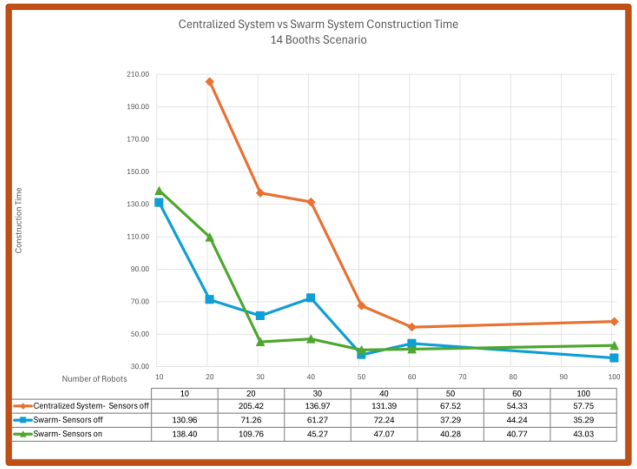
grasshopper

python

1. Design phase → Architectural Layout Design → **2. Simulation Phase** → Architectural Layout Construction by Swarm Robots → **3. Experiments & Analysis** → Simulation Results Analysis of Construction Scenarios







	10	20	30	40	50	60	100
Centralized System- Sensors off		205.42	136.97	131.39	67.52	54.33	57.75
Swarm- Sensors off	130.96	71.26	61.27	72.24	37.29	44.24	35.29
Swarm- Sensors on	138.40	109.76	45.27	47.07	40.28	40.77	43.03

WORKFLOW

grasshopper

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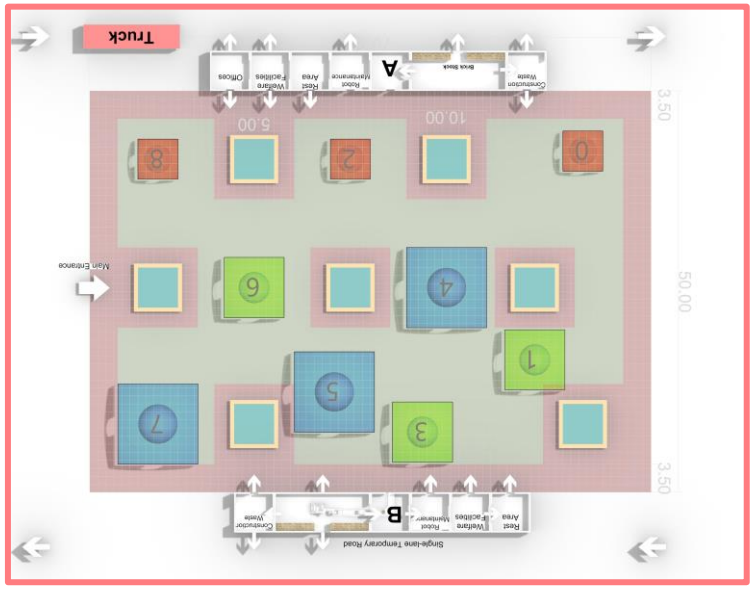
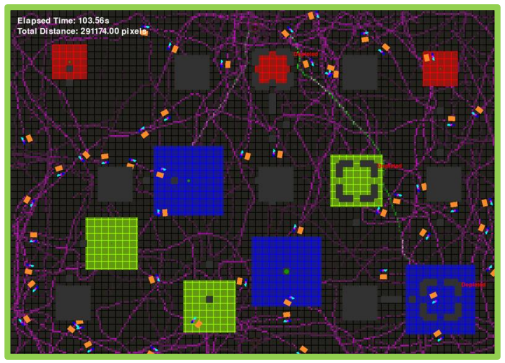
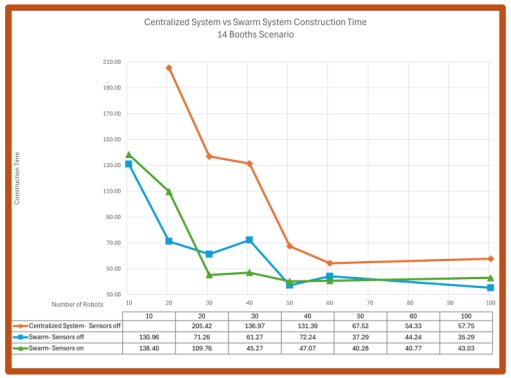


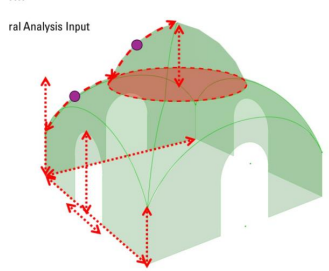




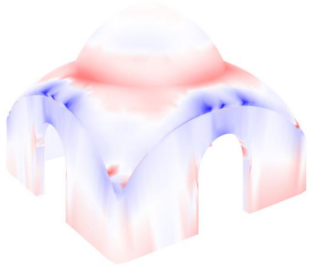
1.
Design phase

Architectural Layout Script

Booth Parametric Script

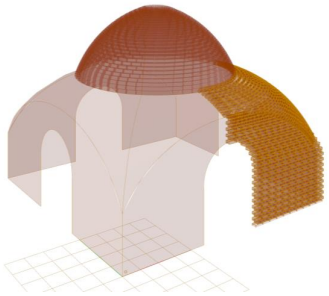


Geometry Extract



Booth Structural Analysis

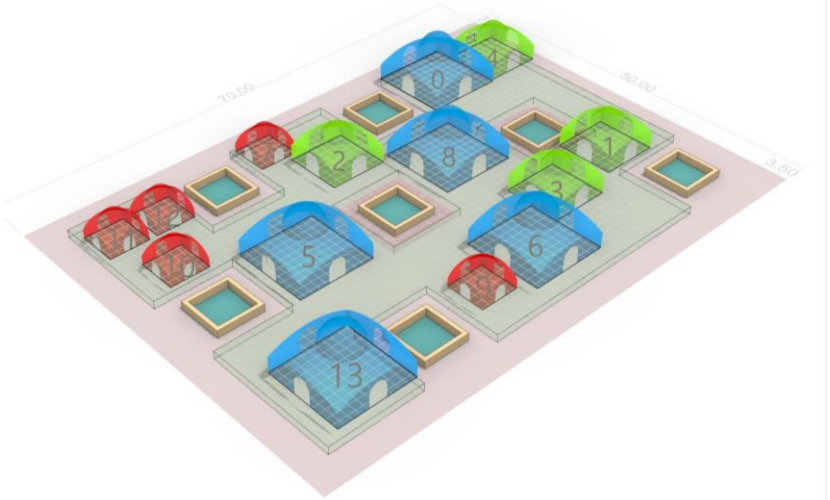
Wall Thicknes s Extract

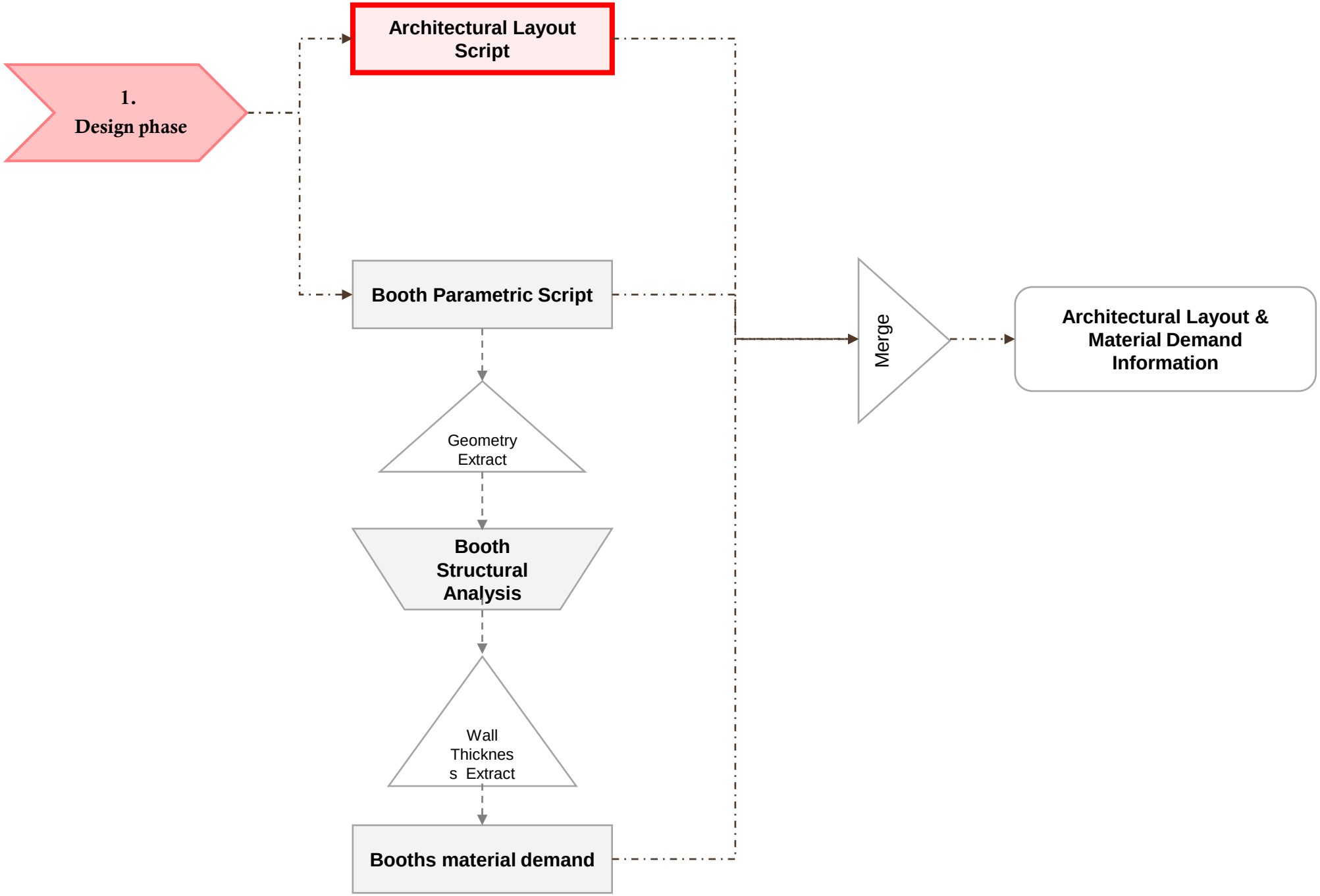


Booths material demand

Merge

Architectural Layout & Material Demand Information



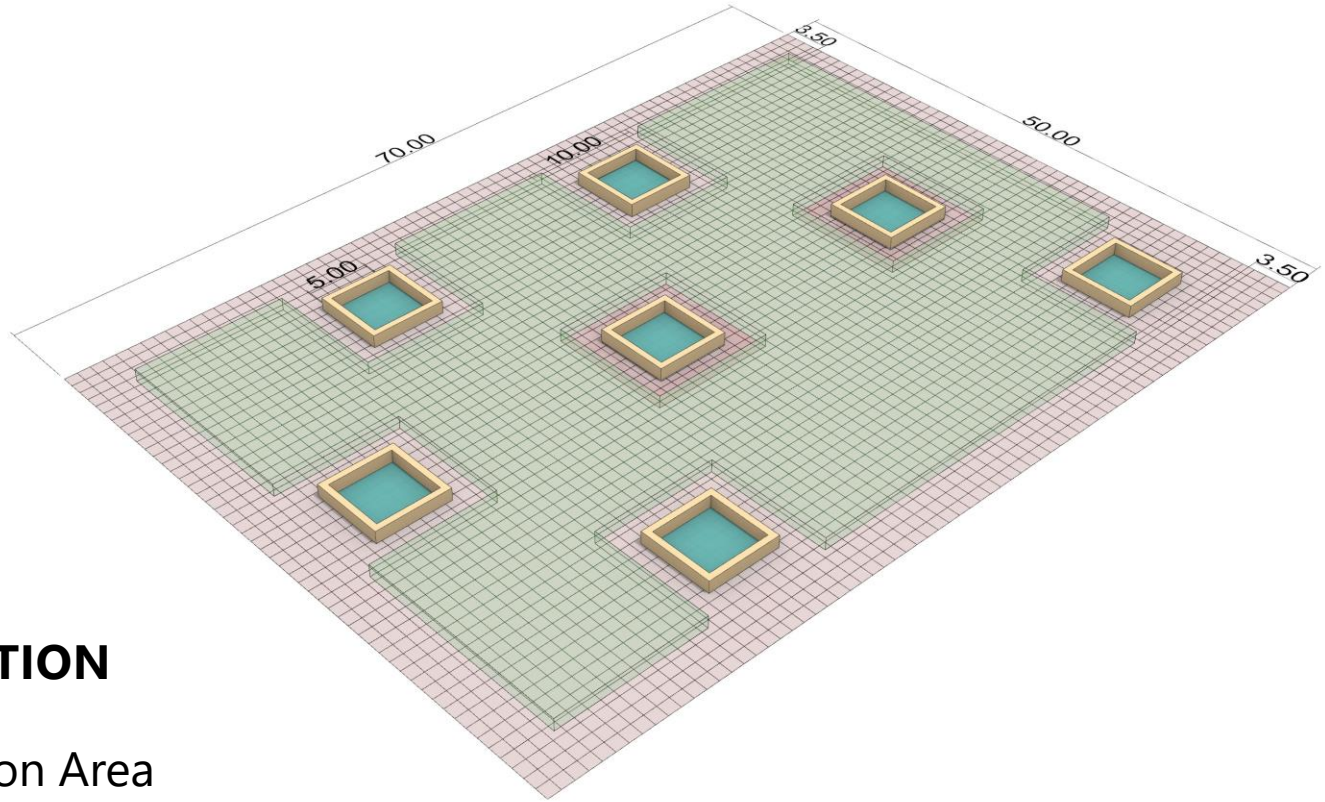

1.
Design phase
Architectural Layout Script
Booth Parametric Script
Geometry Extract
Booth Structural Analysis
Wall Thicknes s Extract
Booths material demand
Merge
Architectural Layout & Material Demand Information

CONSTRUCTION SITE LAYOUT INITIALIZATION

- 70m*50m rectangle with a grid system of 1

STATIC OBSTACLE CONFIGURATION

- Ponds are fixed as seven squares, each 5m x 5m with an additional margin of 2.5m.



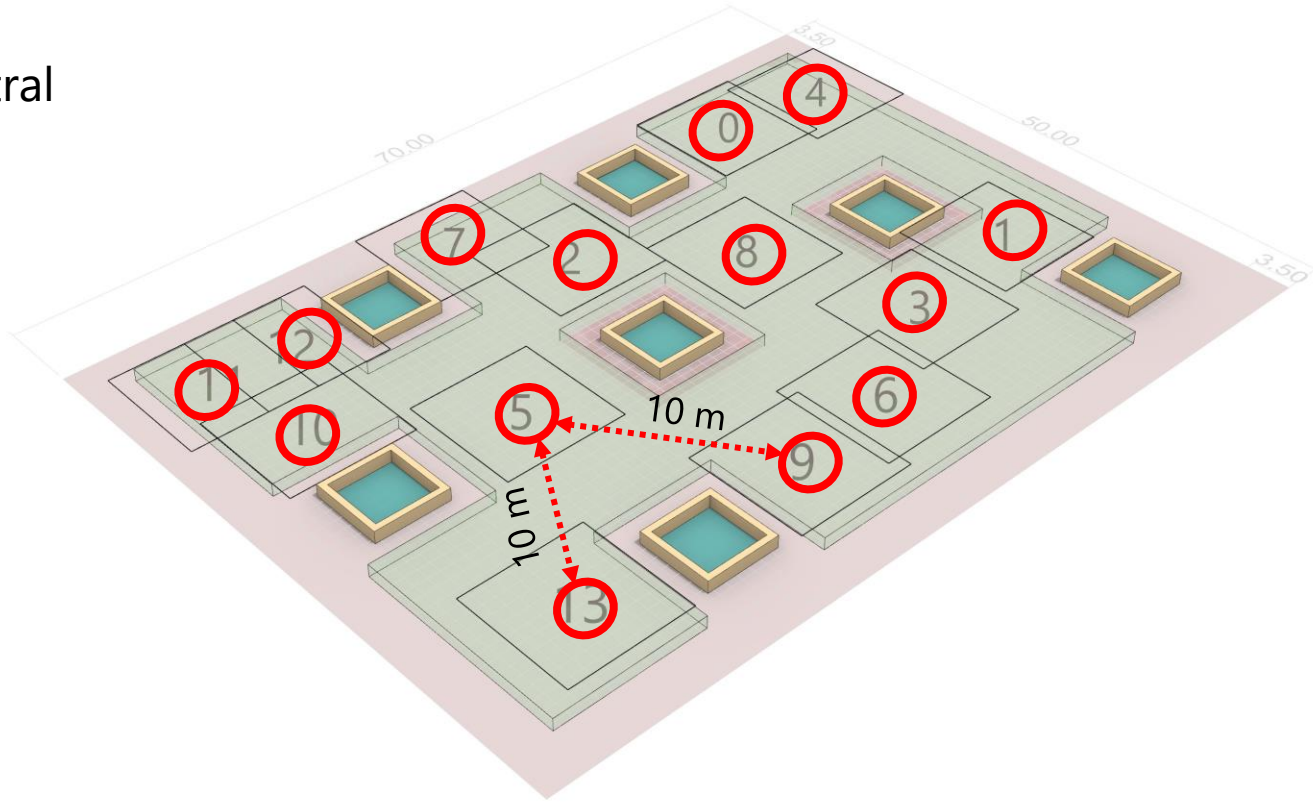
BOOTH PLACEMENT AND DISTANCE VALIDATION

- The cells in the green area: Allowed Construction Area

BOOTH PLACEMENT AND DISTANCE VALIDATION

- From the green area. the desired number of points - are randomly selected to serve as central locations for the booths.

- Each chosen point must have a minimum distance of 10 meters from any other booth’s central point.

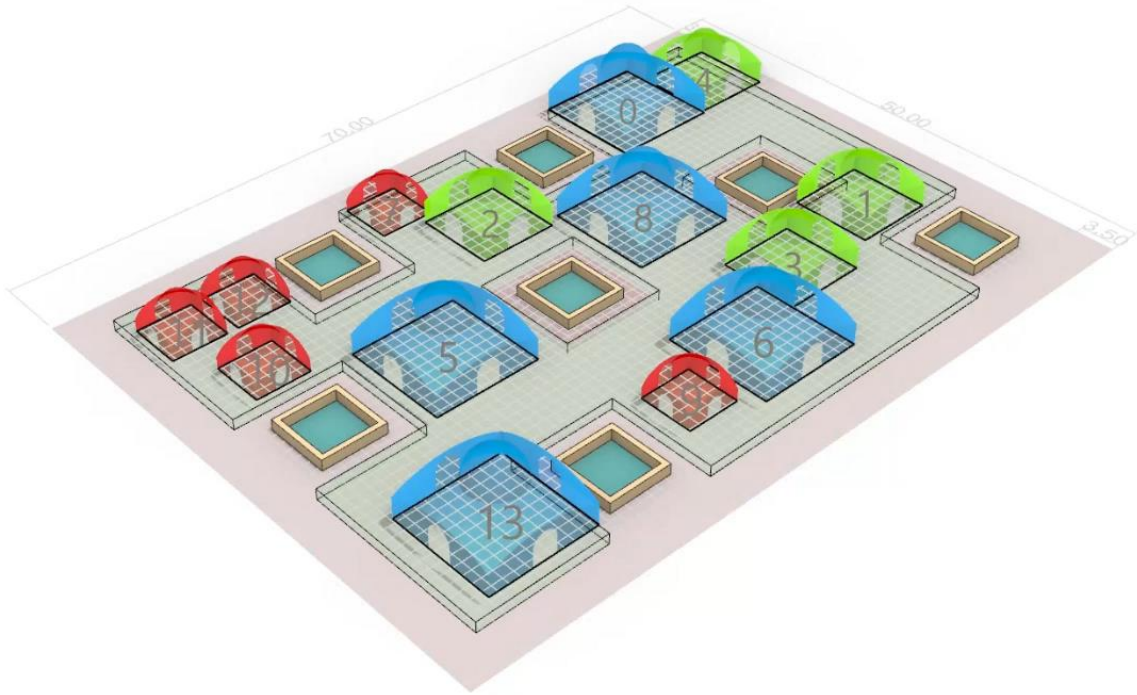


BOOTH PLACEMENT AND DISTANCE VALIDATION

- To make this condition true:

Manual adjustments of the booths' positions in the

X and Y directions by number sliders.

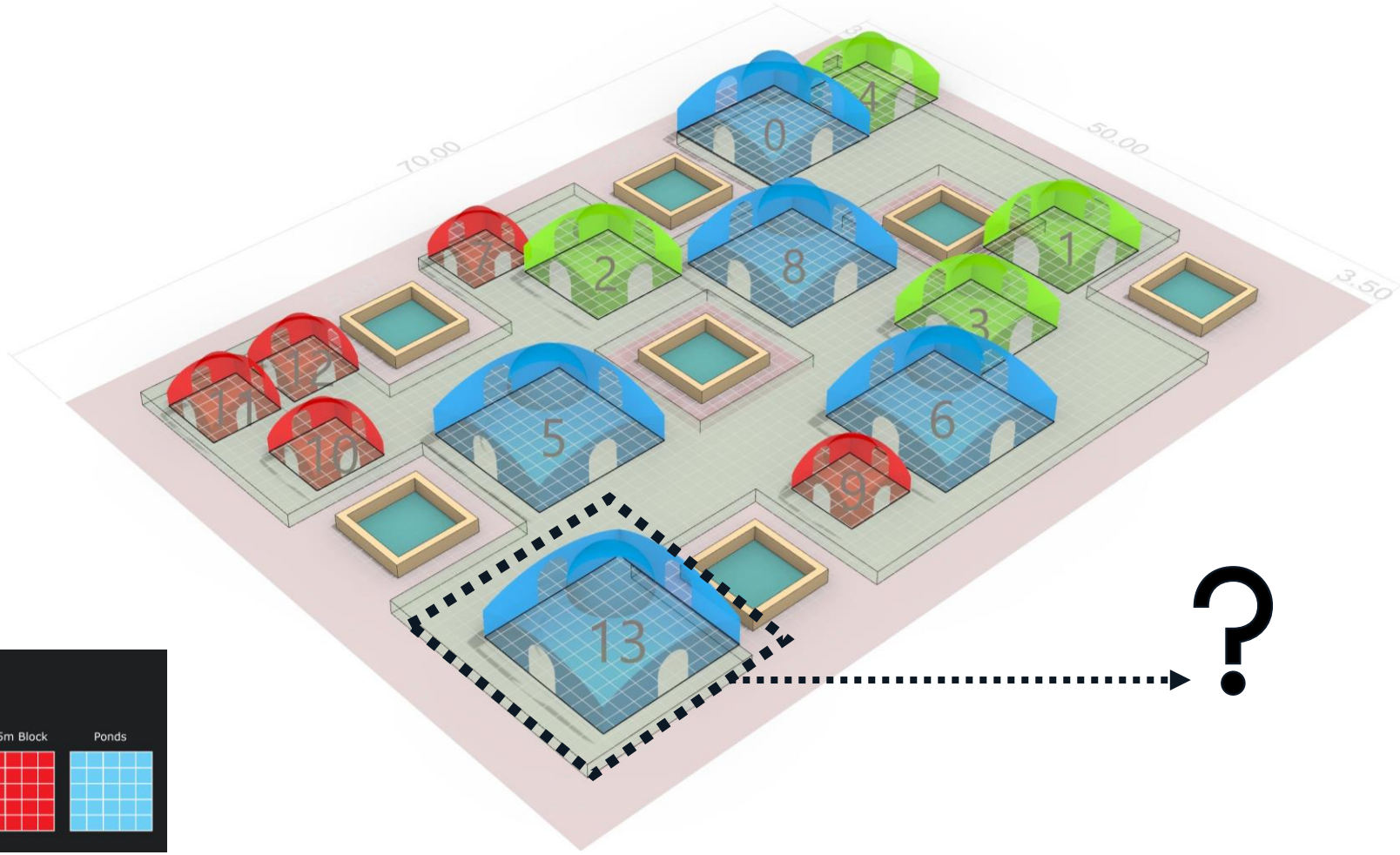


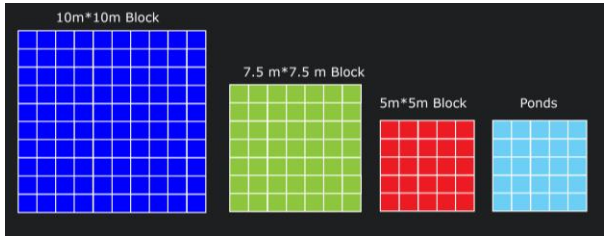
- If the design is confirmed:

Booths get scaled by factors of 1, 0.75, and 0.5

randomly.

BOOTH PLACEMENT



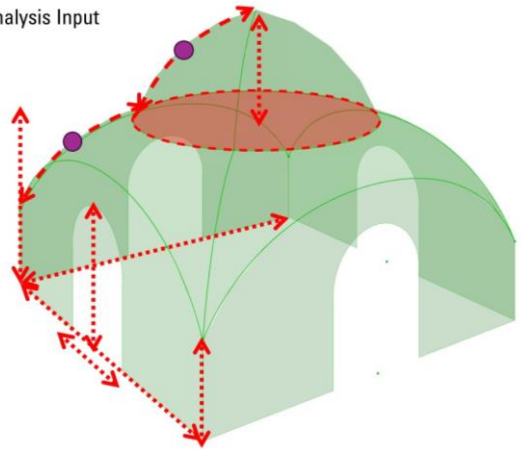


1.
Design phase

Architectural Layout Script

Booth Parametric Script

ral Analysis Input



Geometry Extract

Booth Structural Analysis

Wall Thicknes s Extract

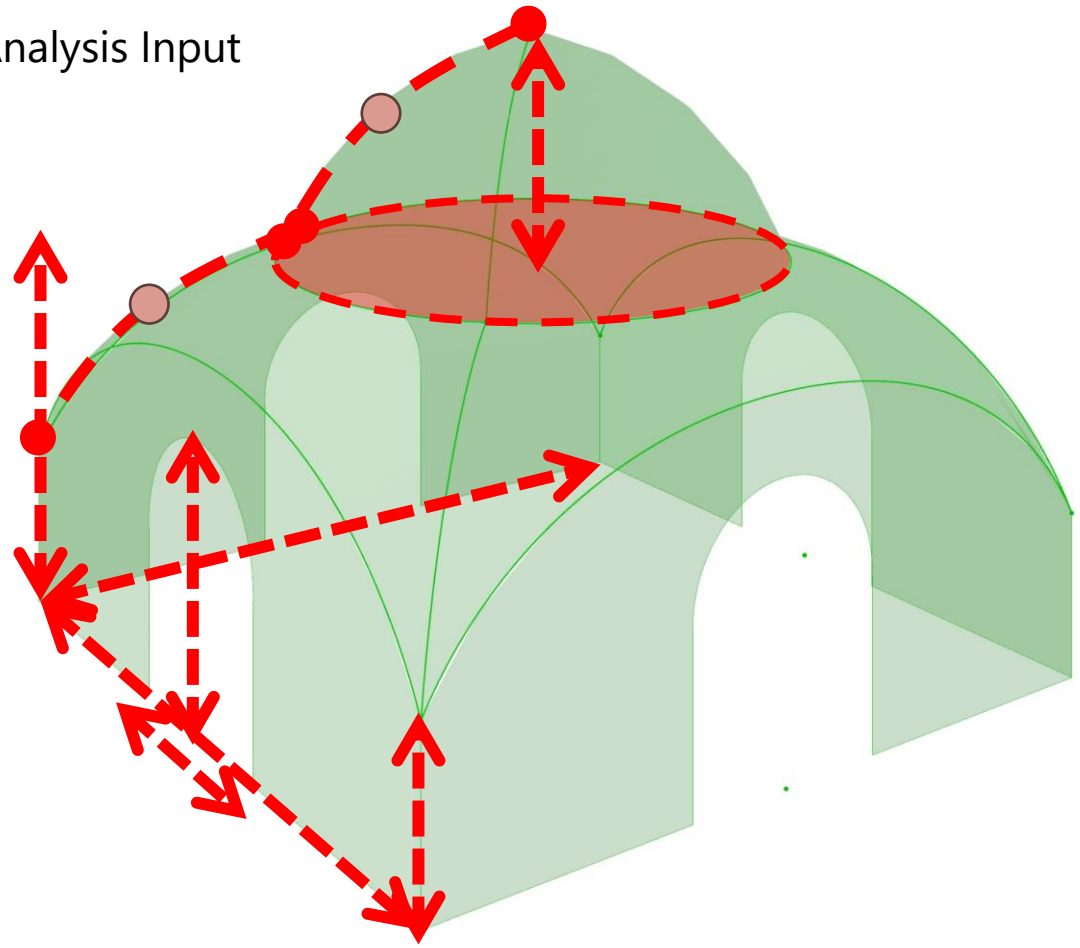
Booths material demand

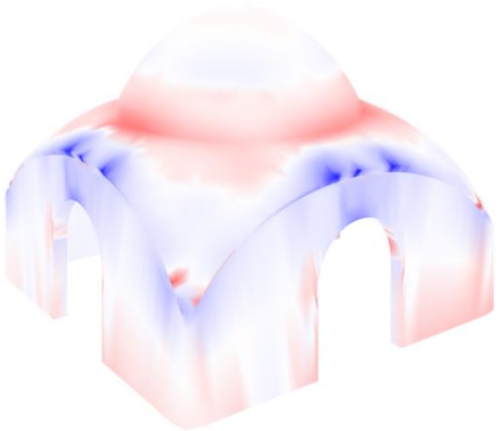
Merge

Architectural Layout & Material Demand Information

Final Form

- Structural Analysis Input





1.
Design phase

Architectural Layout Script

Booth Parametric Script

Geometry Extract

Booth Structural Analysis

Wall Thicknes s Extract

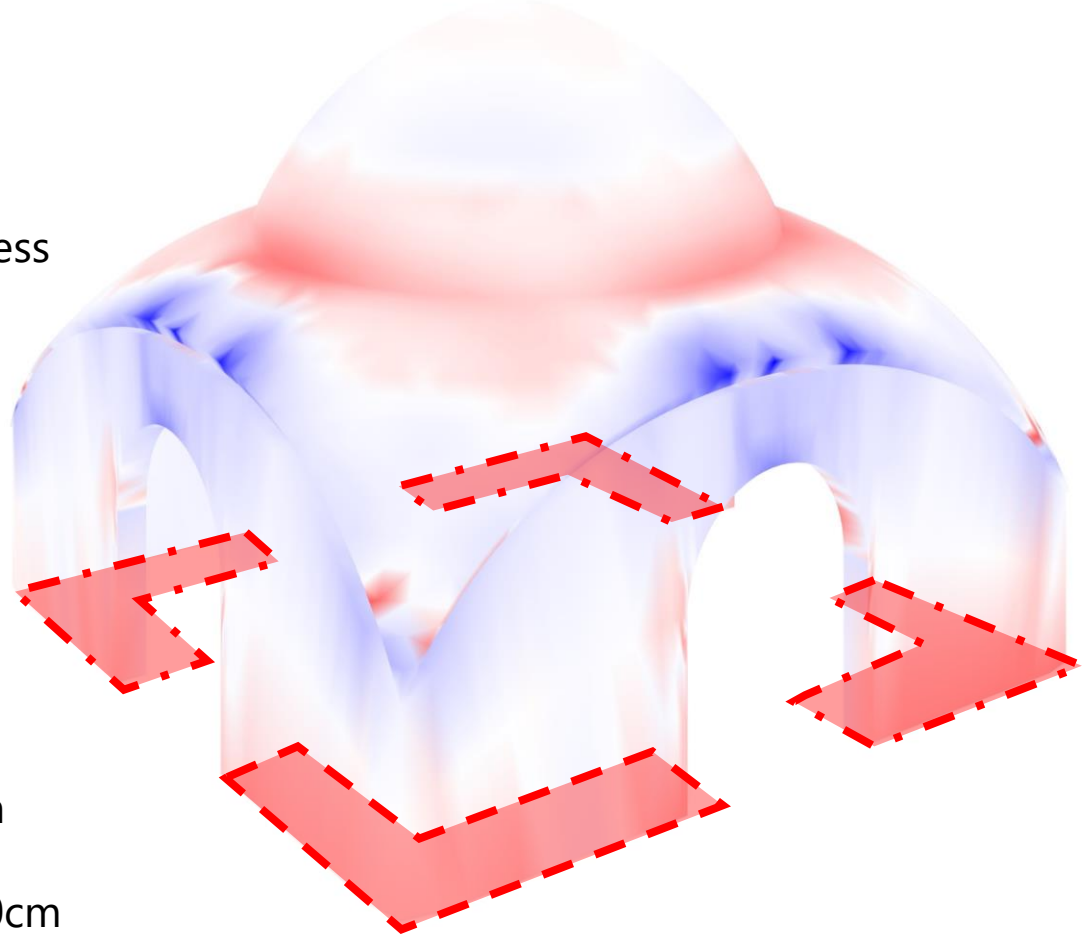
Booths material demand

Merge

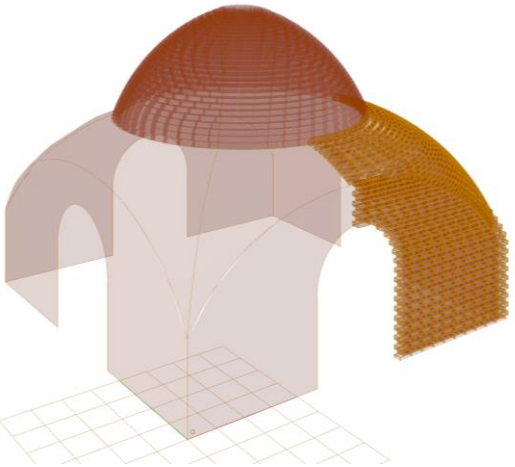
Architectural Layout & Material Demand Information

Structural Analysis

- As a shell structure
- Utilization Factor
- Extract Wall Thickness



- Small Booth: 20cm
- Medium Booth: 20cm
- Large Booth: 50 cm



1.
Design phase

Architectural Layout Script

Booth Parametric Script

Geometry Extract

Booth Structural Analysis

Wall Thicknes s Extract

Booths material demand

Merge

Architectural Layout & Material Demand Information

Brick Demand Estimation

- **Small Booth**

11500 Bricks-325 Trips

- **Medium Booth**

22500 Bricks- 650 Trips

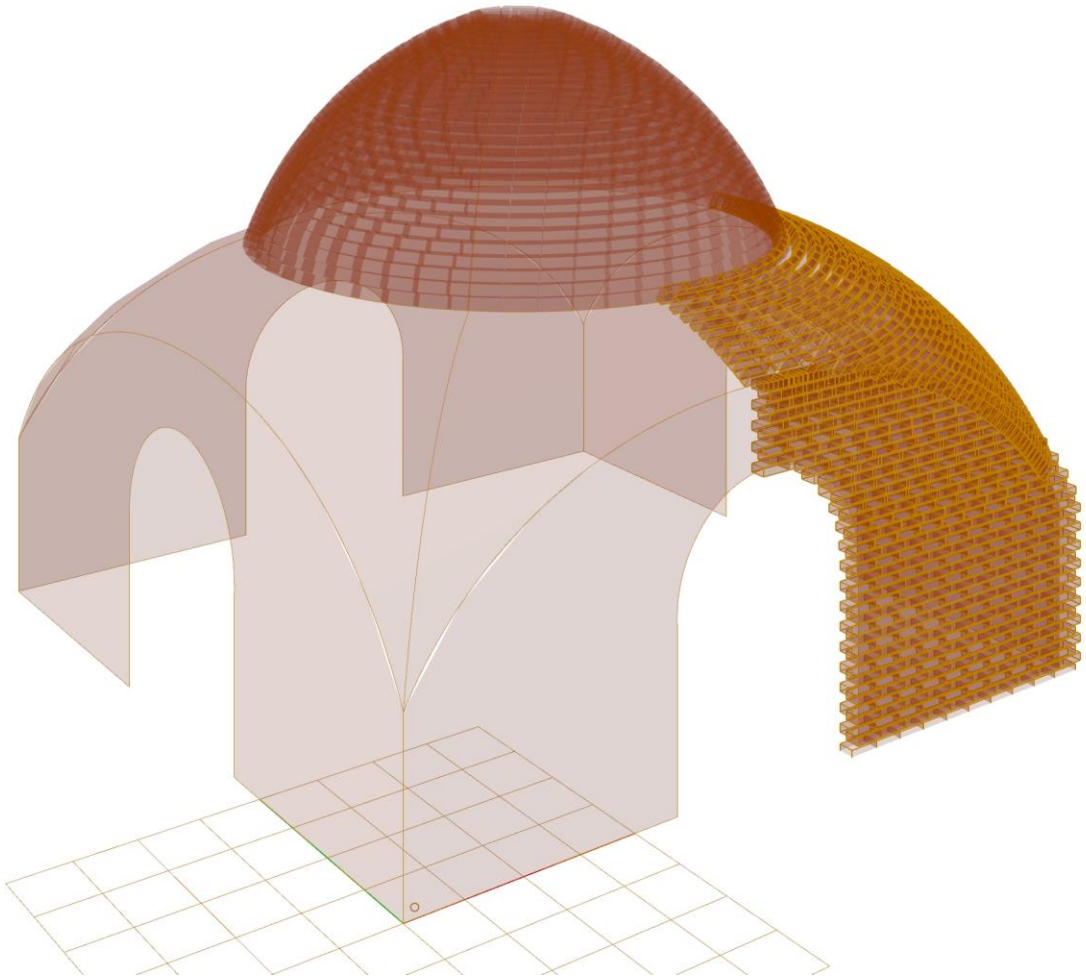
- **Large Booth**

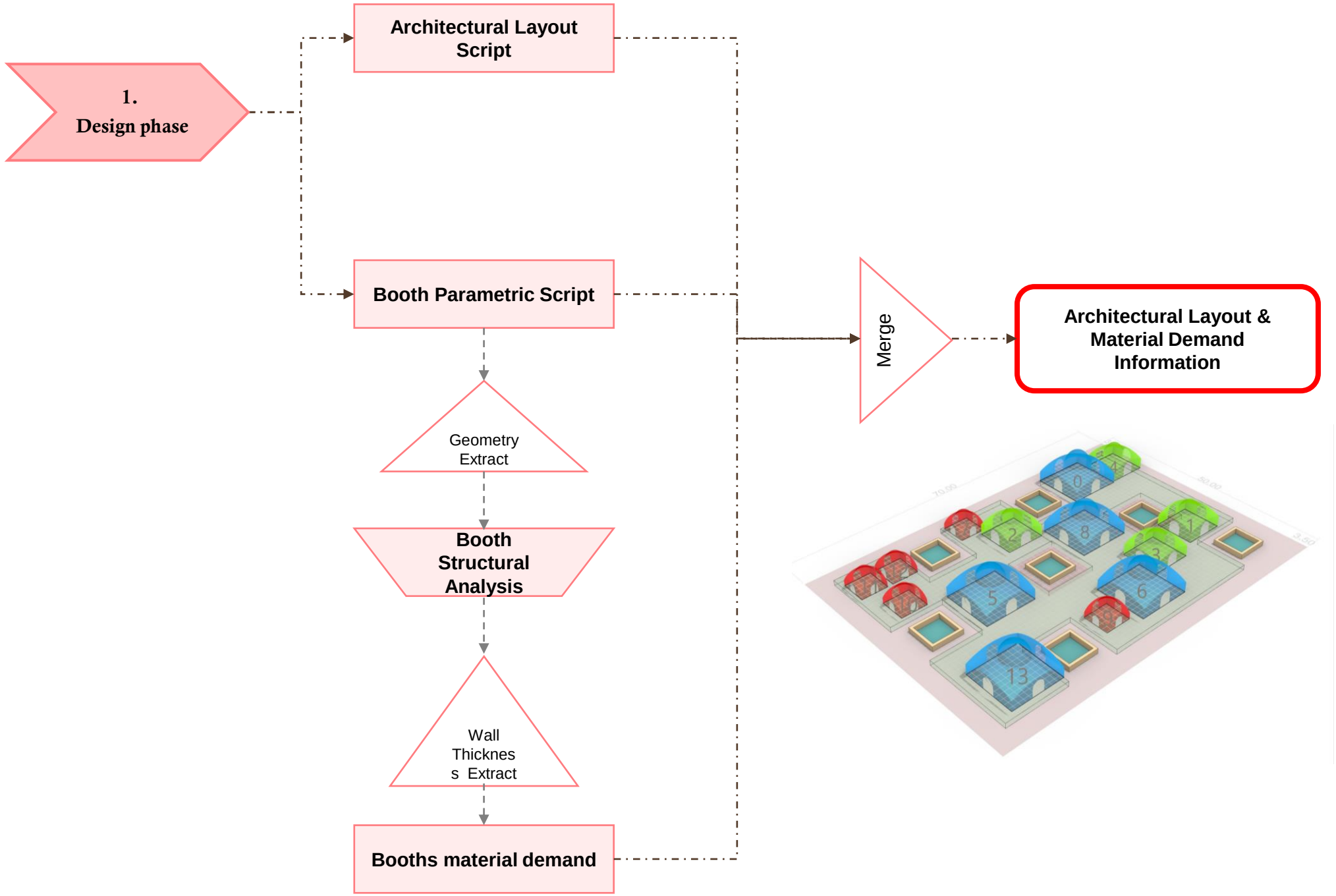
95000 Bricks- 2720 Trips

Total number:

129000 Bricks

370 Trips




1.
Design phase
Architectural Layout Script
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Geometry Extract
Booth Structural Analysis
Wall Thicknes s Extract
Booths material demand
Merge
Architectural Layout & Material Demand Information

DATA EXPORT- CSV FILE

Material Supplies as Nests

Ponds as static obstacles

Booths Coordinate as food points and dynamic obstacles.

Booth material demand as food amount.

WORKFLOW

python™

1. **Design phase**

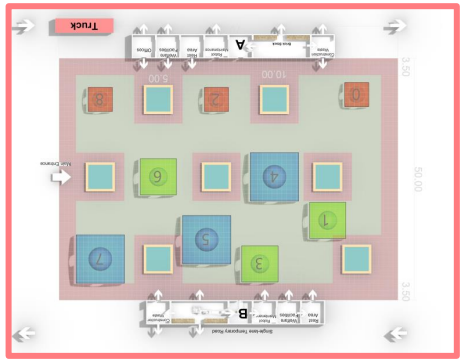
Architectural Layout Design

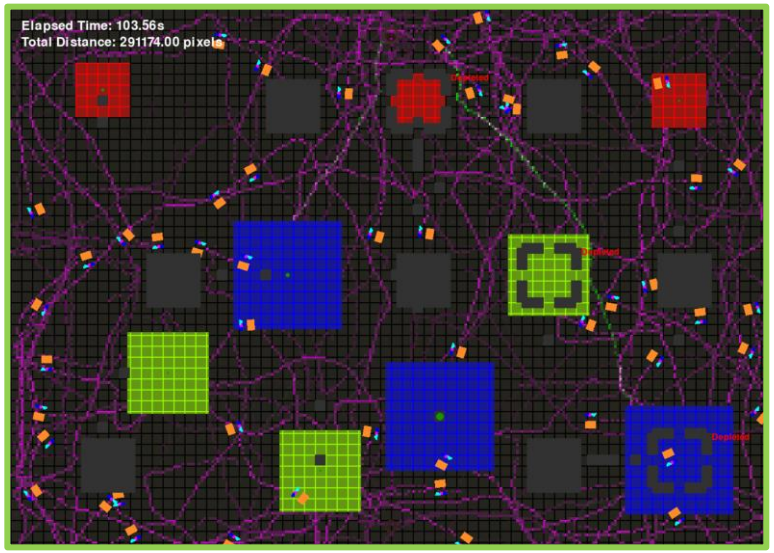
2. Simulation Phase

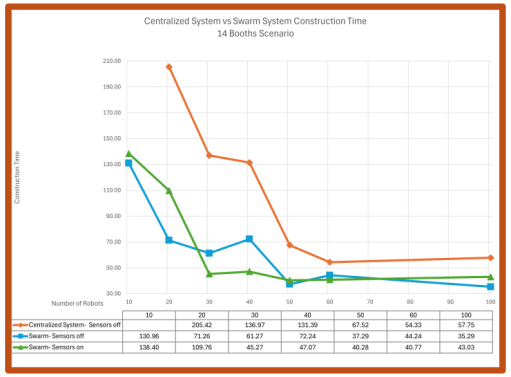
Architectural Layout Construction by Swarm Robots

3. Experiments & Analysis

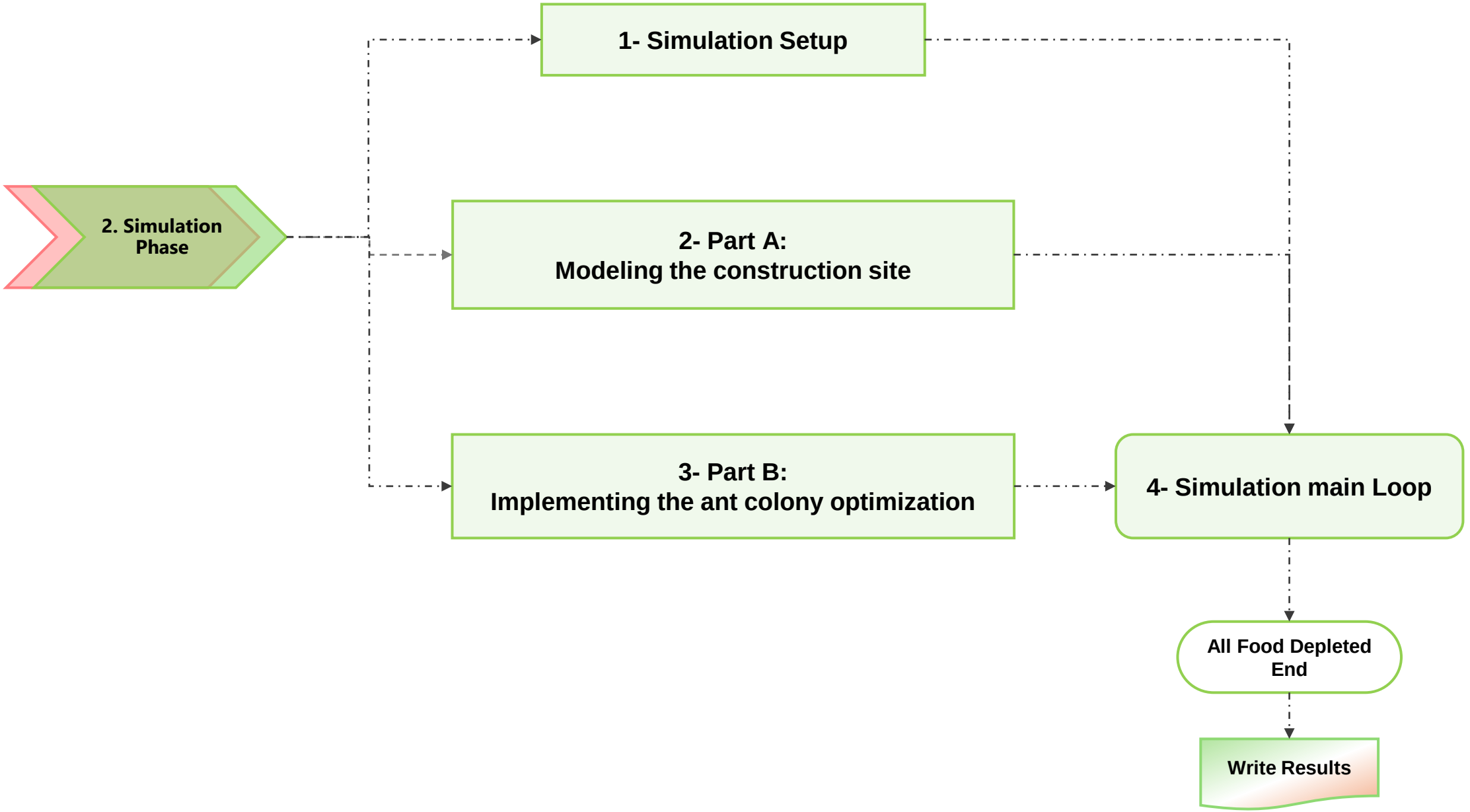
Simulation Results Analysis of Construction Scenarios

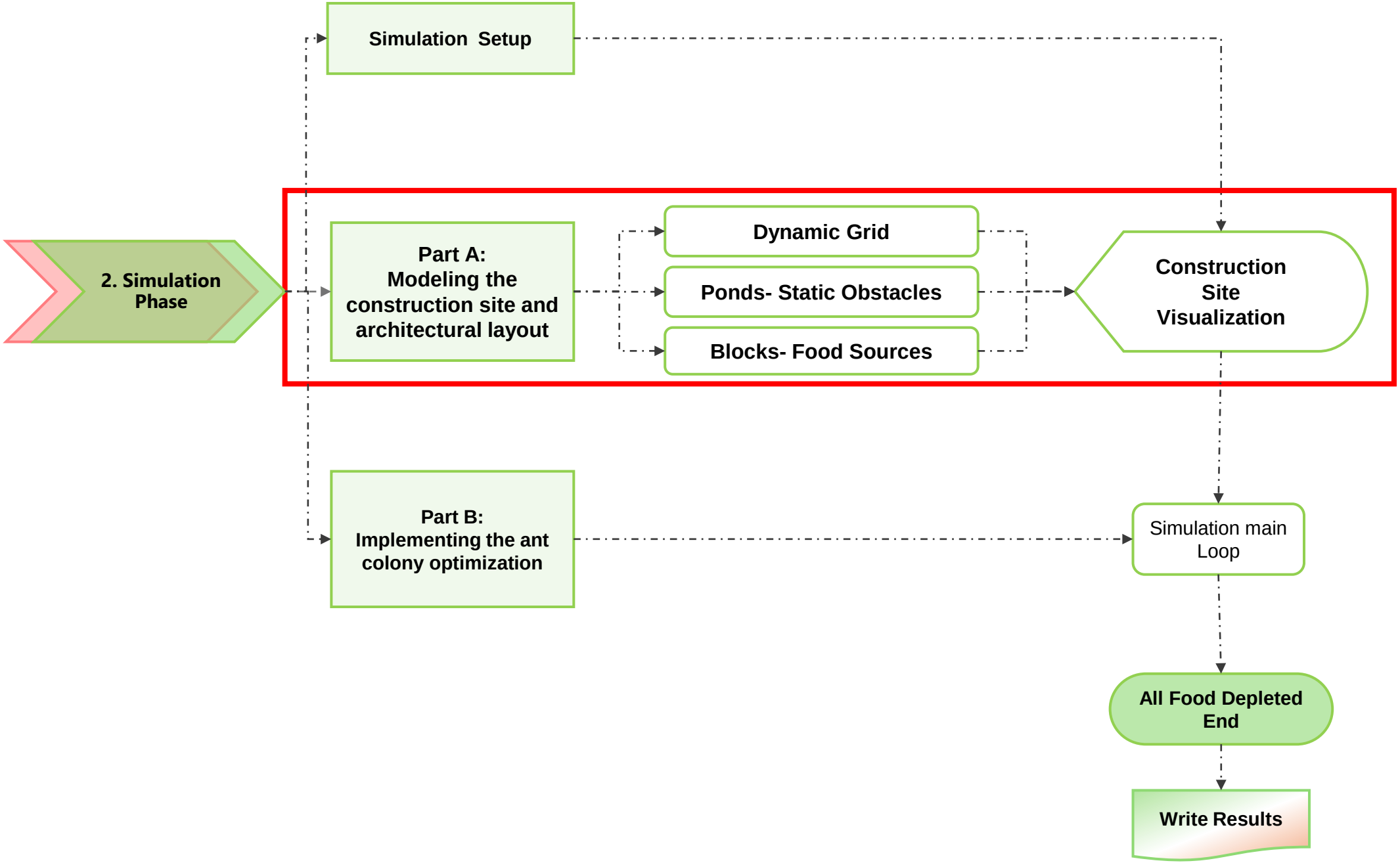




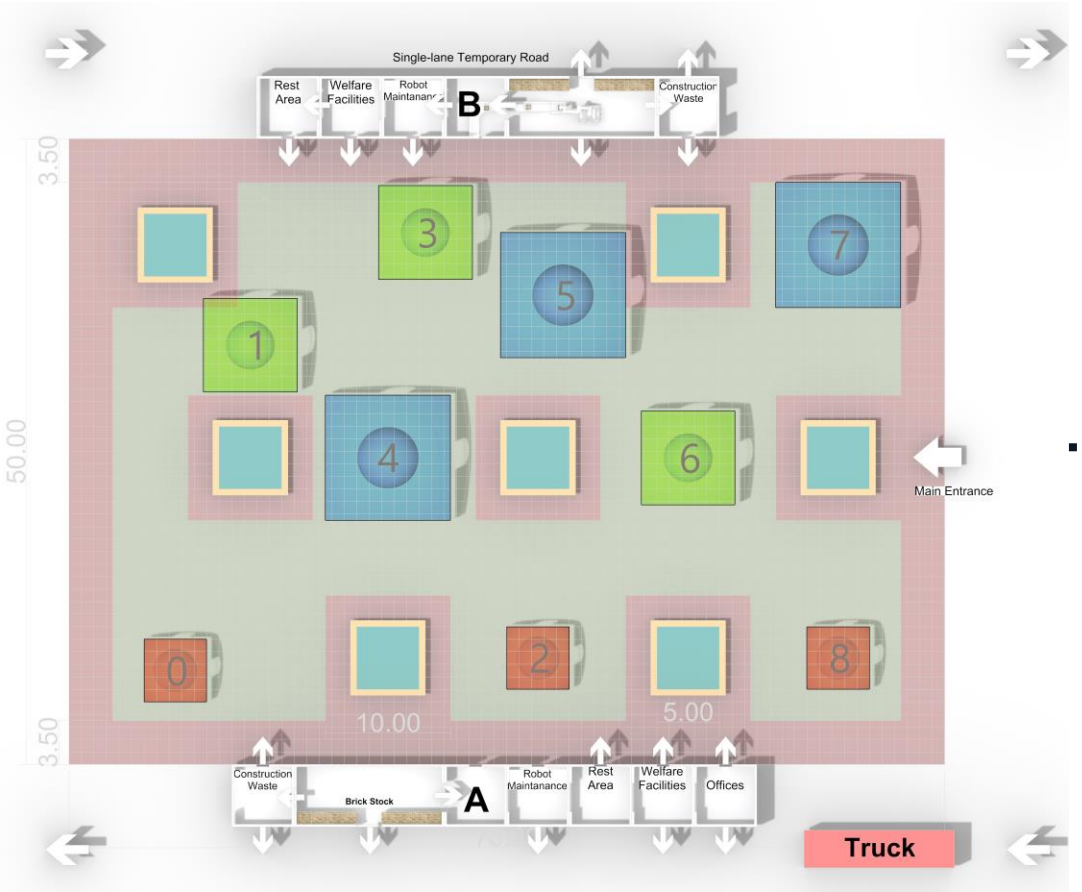


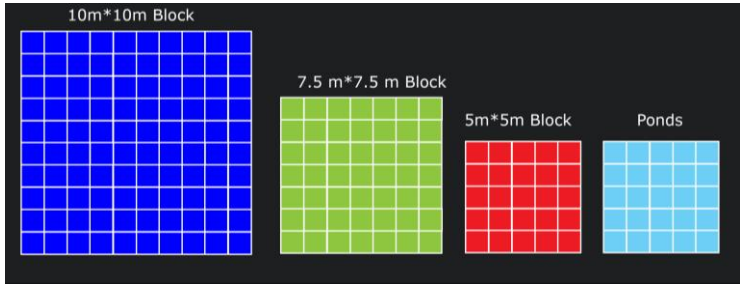
	10	20	30	40	50	60	100
Centralized System- Sensors off		205.42	136.97	131.39	67.52	54.33	57.75
Swarm- Sensors off	130.96	71.26	61.27	72.24	37.29	44.24	35.29
Swarm- Sensors on	138.40	109.76	45.27	47.07	40.28	40.77	43.03

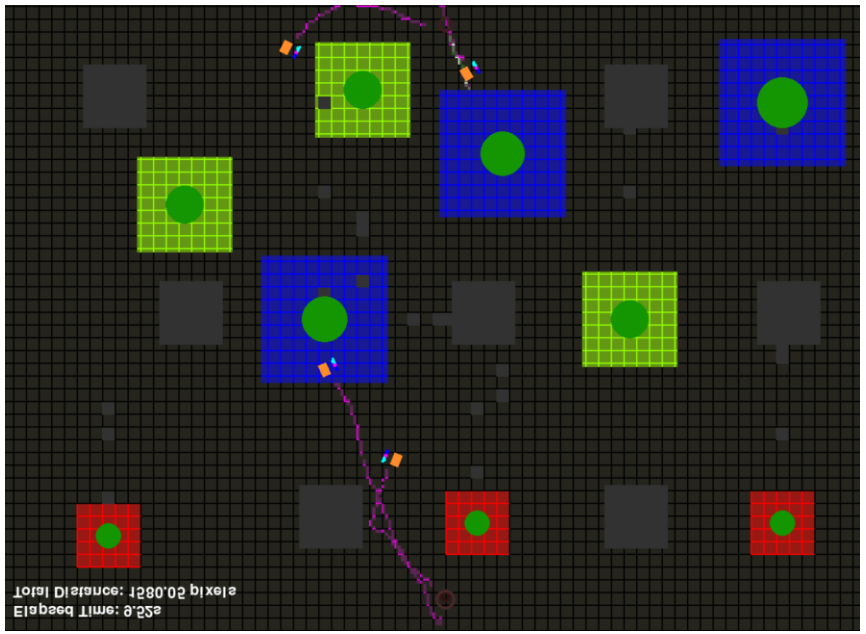

1- Simulation Setup
2. Simulation Phase
2- Part A:
Modeling the construction site
3- Part B:
Implementing the ant colony optimization
4- Simulation main Loop
All Food Depleted
End
Write Results


Simulation Setup
2. Simulation Phase
Part A: Modeling the construction site and architectural layout
Dynamic Grid
Ponds- Static Obstacles
Blocks- Food Sources
Construction Site Visualization
Part B: Implementing the ant colony optimization
Simulation main Loop
All Food Depleted End
Write Results

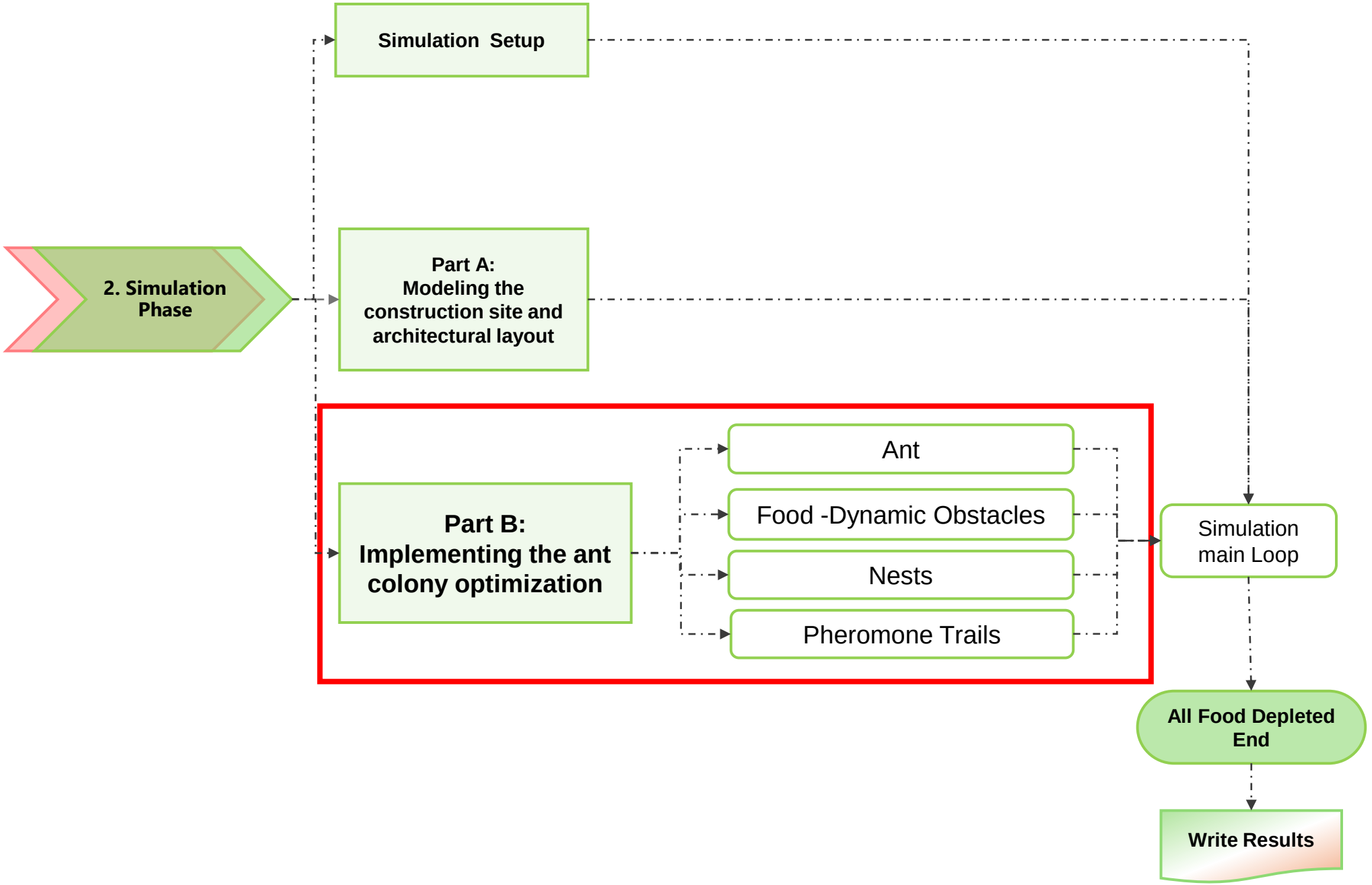
PART A: CONSTRUCTION SITE VISUALIZATION







Enhancing Construction Autonomy on Dynamic Building Sites Through Implementation of Swarm Robotics


Simulation Setup
2. Simulation Phase
Part A: Modeling the construction site and architectural layout
Part B: Implementing the ant colony optimization
Ant
Food -Dynamic Obstacles
Nests
Pheromone Trails
Simulation main Loop
All Food Depleted End
Write Results

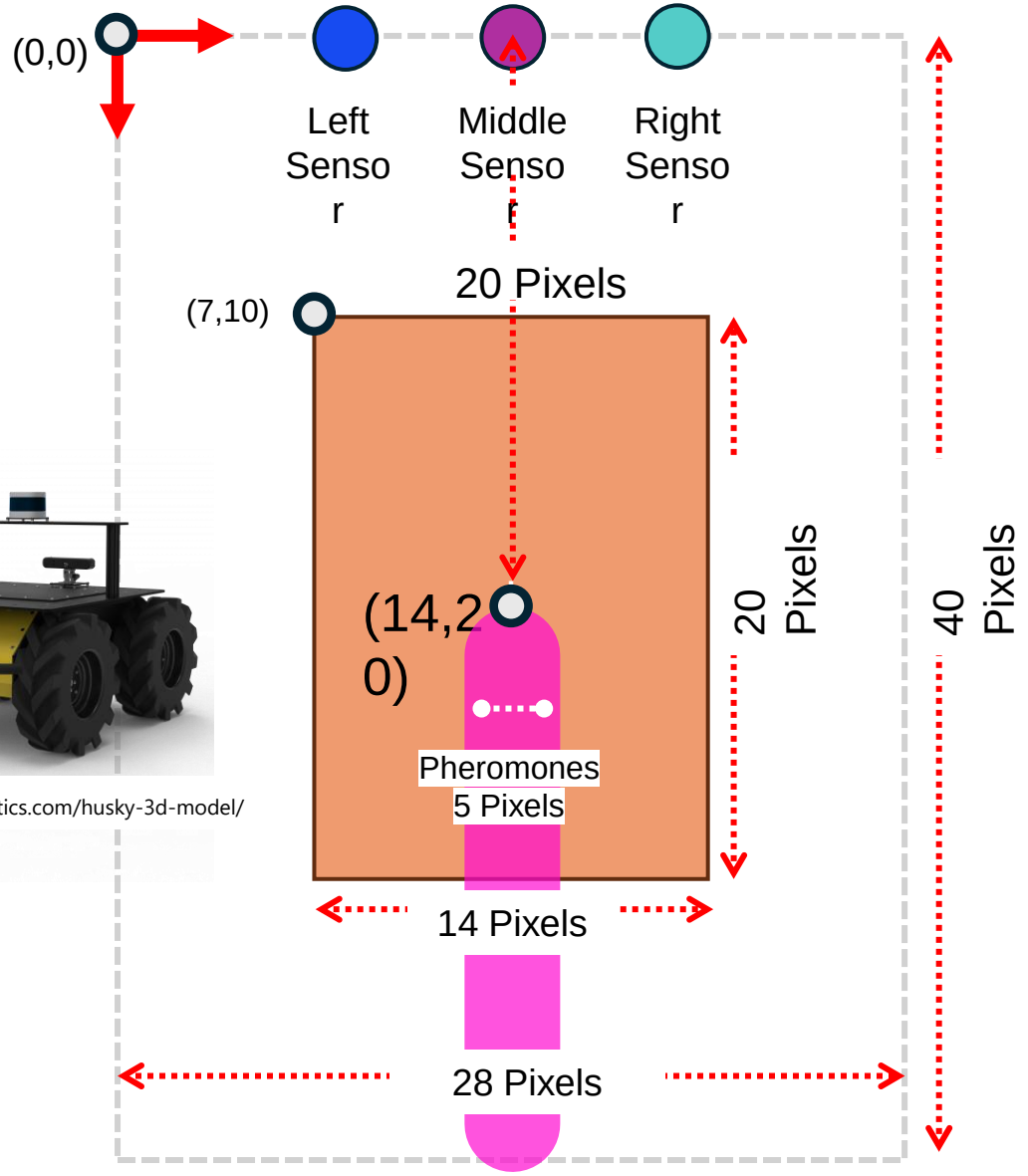
TECHNICAL FEATURES

- Husky's capacity of 35 bricks= the ant's consumption rate.
- Max Speed= 1m/s
- Dimension= Husky's Dimension Scaled
- Three Sensors
- Sensors Detection Values

  1- Pheromone value Result at the sensor point.

  2- RGB Values at the sensor point.

Source: https://clearpathrobotics.com/husky-3d-model/



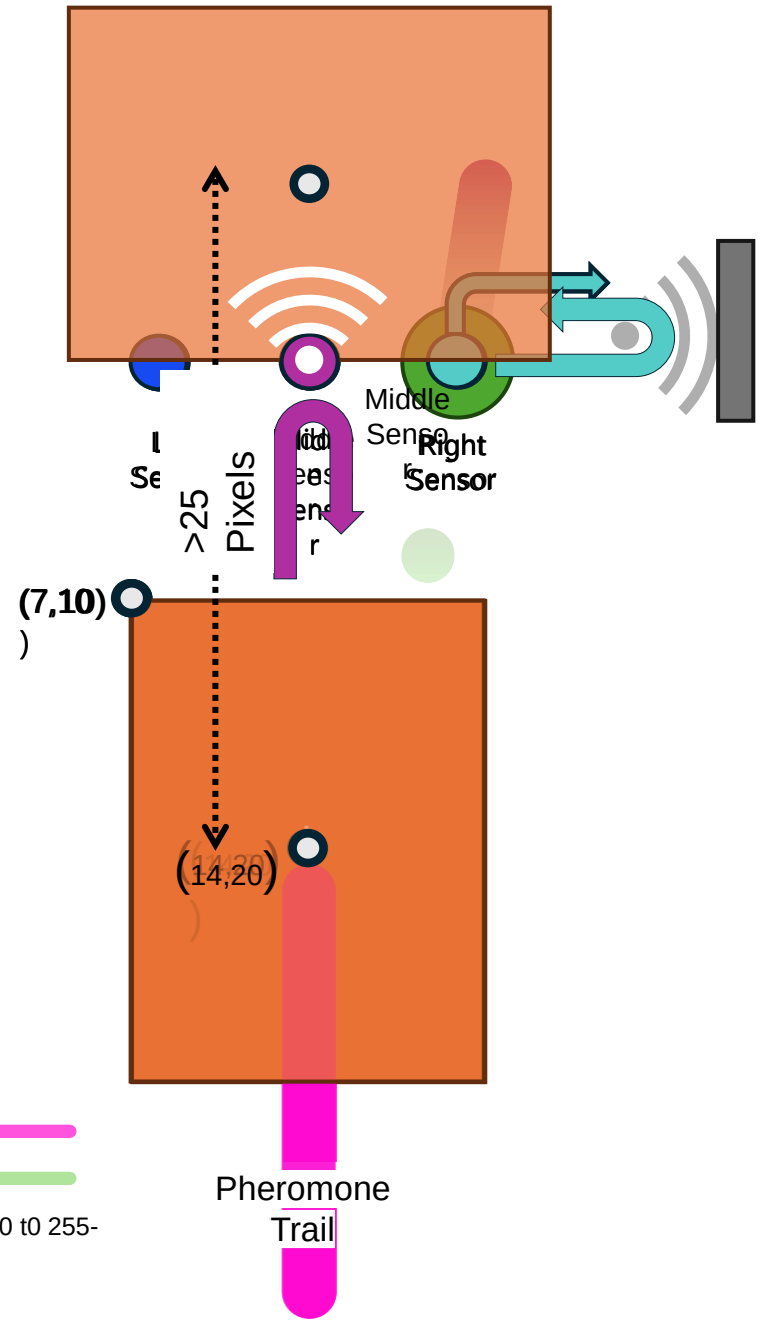
Behavioral Adjustments

1- Higher Pheromone Detection

2- Finding Food

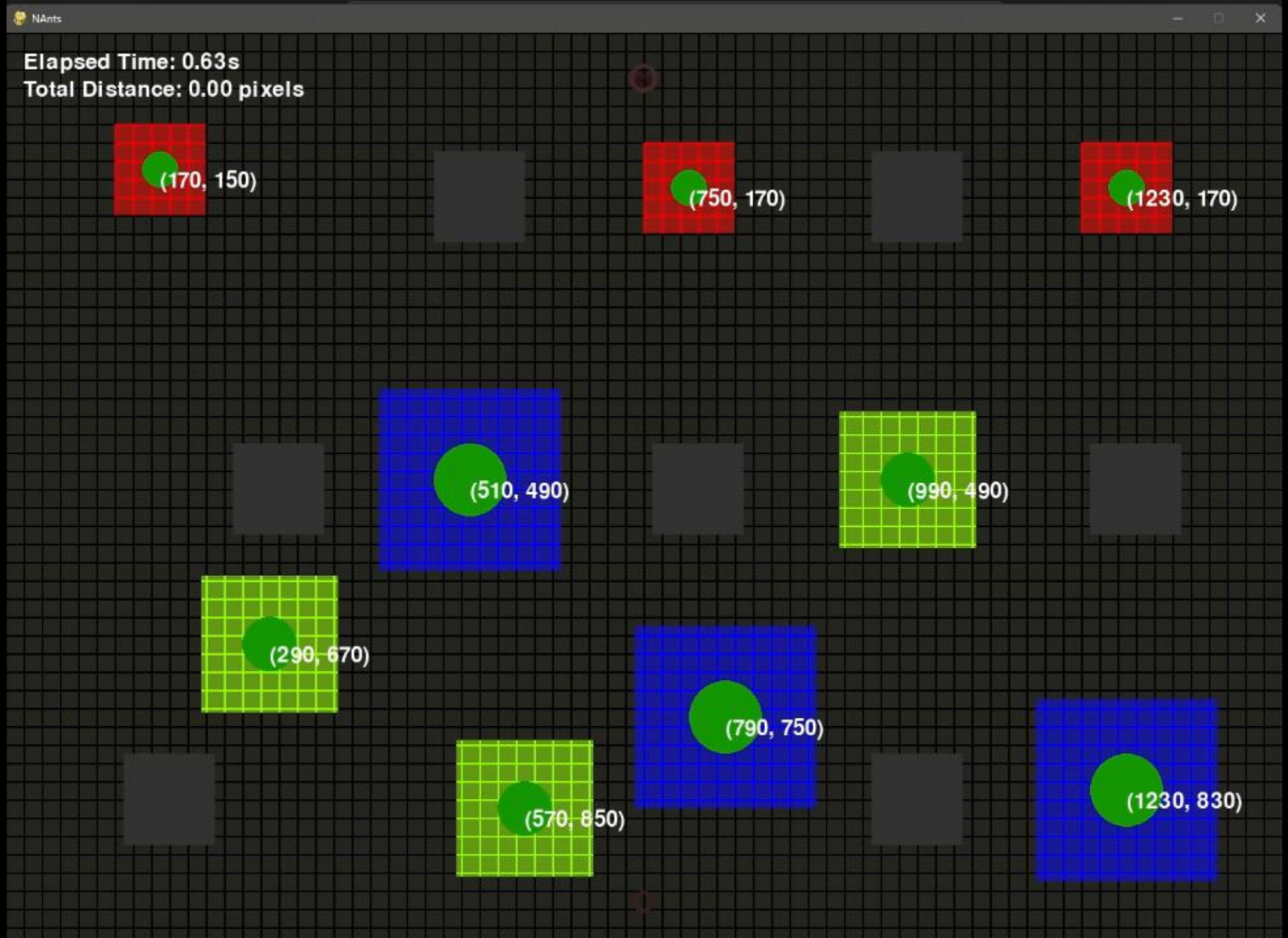
3- Obstacle Detection

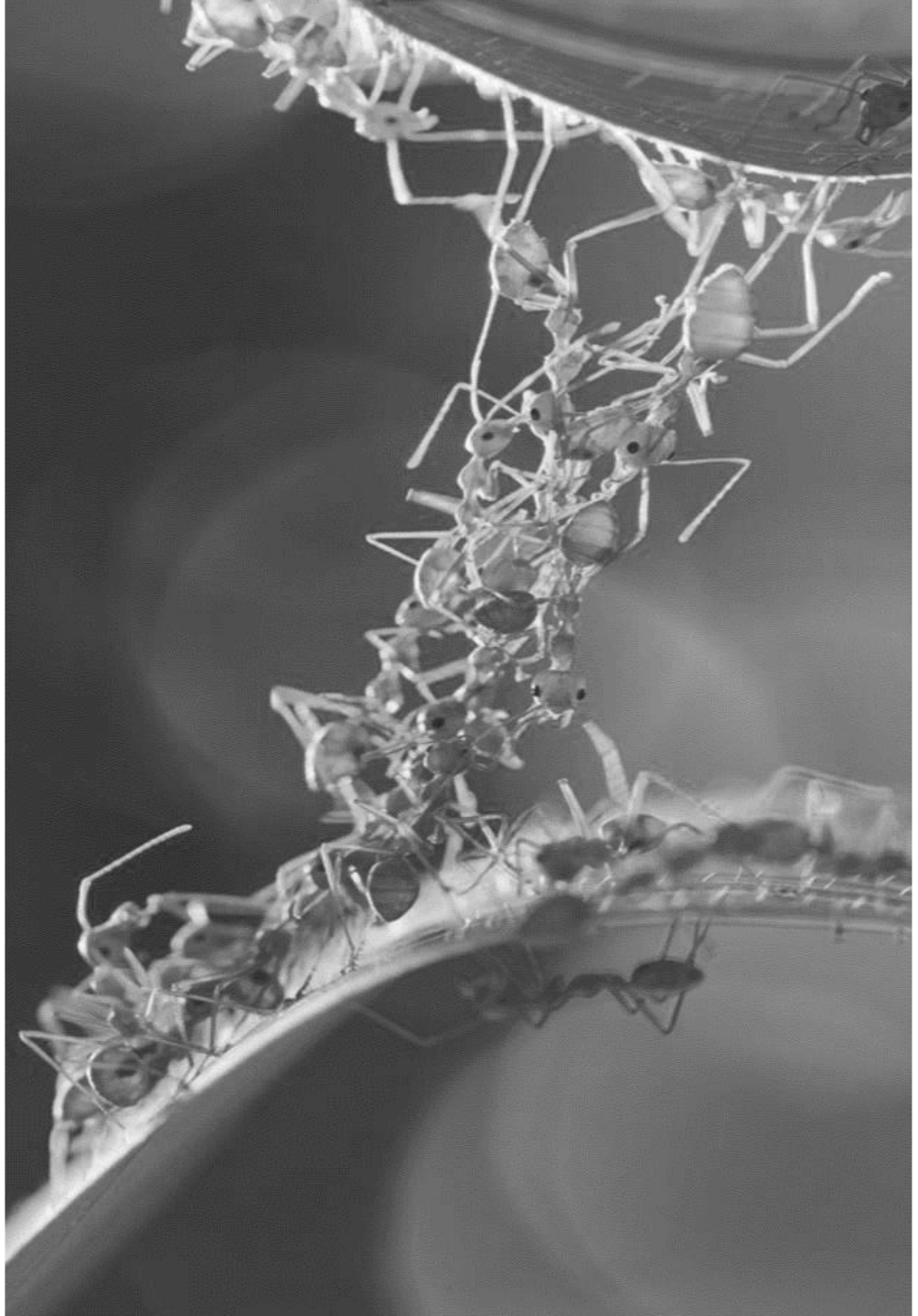
4- Collision Detection with Other Robots



Carrying food to nest= Green Trail- (0, 255, 0)

Pheromone Intensity= Green Color Intensity mapped – 0 t0 255-

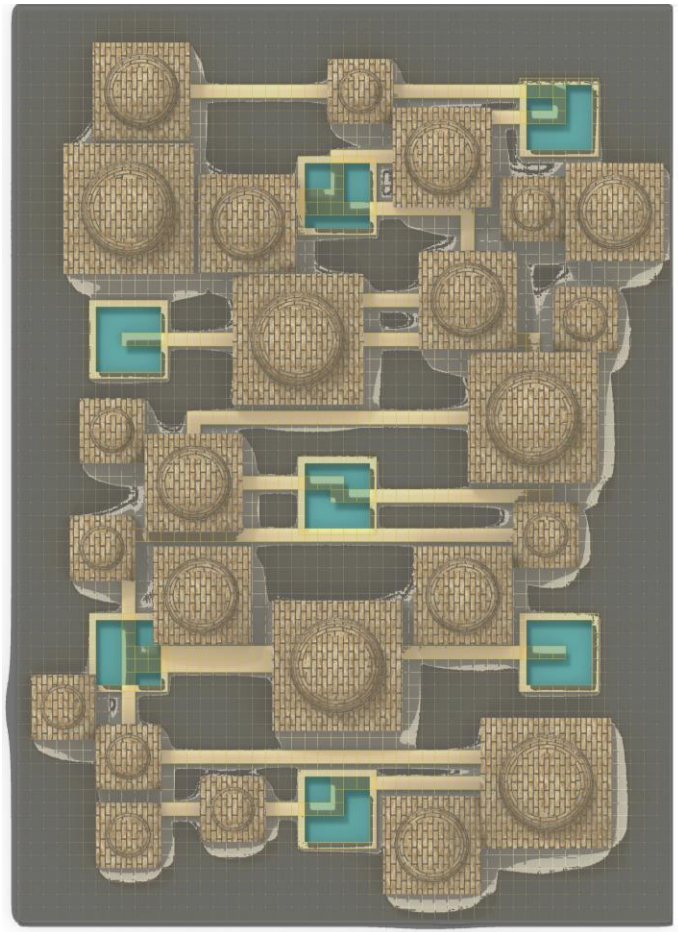

NAnts
Elapsed Time: 0.63s
Total Distance: 0.00 pixels
(170, 150)
(750, 170)
(1230, 170)
(510, 490)
(990, 490)
(290, 670)
(790, 750)
(570, 850)
(1230, 830)

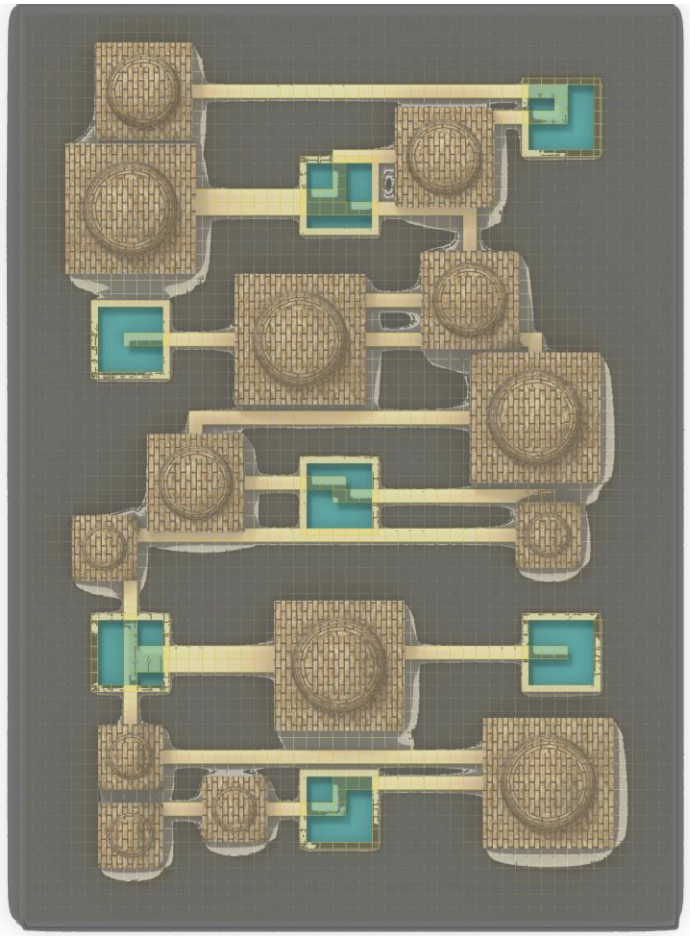


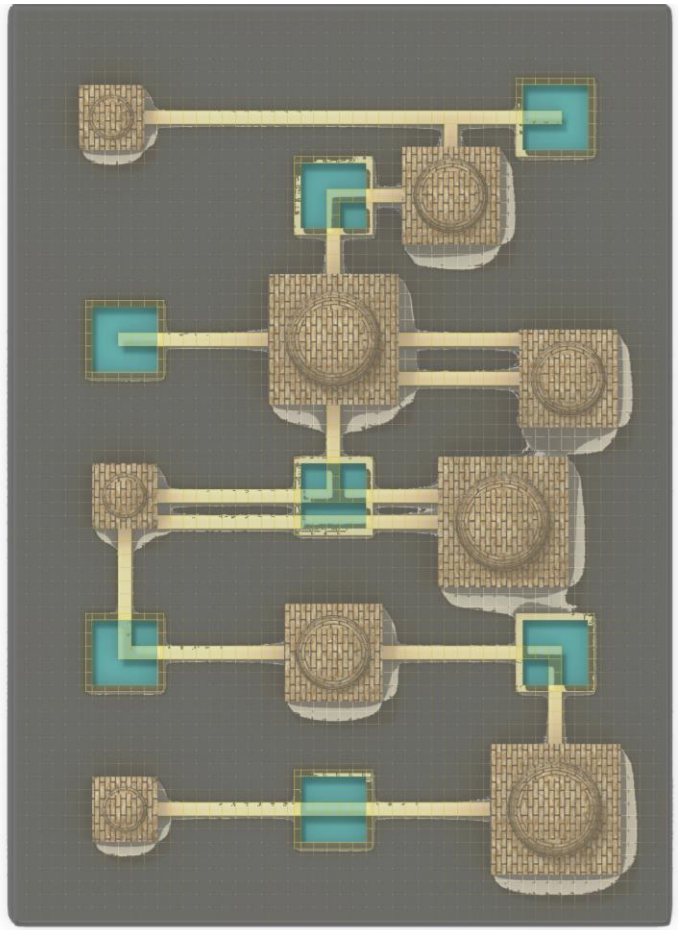
CHAPTERS

1. Introduction
2. Literature Review
3. Implementation
4. Simulation
5. Experiments
6. Results
7. Conclusion
8. Discussion
9. Reflection

WHAT HAPPENS?

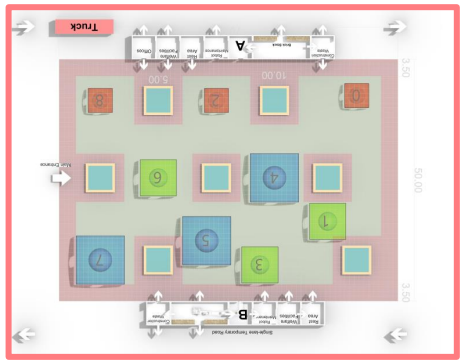


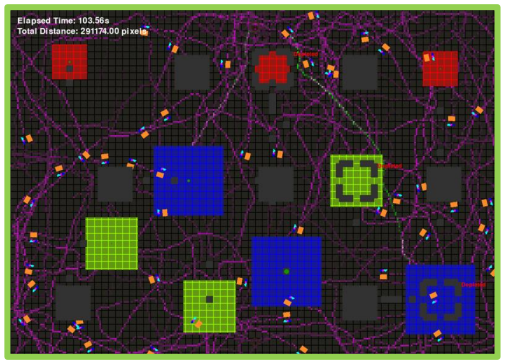


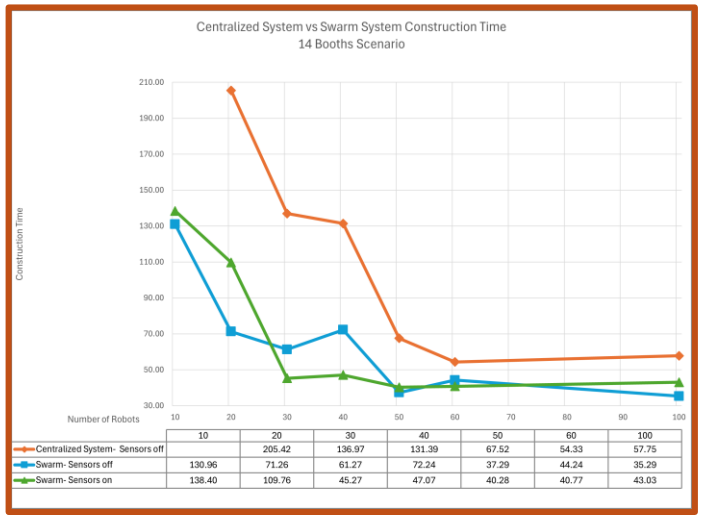


WORKFLOW

1. Design phase → Architectural Layout Design → **2. Simulation Phase** → Architectural Layout Construction by Swarm Robots → **3. Experiments & Analysis** → Simulation Results Analysis of Construction Scenarios







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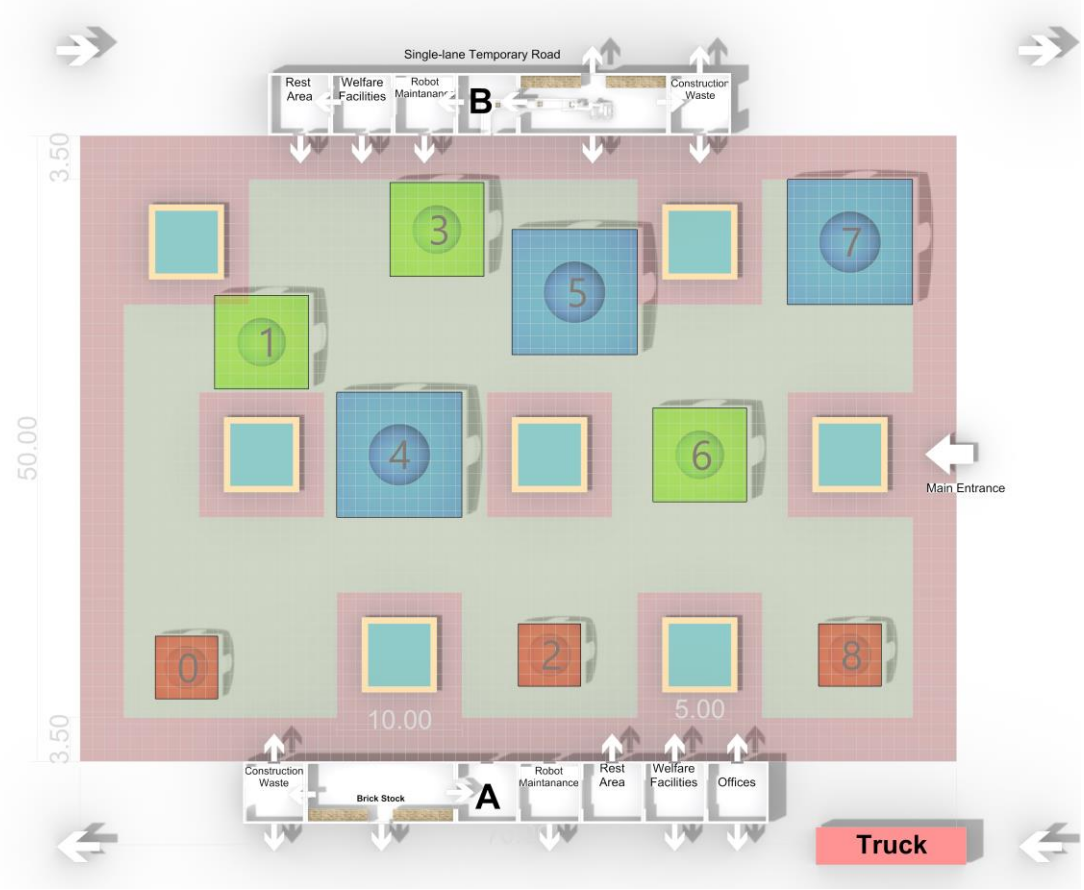
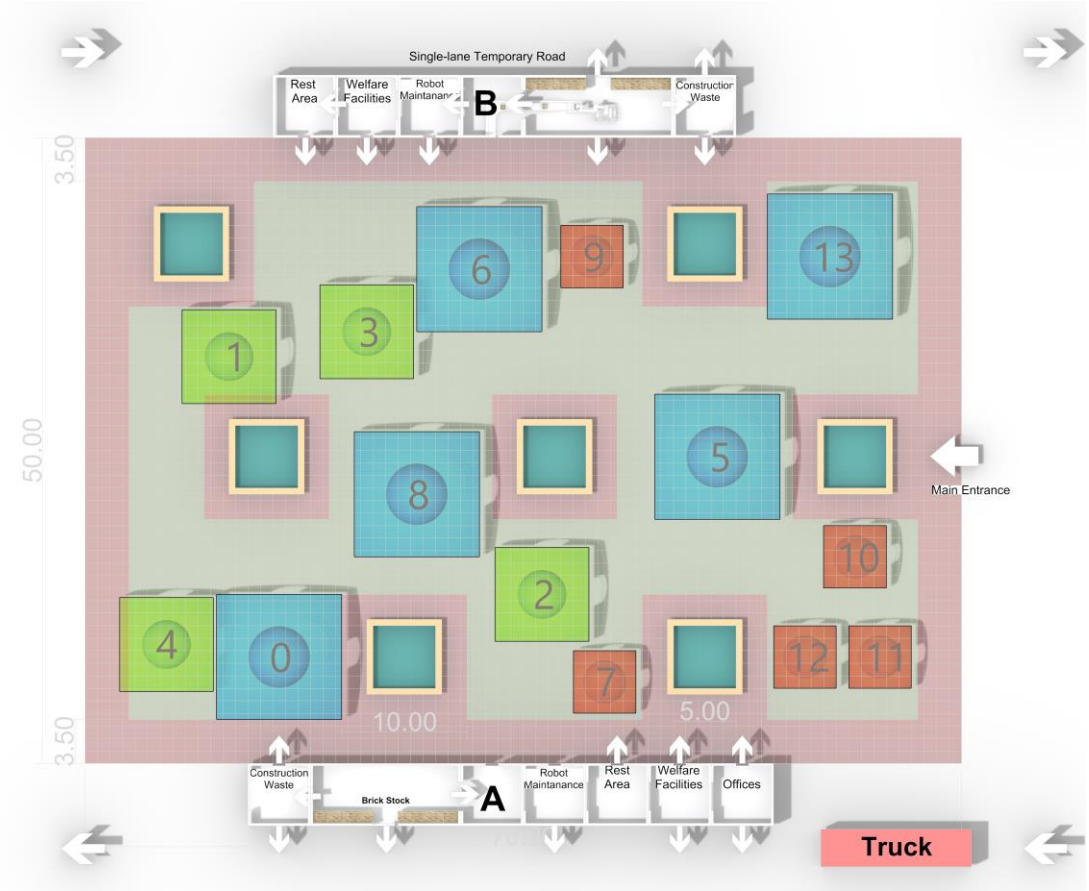
SCENARIOS



LESS COMPACT-9 BOOTHS



MORE COMPACT- 14 BOOTHS

VARIABLES UNDER INVESTIGATION

- **Number of Robots**

7 values tested: Tested with 10, 20, 30, 40, 50, 80, and 100 robots.

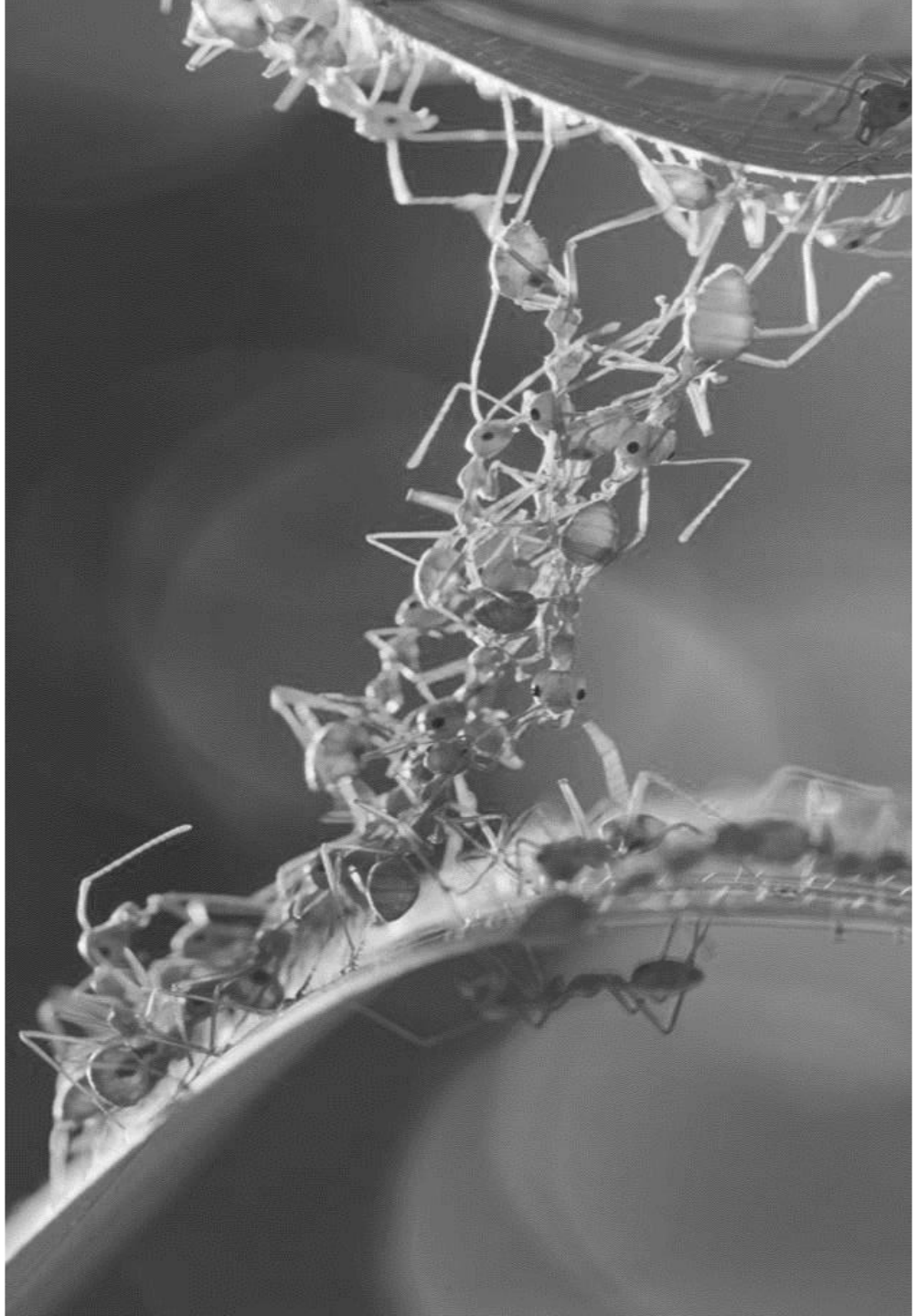
- **Pheromone Evaporation Rate**

8 values tested: No Evaporation, 1%, 5% , 10%, 20%, 30%, 50%, 80% and Full Evaporation.

Assessment Criteria:

Total construction time

Total Walking Distance



CHAPTERS

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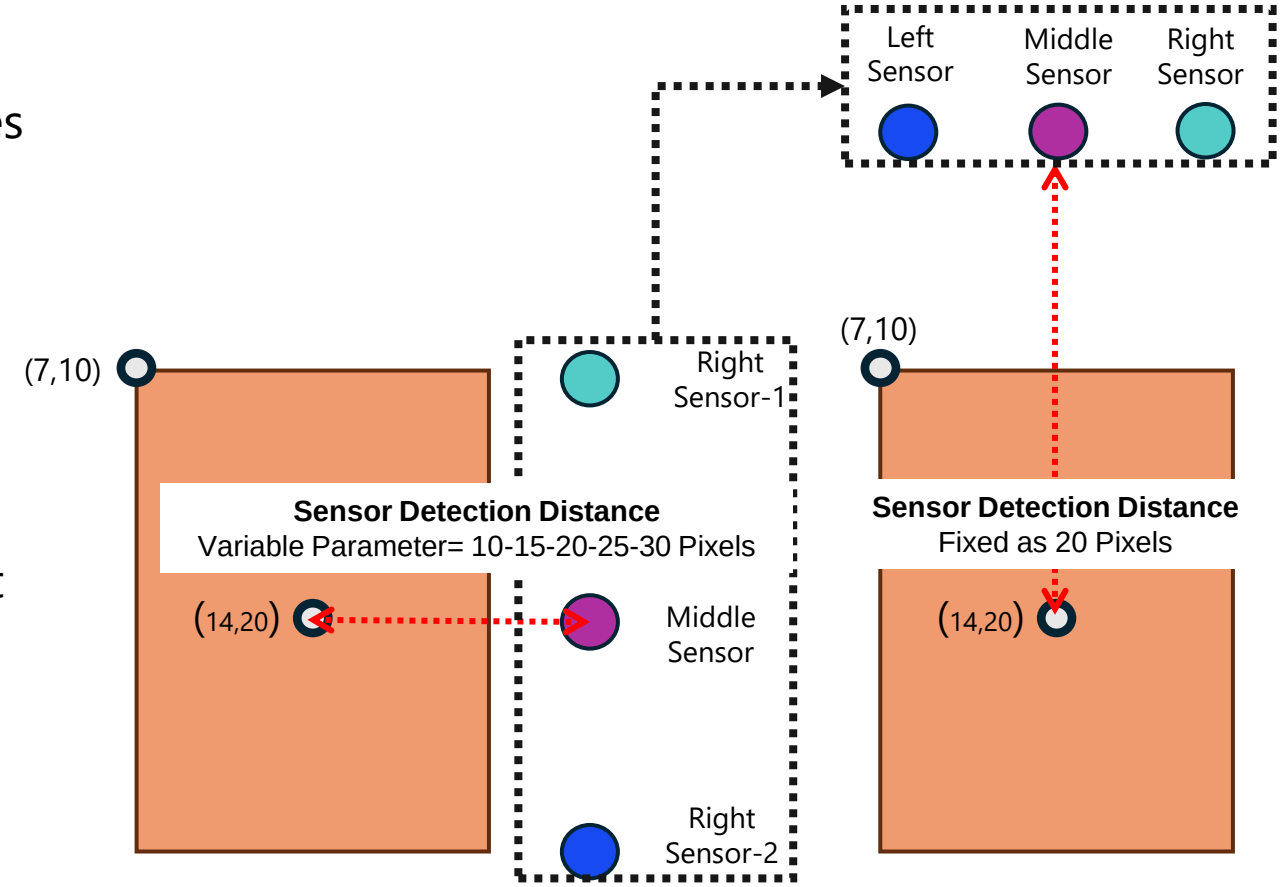
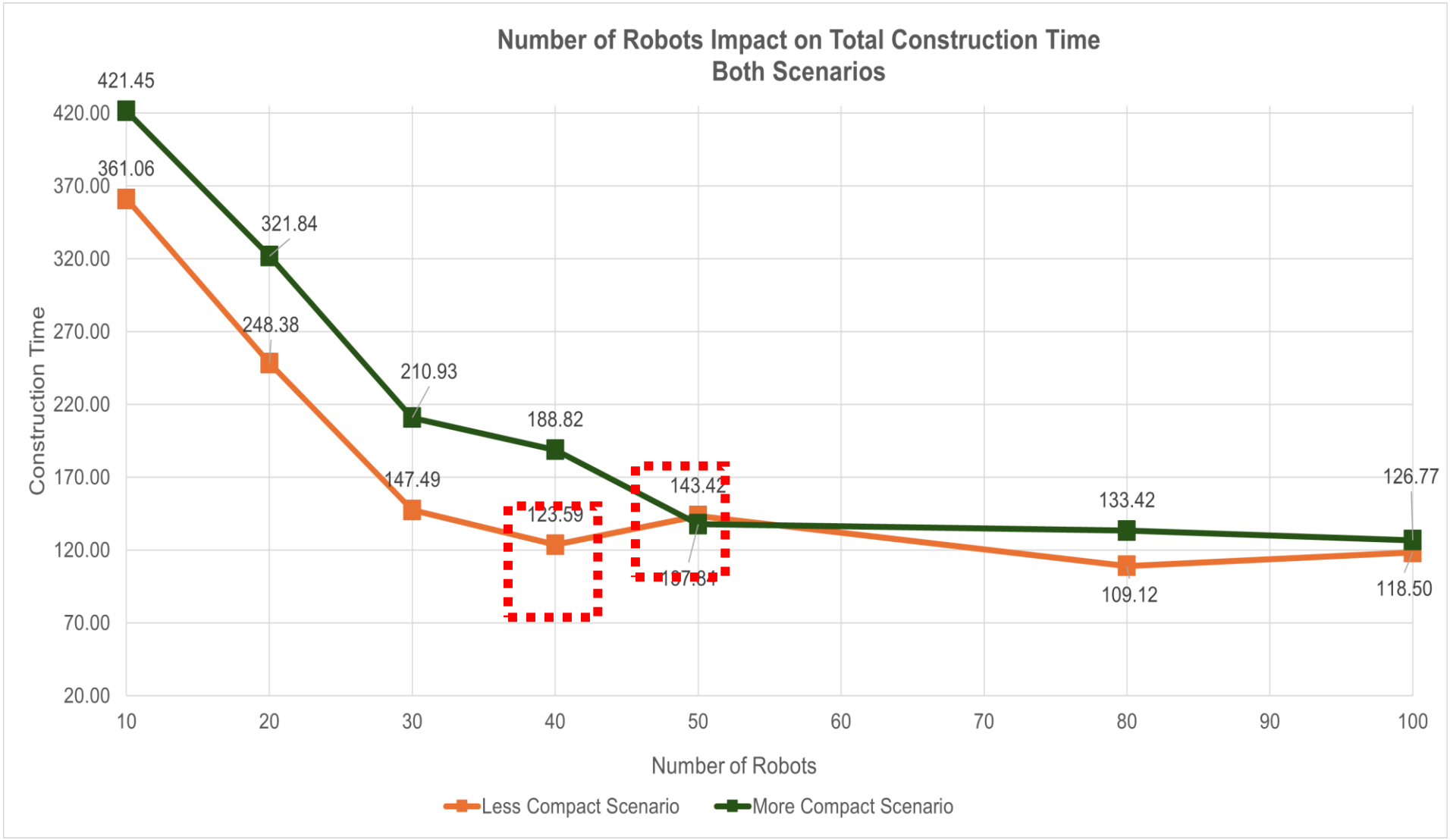
EXPERIMENTS

- Experiments so far 92 ⋯⋯▶ Repeated 3 times
- 60 belongs to before sensor relocation
- After the Sensor Relocation from Right to Front

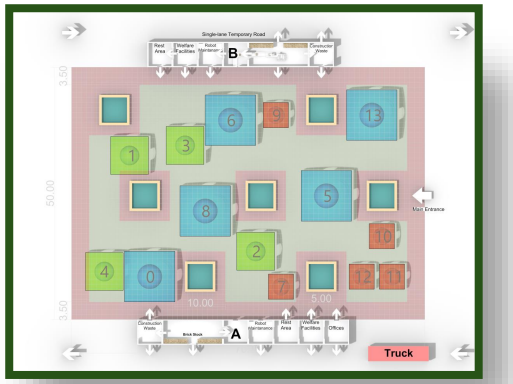
  32 Experiments



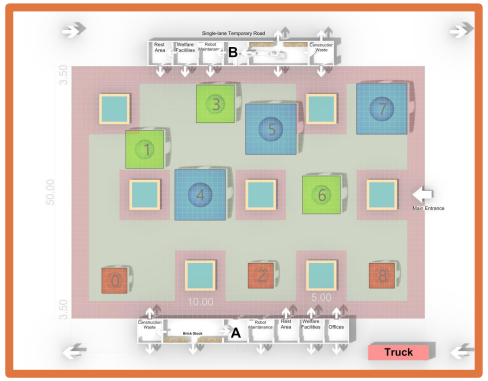
1- The Impact of the Number of Robots on Construction Time



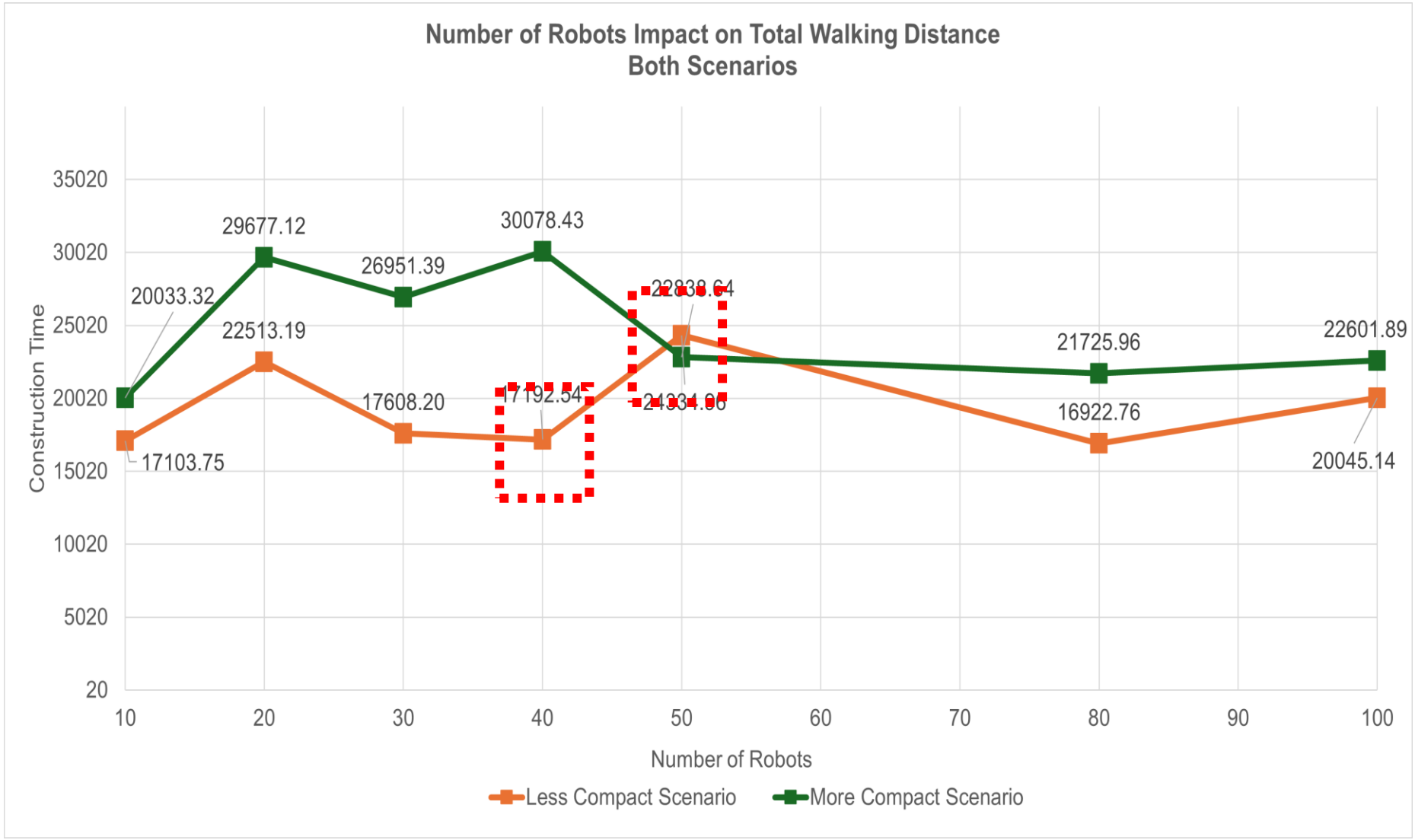
MORE COMPACT- 14 BOOTHS



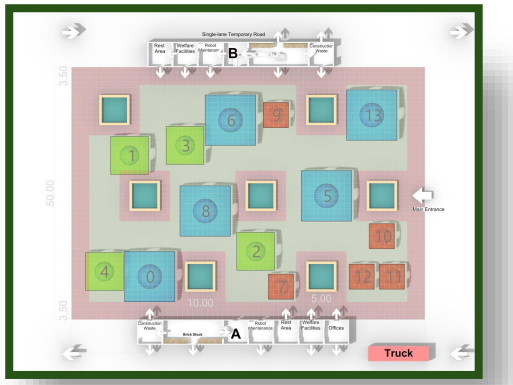
LESS COMPACT-9 BOOTHS



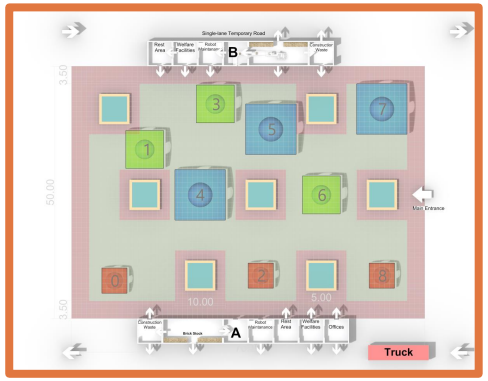
2- The Impact of the Number of Robots on Walking Distance



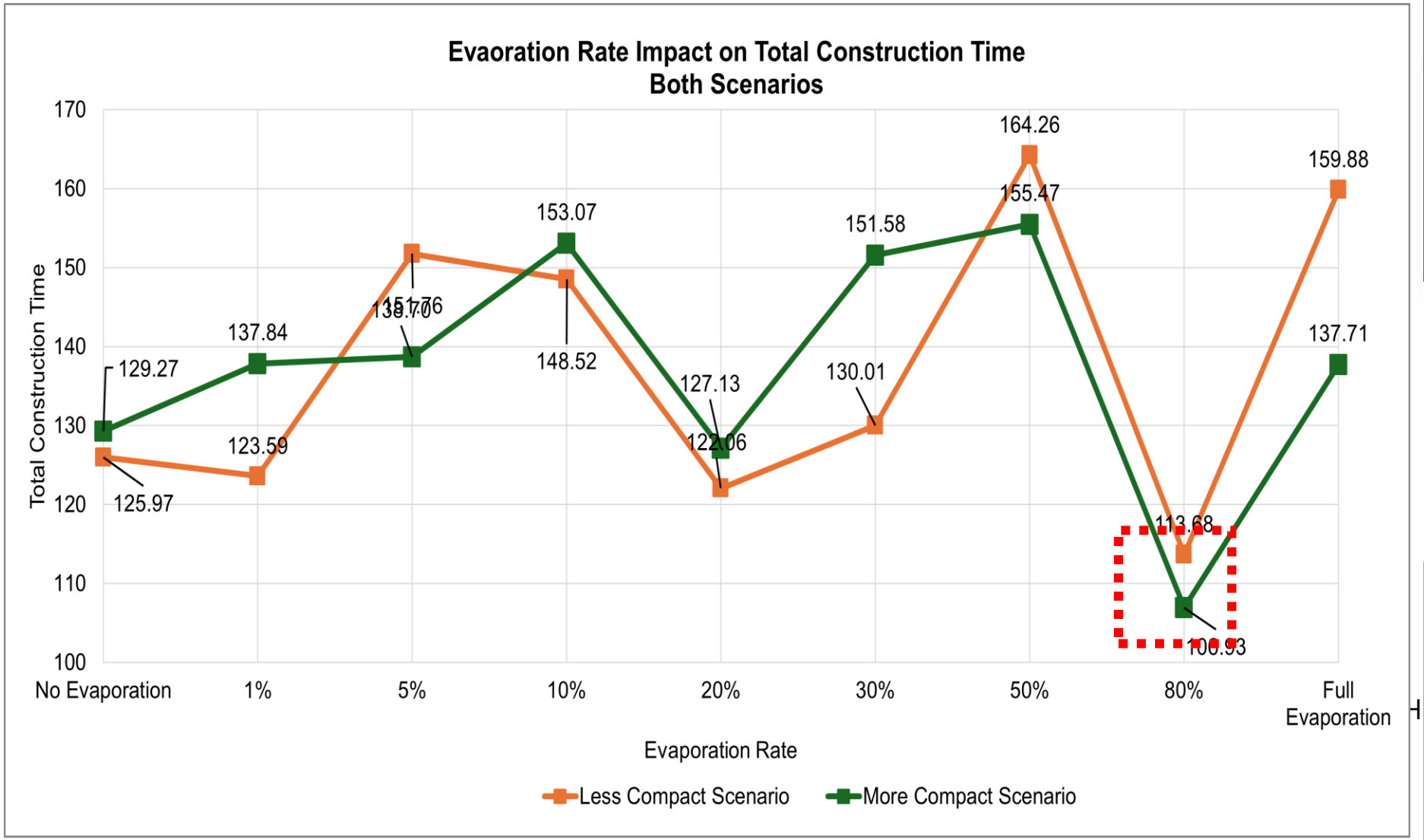
MORE COMPACT- 14 BOOTHS



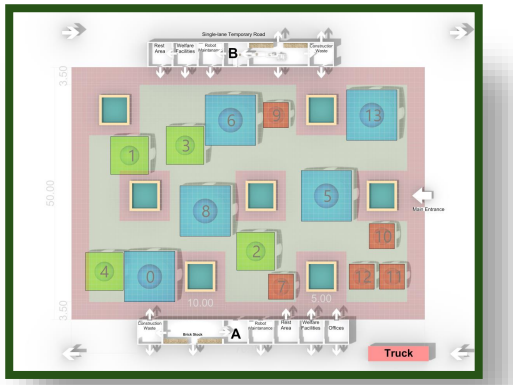
LESS COMPACT-9 BOOTHS



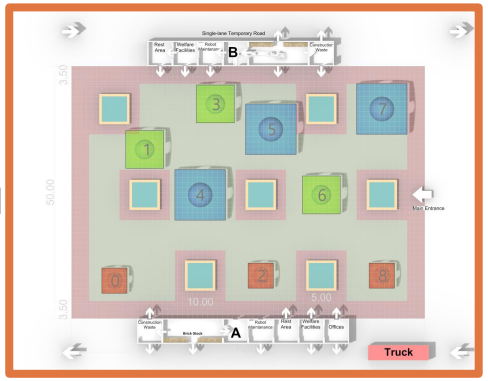
3- The Impact of Pheromone Evaporation Rate on Construction Time



MORE COMPACT- 14 BOOTHS

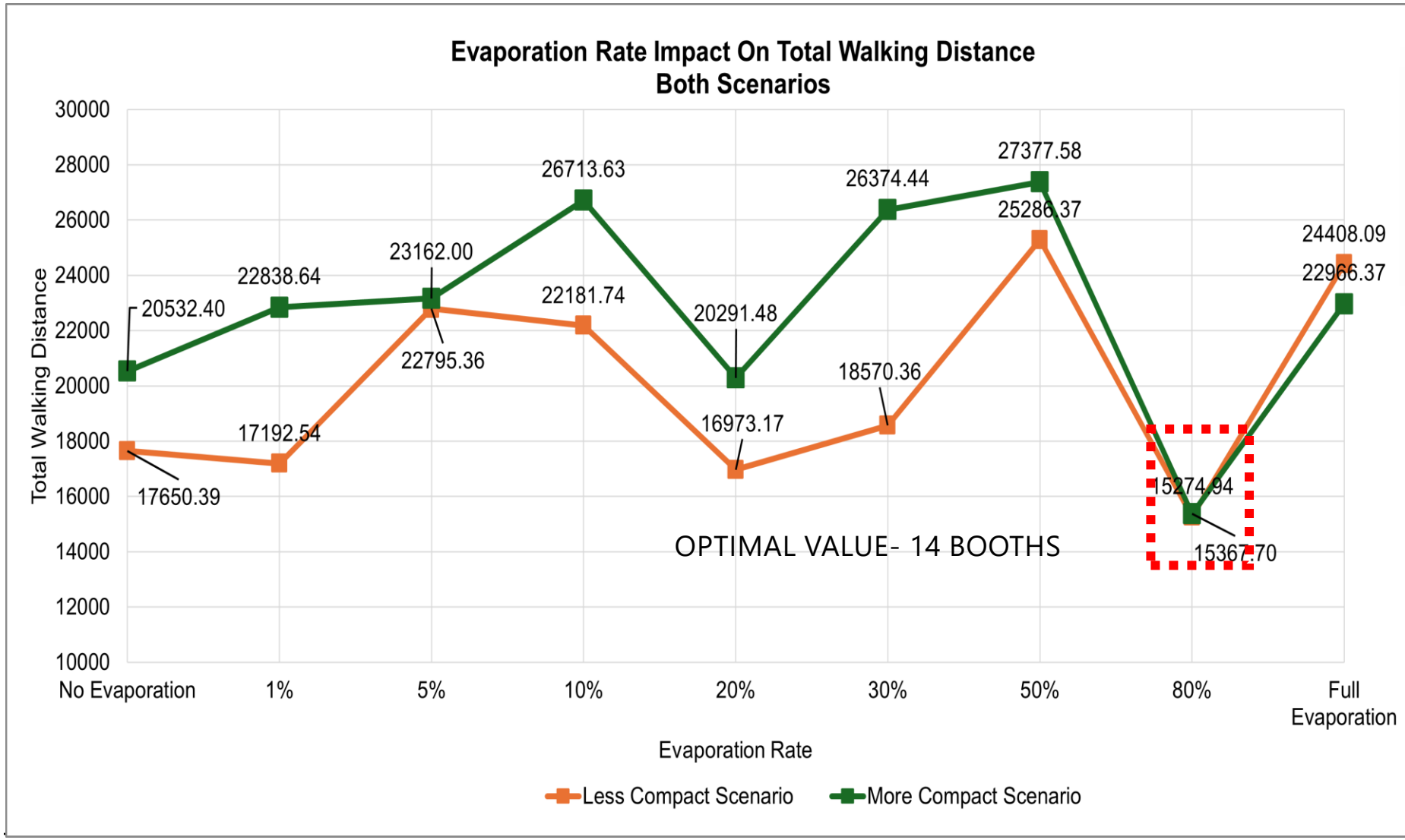


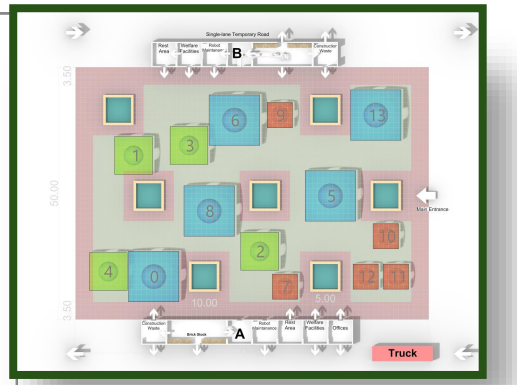
LESS COMPACT-9 BOOTHS



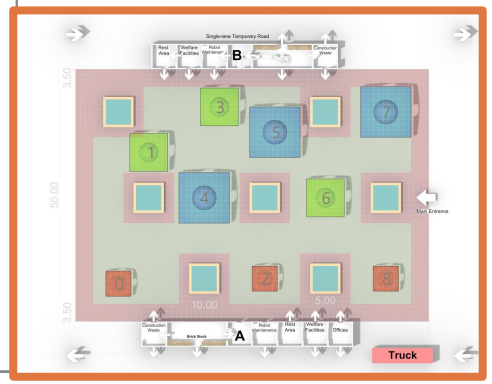
4- The Impact of Pheromone Evaporation Rate on Walking Distance

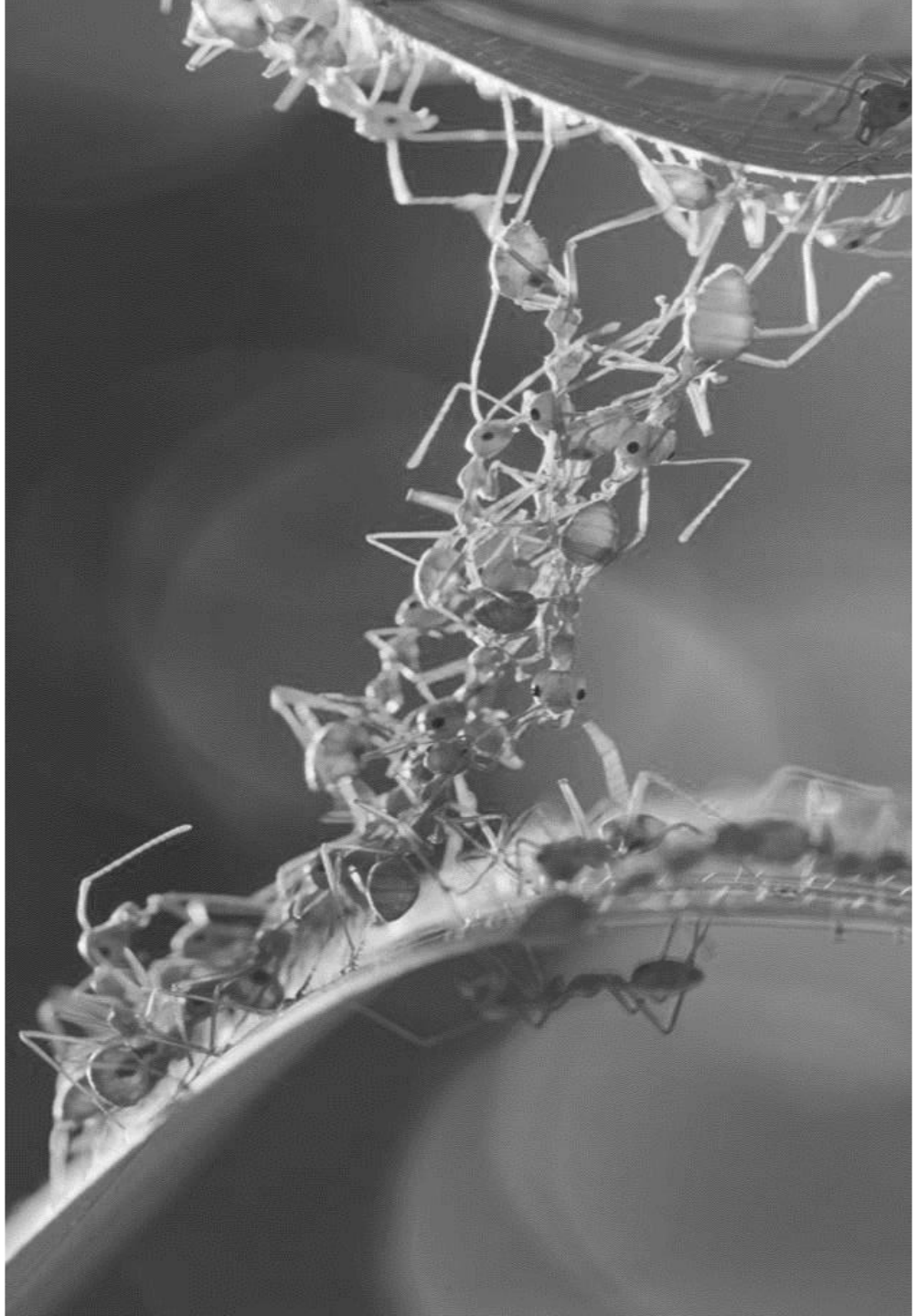
MORE COMPACT- 14 BOOTHS





LESS COMPACT-9 BOOTHS





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FINDINGS

The number of Robots

More straightforward correlation with Construction time/ Walking Distance

Less Sensitive to changes

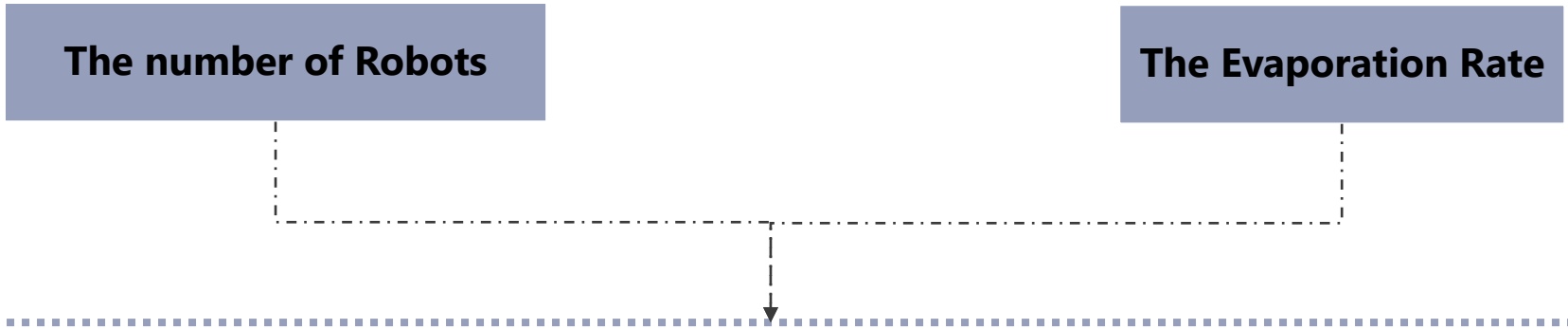
The Evaporation Rate

More Complex correlation with Construction time/ Walking Distance

More Sensitive to changes

Should be Investigated in the whole spectrum, Not a specific section

FINDINGS



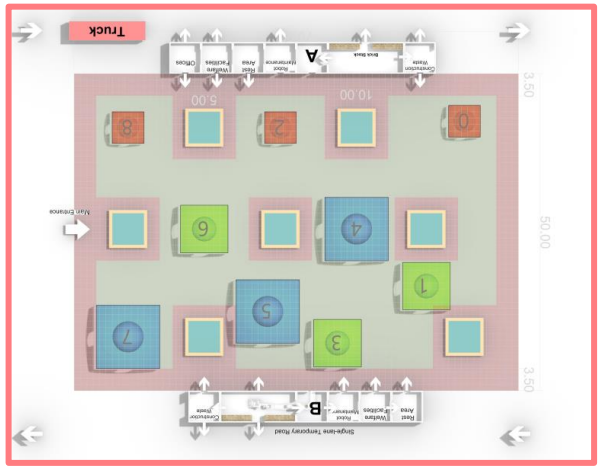
- The optimal parameters are highly scenario-dependent.
- A unique set of parameters cannot be applied to all scenarios, even within the same construction site.
- Each scenario should be individually optimized before construction.

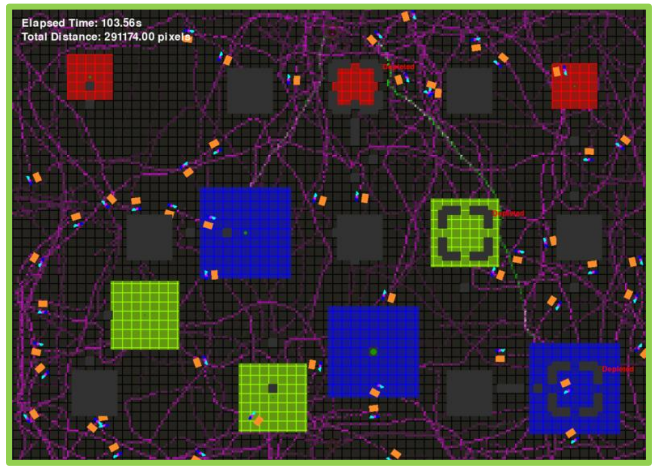
"HOW CAN SWARM ROBOTS PERFORM AS AN ON-SITE ADAPTIVE LOGISTIC SYSTEM ON A DYNAMIC CONSTRUCTION SITE?"

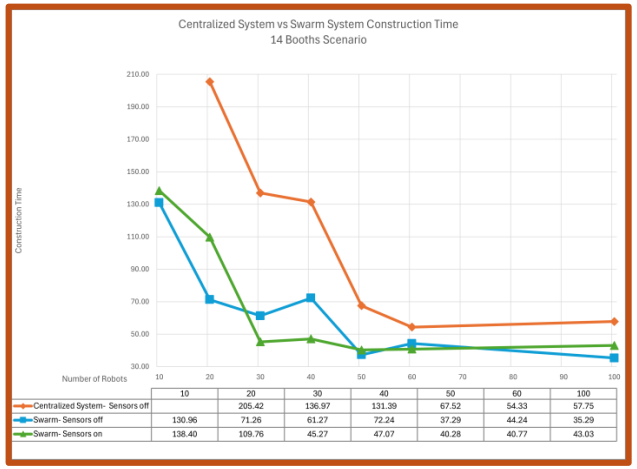
grasshopper

python™

1. Design phase → Architectural Layout Design → **2. Simulation Phase** → Architectural Layout Construction by Swarm Robots → **3. Experiments & Analysis** → Simulation Results Analysis of Construction Scenarios







	10	20	30	40	50	60	100
Centralized System- Sensors off		205.42	136.97	131.39	67.52	54.33	57.75
Swarm- Sensors off	130.96	71.26	61.27	72.24	37.29	44.24	35.29
Swarm- Sensors on	138.40	109.76	45.27	47.07	40.28	40.77	43.03

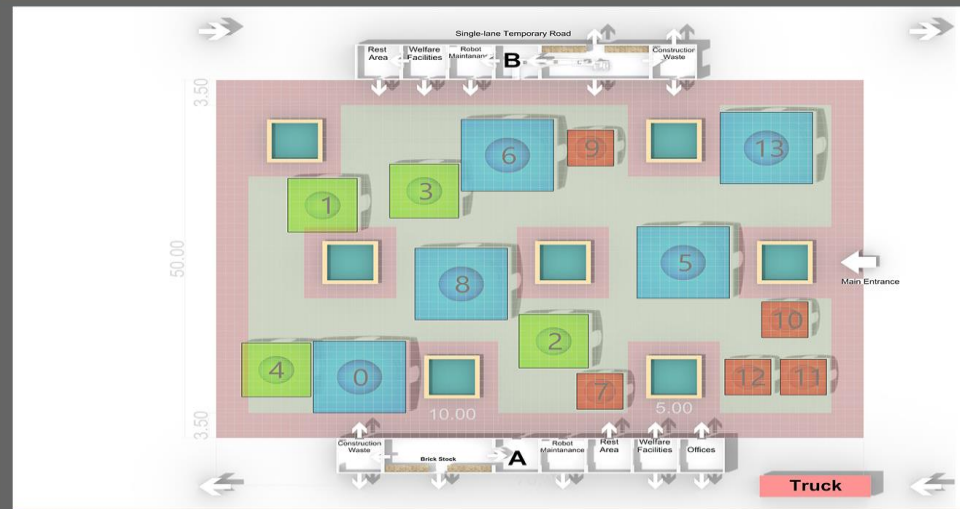
ANT ROLLER

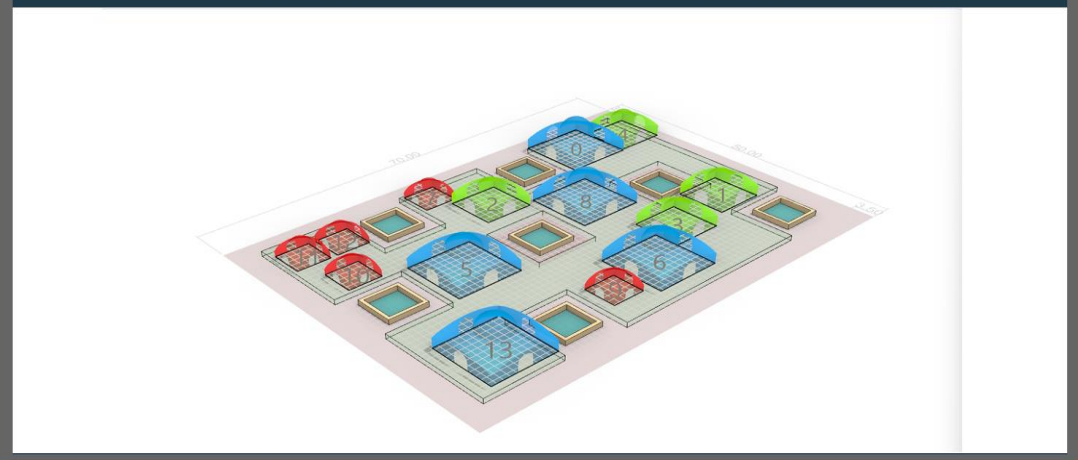
1 Design — 2 Simulator — 3 Analysis — 4 Contract

layout

- Construction Site ✓
- **Booths**
- Material Supply
- Material Type
- Obstacles
- Further Specifications

Overview





Next

Specifications

Total Number

Type A- Booth
Number
Dimensions
Material Demand

Type B- Booth
Number
Dimensions
Material Demand

Type C- Booth
Number
Dimensions
Material Demand

Coordinates

ANT ROLLER

1 Design — 2 Simulator — 3 Analysis — 4 Contract

layout

- Construction Site ✓
- *Booths*
- Material Supply
- Material Type
- Obstacles
- Further Specifications

Overview

Next

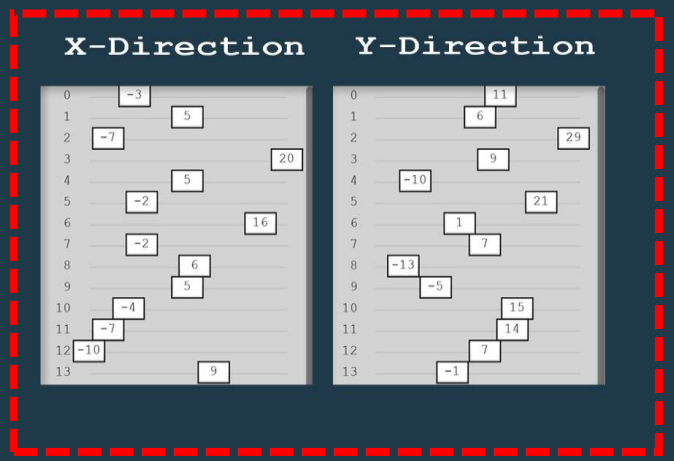
Specifications

Total Number

Coordinates

Import File ✓

Manual Adjustments ○



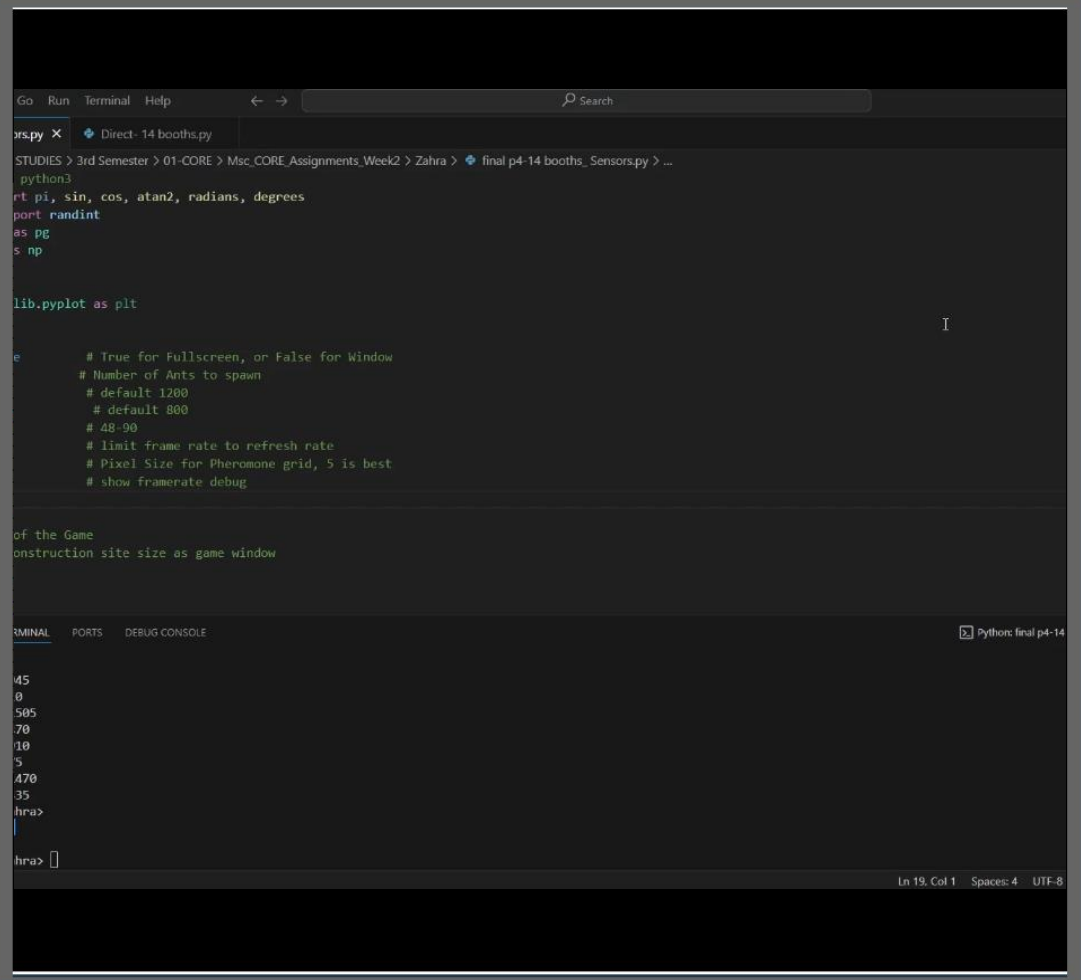
Ant Roller

1 Design — 2 Simulator — 3 Analysis — 4 Contract

Simulation

- Robot Selection ✓
- Site Topography Files ✓
- Project Planning Files ✓
- **Simulation**

Overview



Specifications

Number of Robots

30

- Robot Operation Time
- Construction Order
- Construction Rate
- Construction Site Files

Next

Ant Roller

1 Design — 2 Simulator — 3 Analysis — 4 Contract

Time Elapsed

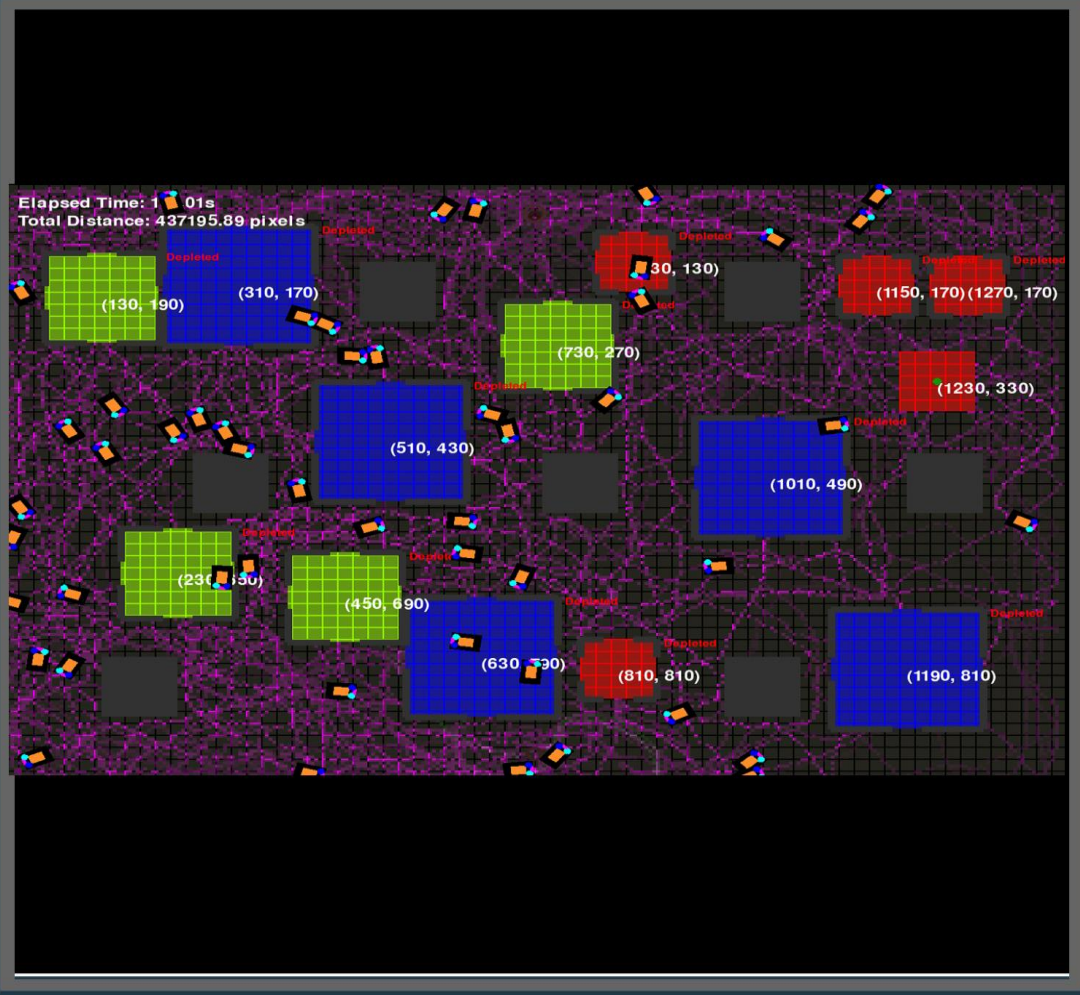
14: 04 :36

Estimated Time	16:30:30
Distance	7950 m
Material	
Used	75%
Remained	25%
Robots	
Operating	19
Charging	5
Maintenance	7

PAUSE

ABORT

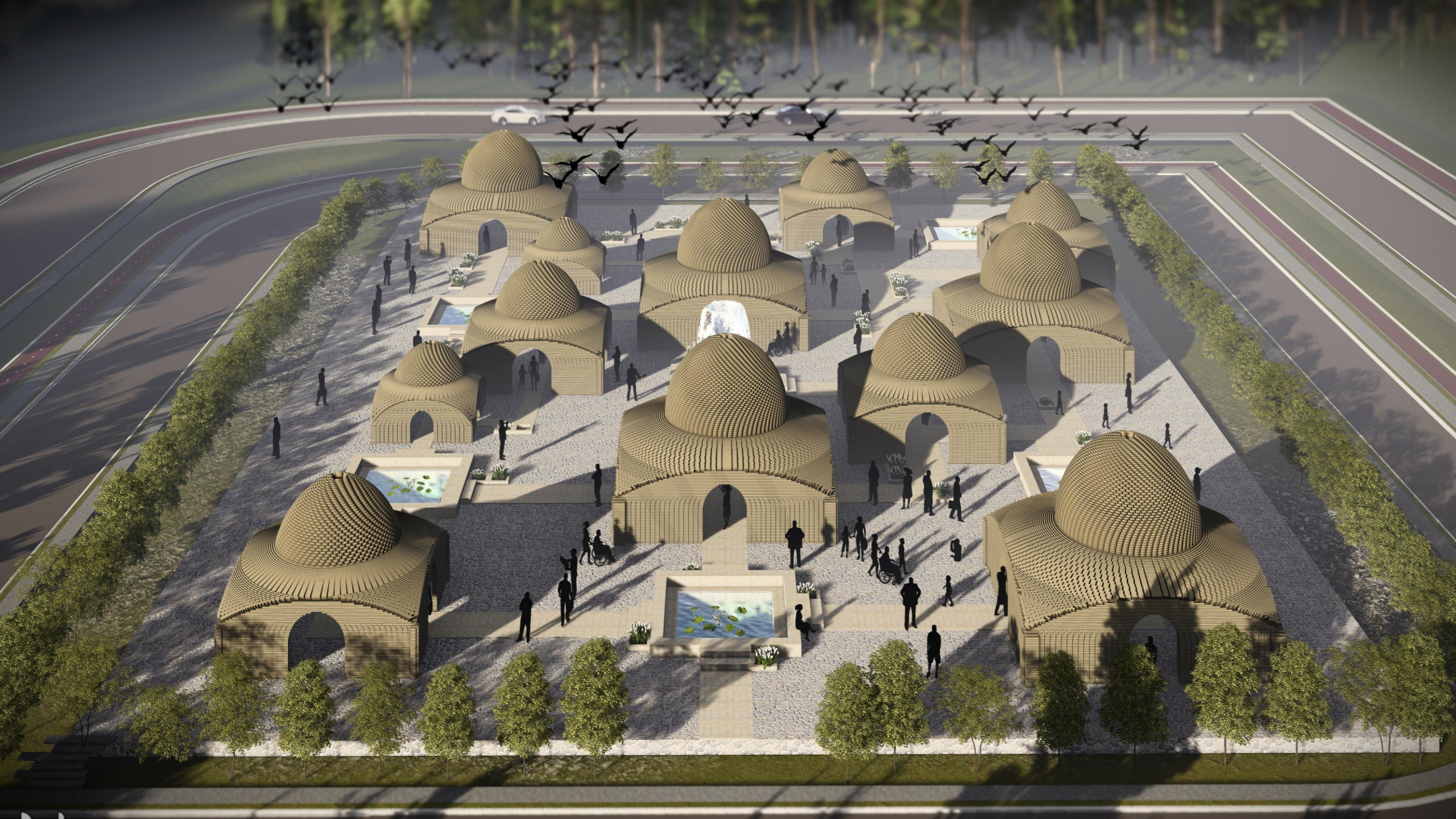
Overview

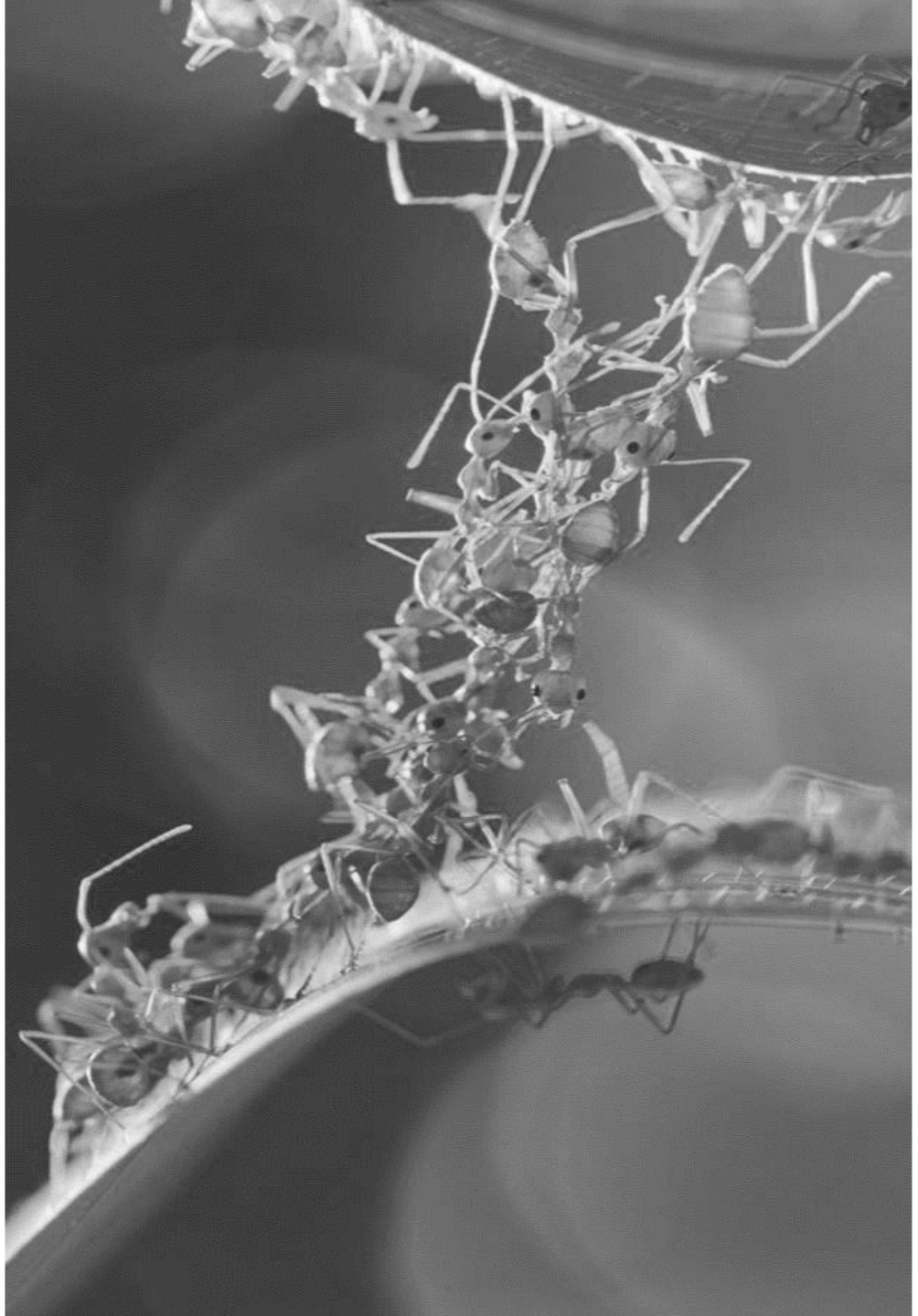


Next

Specifications

- Found Issues
- Reports
- Technical Support





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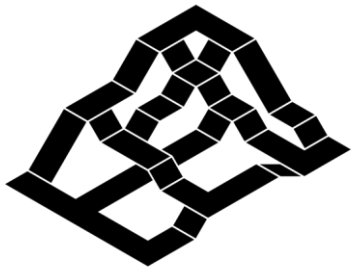
DISCUSSION-LIMITATIONS

- Fully Replicating a Dynamic Construction Process

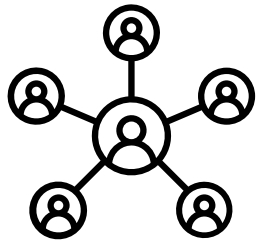


Created by Zach Bogart from Noun Project

- Robotic Physical Translation

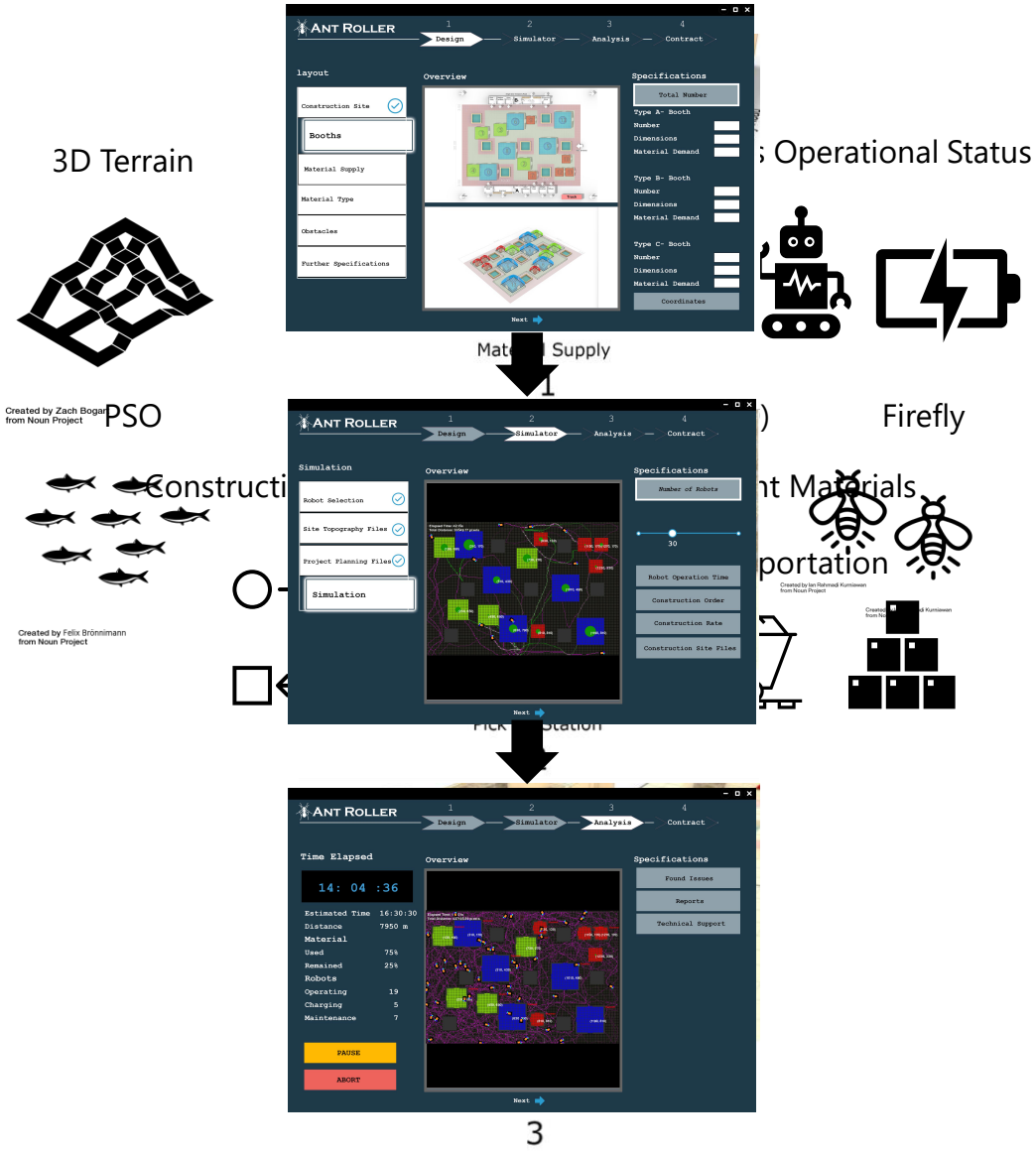
Source: https://clearpathrobotics.com/husky-3d-model/

- Simulation Difficulties regarding the background and interdisciplinary nature of the research



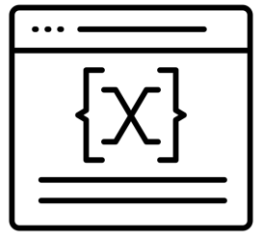
FUTURE RESEARCH

- Replicating a More Realistic Site
- Exploring Other Swarm Algorithms
- Automating the Entire Construction Process
- Developing a Unified Tool(UI)



FUTURE RESEARCH

- Incorporating more variables
- Linking to a Machine Learning Model
- More Complex Architectural Design



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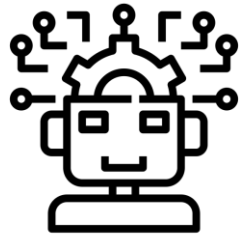

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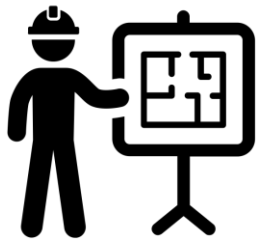
from Noun Project



Created by Adrien Coquet
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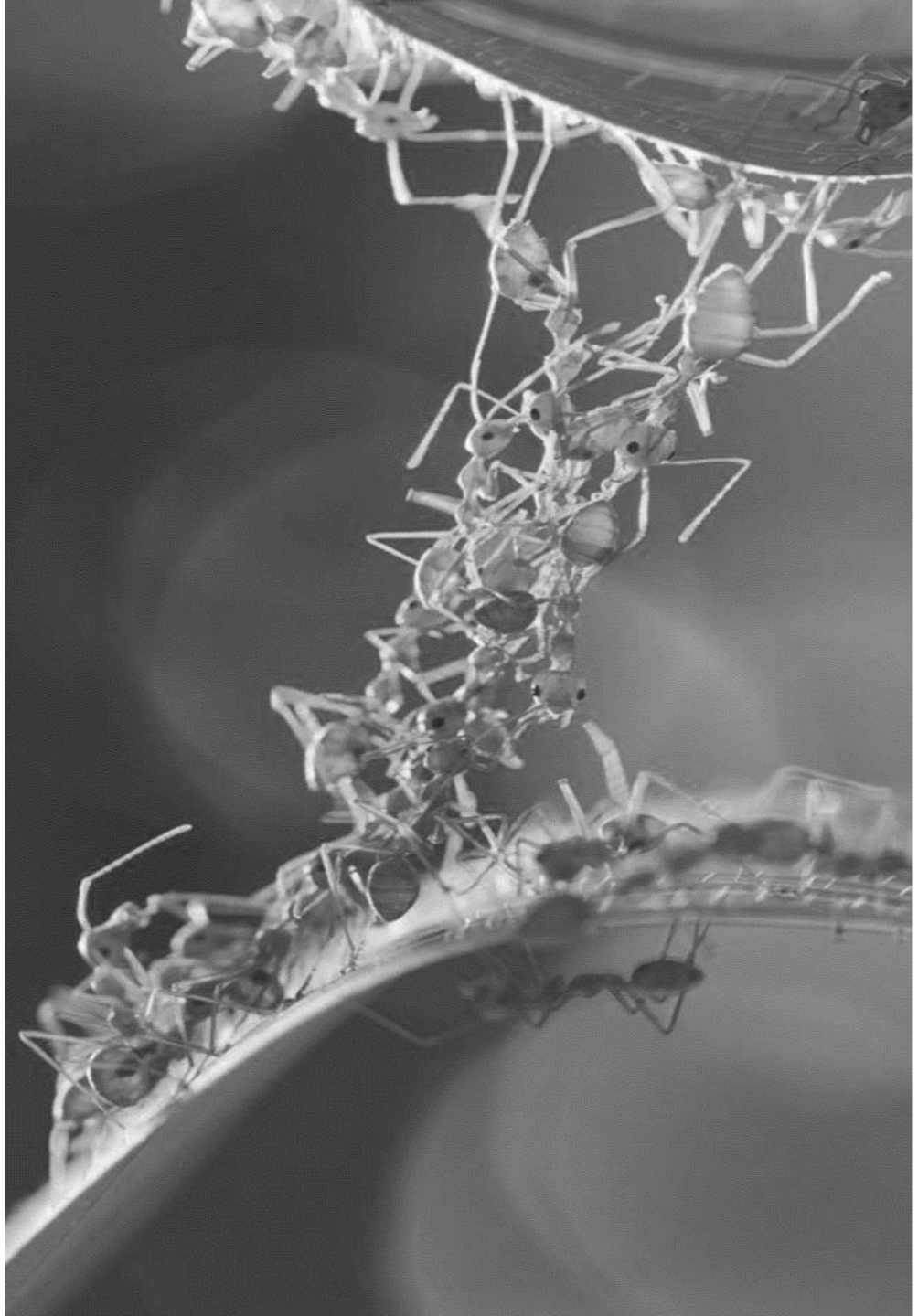

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REFLECTION-SOCIETAL IMPACT

Project Efficiency

- Mitigation of disruptions, delays, and inefficiencies
- Enhanced efficiency in the construction industry and economic growth
- Making the industry more resilient and productive.

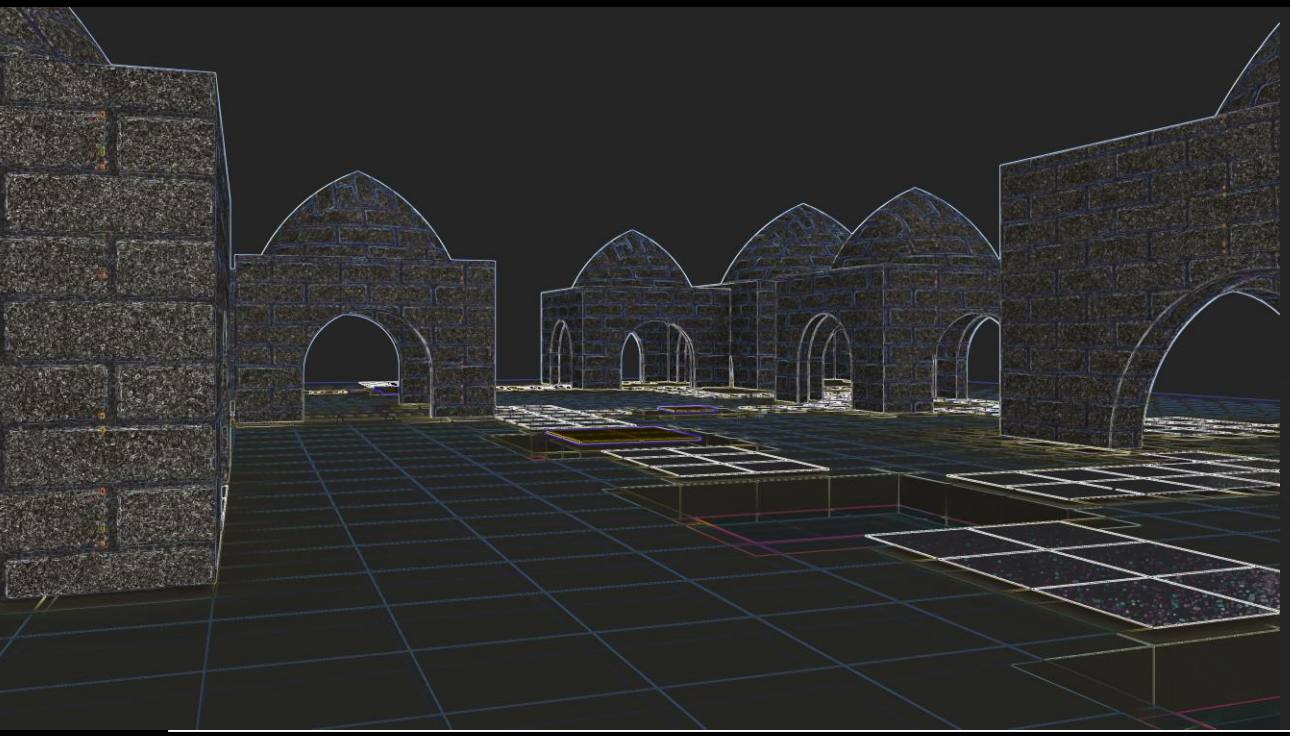
REFLECTION-SOCIETAL IMPACT

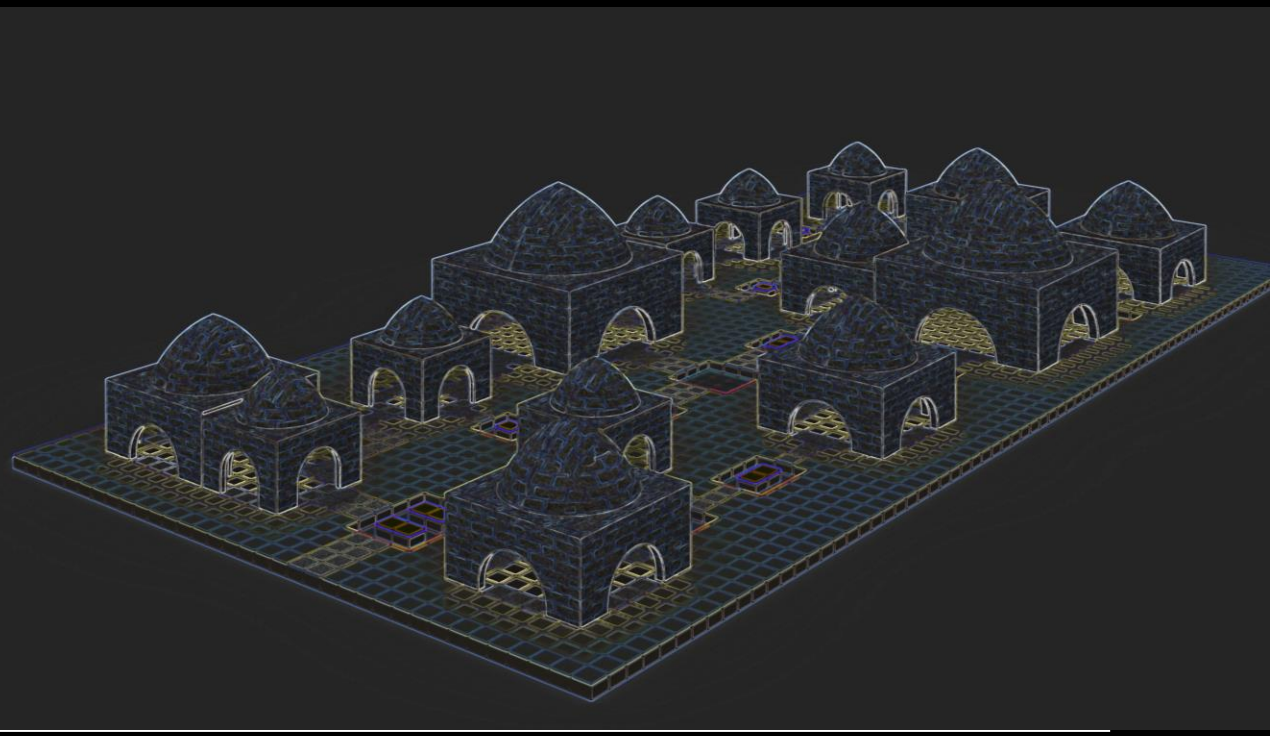
Workforce Health

- Preventing the human workforce from various injuries and accidents related to material handling.

- Might lead to a safer work environment.

Source: https://www.southparkstudios.com/video-clips/v4m5w7/south-park-ordering-everything-online





THANK YOU

Zahra Khoshnevis