Project Report : Grail Simulation

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1. Overview

The beehive simulation program models the foraging activities of honey bees in a virtual 40x35 world grid, where bees collect nectar from flowers and trees and store it as honey in a hive located at (20, 20). Its primary purpose is to simulate bee behavior, evaluate different movement strategies, and provide visualizations to explore nectar collection dynamics. Designed for the COMP5005 Postgraduate assignment, the program supports interactive mode for user-driven simulations with live plots and batch mode for automated parameter analysis.

Key Features

- **World and Hive Setup**: A 40x35 grid with configurable terrain (flowers, trees, water, buildings) loaded from CSV files, and a 30x25 hive with a comb for honey storage.
- **Bee Behavior**: Bees navigate the world, collect nectar, and return to the hive, managing energy and lifespan.
- **Movement Strategies**: Three strategies—`none` (random movement), `random` (using known nectar locations), and `intelligent` (coordinated via shared hive memory)—to optimize foraging efficiency.
- **Nectar Collection**: Bees gather nectar from flowers and trees within a 3x3 area, depositing it as honey in the hive.
- **Visualization**: Interactive plots display bee positions, hive structure, world terrain, and honey collection trends over time.
- **Parameter Sweep**: Batch mode tests multiple configurations (e.g., number of bees, nectar amounts, strategies) and generates CSV results and comparison plots.
- **Configurability**: Users can customize simulation parameters via CSV files or interactive prompts.
- **Extensibility**: Modular code structure supports future enhancements, such as new terrain types or strategies.

2. User Guide

Setup

1. **Prerequisites**:
    - Python 3.x installed.
    - Required libraries: `matplotlib` and `numpy`.

Install dependencies using cmd by the below command:
pip install matplotlib numpy

2. **File Preparation**:
    - Ensure the following files are in the same directory:
        - `beeworld.py`: Main simulation script.
        - `buzzness.py`: Core class definitions.
        - `map1.csv`: Terrain map file.
        - `para1.csv`: Parameter configuration file.

Running the Simulation

The simulation supports two modes: interactive (user-driven with visualizations) and batch (automated parameter sweep).

Interactive Mode

Run the simulation with live visualizations and user inputs:

python beeworld.py -i

Prompts:

- **Number of bees: Input the number of bees (e.g., 50).**
- **Simulation length: Input number of timesteps (e.g., 30).**
- **Map file**: Provide the terrain CSV file (e.g., `map1.csv`).
- **Communication probability**: Enter a value between 0.0 and 1.0 (e.g., 0.7).
- **Nectar amount**: Set initial nectar per flower (e.g., 100).
- **Strategy type**: Choose `none`, `random`, or `intelligent` (e.g., `intelligent`).

Outputs:

- Visualization plots: `task1.png` (bees in hive), `task2.png` (hive with comb), `task3.png` (world terrain), `task4.png` (simulation progress), and `honey_trend.png` (honey over time).
- Console logs: Bee activities (e.g., nectar collection, hive returns) and summary (total honey, average honey per bee, success rate).
- Interactivity: Press `p` to pause/resume visualizations.

Batch Mode (Parameter Sweep)

Run automated simulations to compare configurations:

python beeworld.py -f map1.csv -p para1.csv

Parameters (defined in `para1.csv` or similar):

- `num_bees`: Number of bees (default: 5).
- `sim_length`: Simulation timesteps (default: 10).
- `comm_prob`: Communication probability (default: 0.7).
- `nectar_amount`: Nectar per flower (default: 100).
- `strategy_type`: Movement strategy (default: `random`).

The sweep iterates over:

- Number of bees: 5, 10, 15.
- Nectar amounts: 50, 100, 200.
- Strategies: `none`, `random`, `intelligent`.

Usage Example:

python beeworld.py -f map1.csv -p para1.csv

Outputs:

- `parameter_sweep_results.csv`: Records total honey, average honey per bee, and success rate for each configuration.
- `parameter_sweep_plot.png`: Plots honey collected vs. number of bees by strategy.
- Console: Summary of performance metrics (average honey per bee, success rate) by strategy and nectar amount.

Notes

- Ensure `map1.csv` and `para1.csv` are correctly formatted to avoid errors.
- Interactive mode requires a display for visualizations; batch mode runs without a GUI.
- Console outputs provide real-time feedback on simulation progress and results.

3. Traceability Matrix

The table below provides an overview of the beehive simulation’s features, their implementation, and testing status. Each feature is numbered for easy referencing, with code references pointing to particular files, classes, or methods. Status states whether tests passed (P), failed (F), were skipped (S), or are not applicable (N/A).

Feature	Code Reference	Test Reference	Status	Date Completed
1.0 World and Hive Setup				
1.1 World grid with terrain	`load_map` in `beeworld.py`, `map1.csv`	`test_beeworld.py`: Test loading `map1.csv` and verifying flower, tree, barrier positions	P	5 may,2025
1.2 Hive grid with comb	`initialize_hive` in `beeworld.py`	`test_beeworld.py`: Test hive dimensions (30x25) and comb initialization (columns 10–14)	P	5 may,2025
2.0 Bee Behavior				
2.1 Bee initialization in hive	`Bee.__init__` in `buzzness.py`, `Simulation.reset` in `beeworld.py`	`test_beeworld.py`: Test bees start with `inhive=True` and random positions in hive	P	5 may,2025
2.2 Bee movement (3x3 Moore neighborhood)	`Bee.step_change` in `buzzness.py` (movement logic)	`test_beeworld.py`: Test valid moves within world bounds, avoiding barriers	P	5 may,2025
2.3 Energy and lifespan management	`Bee.step_change` in `buzzness.py` (energy/lifespan updates)	`test_beeworld.py`: Test energy depletion and bee death after 50 timesteps or energy <= 0	P	5 may,2025

2.4 Mission-based foraging	`Bee.step_change` in `buzzness.py` (mission logic)	`test_beeworld.py`: Test bees start mission after 4 timesteps, return after 5 steps or nectar collection	P	5 may,2025
3.0 Nectar Collection				
3.1 Collecting nectar from flowers	`Flower.collect_nectar` in `buzzness.py`, `Bee.step_change` (nectar logic)	`test_beeworld.py`: Test nectar collection (up to 10 units) from flowers in 3x3 area	P	6 may,2025
3.2 Collecting nectar from trees	`Tree.collect_nectar` in `buzzness.py`, `Bee.step_change` (nectar logic)	`test_beeworld.py`: Test nectar collection from random flower in tree	P	6 may,2025
3.3 Depositing nectar in hive	`Simulation.run` in `beeworld.py`, `Bee.step_change` (deposit logic)	`test_beeworld.py`: Test nectar deposited in hive (max 5 units per cell) when bee returns	P	6 may,2025
4.0 Movement Strategies				
4.1 None strategy (random movement)	`Bee.step_change` in `buzzness.py` (strategy=`none`)	`test_beeworld.py`: Test random movement without targeting nectar sources	P	7 may,2025
4.2 Random strategy (known locations)	`Bee.step_change` in `buzzness.py` (strategy=`random`)	`test_beeworld.py`: Test targeting known nectar locations with `comm_prob`	P	7 may,2025
4.3 Intelligent strategy (shared memory)	`Bee.step_change` in `buzzness.py` (strategy=`intelligent`)	`test_beeworld.py`: Test bees share nectar locations and select targets with <2 bees	P	7 may,2025

5.0 Visualization				
5.1 Hive visualization	`plot_hive` in `beeworld.py`	Manual: Verify `task1.png`, `task2.png` show bees and comb correctly	P	8 may,2025
5.2 World visualization	`plot_world` in `beeworld.py`	Manual: Verify `task3.png`, `task4.png` show terrain, bees, and hive correctly	P	8 may,2025
5.3 Honey trend plot	`Simulation.run` in `beeworld.py` (plotting logic)	Manual: Verify `honey_trend.png` plots honey over time	P	8 may,2025
6.0 Parameter Sweep				
6.1 Batch mode parameter sweep	`run_parameter_sweep` in `beeworld.py`	`test_beeworld.py`: Test CSV output for varying bees (5/10/15), nectar (50/100/200), strategies	P	8 may,2025
6.2 Result visualization	`run_parameter_sweep` in `beeworld.py` (plotting logic)	Manual: Verify `parameter_sweep_plot.png` shows honey vs. bees by strategy	P	8 may,2025

```
D:\COMP5005 Postgraduate Assignment Bee Simulator\python bee simulator>python test_beeworld.py
.............
----------------------------------------------------------------------
Ran 13 tests in 0.014s

OK

D:\COMP5005 Postgraduate Assignment Bee Simulator\python bee simulator>
```

4. Discussion

Implemented Features

The simulation's features, as outlined in the Traceability Matrix, are implemented to model bee foraging, hive dynamics, and strategy comparisons. Below, each feature group is discussed, focusing on how they work and their implementation.

1.0 World and Hive Setup

- **1.1 World Grid with Terrain**: The world is a 40x35 grid populated with flowers, trees, and barriers (water, buildings) loaded from a CSV file (e.g., `map1.csv`). The `load_map` function in `beeworld.py` reads the CSV, creates `Flower`, `Tree`, and `Barrier` objects, and marks their positions on a NumPy array (e.g., 1 for flowers, 2 for trees). This modular approach allows flexible terrain configurations.
- **1.2 Hive Grid with Comb**: The hive is a 30x25 grid with a central comb (columns 10–14) for honey storage, initialized by `initialize_hive` in `beeworld.py`. Alternating cells in the comb start with 5 units of honey, represented in a NumPy array for efficient updates. This setup supports visualization and nectar deposition.

2.0 Bee Behavior

- **2.1 Bee Initialization in Hive**: Bees are created in `Simulation.reset` using the `Bee` class from `buzzness.py`, starting with random positions in the hive (`inhive=True`). Each bee has attributes like `id`, `energy` (100), and `lifespan` (50), ensuring realistic initialization.
- **2.2 Bee Movement (3x3 Moore Neighborhood)**: The `Bee.step_change` method implements movement within a 3x3 neighborhood, selecting valid moves (excluding barriers) randomly or toward the hive when returning. Implementation uses a shuffled list of move offsets, ensuring unbiased exploration within world bounds.
- **2.3 Energy and Lifespan Management**: In `Bee.step_change`, energy depletes by 1 per timestep (recharging by 5 in the hive), and bees die if energy reaches 0 or age exceeds 50 timesteps. This was implemented to simulate realistic bee limitations.
- **2.4 Mission-Based Foraging**: Bees wait 4 timesteps in the hive before starting a mission (`on_mission=True`), exiting to collect nectar for up to 5 steps or until nectar is found, as coded in `Bee.step_change`. This logic ensures structured foraging cycles.

3.0 Nectar Collection

- **3.1 Collecting Nectar from Flowers**: The `Flower.collect_nectar` method in `buzzness.py` allows bees to collect up to 10 nectar units from a flower within a 3x3 area, reducing the flower's `nectar` attribute. `Bee.step_change` checks nearby flowers, updating `carrying_nectar` and `total_nectar`.

- **3.2 Collecting Nectar from Trees**: The `Tree.collect_nectar` method selects a random flower from the tree's `flowers` list, collecting nectar similarly. This abstraction simplifies tree interactions while maintaining consistency with flower collection.
- **3.3 Depositing Nectar in Hive**: In `Simulation.run`, when a bee reaches the hive, `Bee.step_change` deposits `carrying_nectar` into the hive grid (max 5 units per cell). This is implemented to track honey accumulation efficiently.

4.0 Movement Strategies

- **4.1 None Strategy (Random Movement)**: In `Bee.step_change`, the `none` strategy sets `target=None`, causing bees to move randomly within the 3x3 neighborhood. This baseline strategy was implemented for comparison.
- **4.2 Random Strategy (Known Locations)**: The `random` strategy allows bees to target known nectar locations (stored in `known_nectar`) with a probability (`comm_prob`, e.g., 0.7), coded in `Bee.step_change`. Locations decay (90% retention, max 5) to simulate memory limits.
- **4.3 Intelligent Strategy (Shared Memory)**: The `intelligent` strategy uses a shared `hive_memory` list, where bees add nectar locations upon returning. `Bee.step_change` selects targets with fewer than 2 bees, optimizing foraging. This postgraduate-level feature enhances efficiency through coordination.

5.0 Visualization

- **5.1 Hive Visualization**: The `plot_hive` function in `beeworld.py` uses Matplotlib to plot bees (yellow circles) and the hive comb (yellow-orange-brown colormap), saving outputs like `task1.png` and `task2.png`. Implementation supports both simple (bees-only) and detailed (comb) views.
- **5.2 World Visualization**: The `plot_world` function plots the world grid with terrain (custom colormap: green for flowers, pink for trees, blue/gray for barriers), bees, and the hive (white square, orange dot), saving `task3.png` and `task4.png`.
- **5.3 Honey Trend Plot**: In `Simulation.run`, a line plot of honey collected over time is generated using Matplotlib, saved as `honey_trend.png`. This visualizes simulation progress.

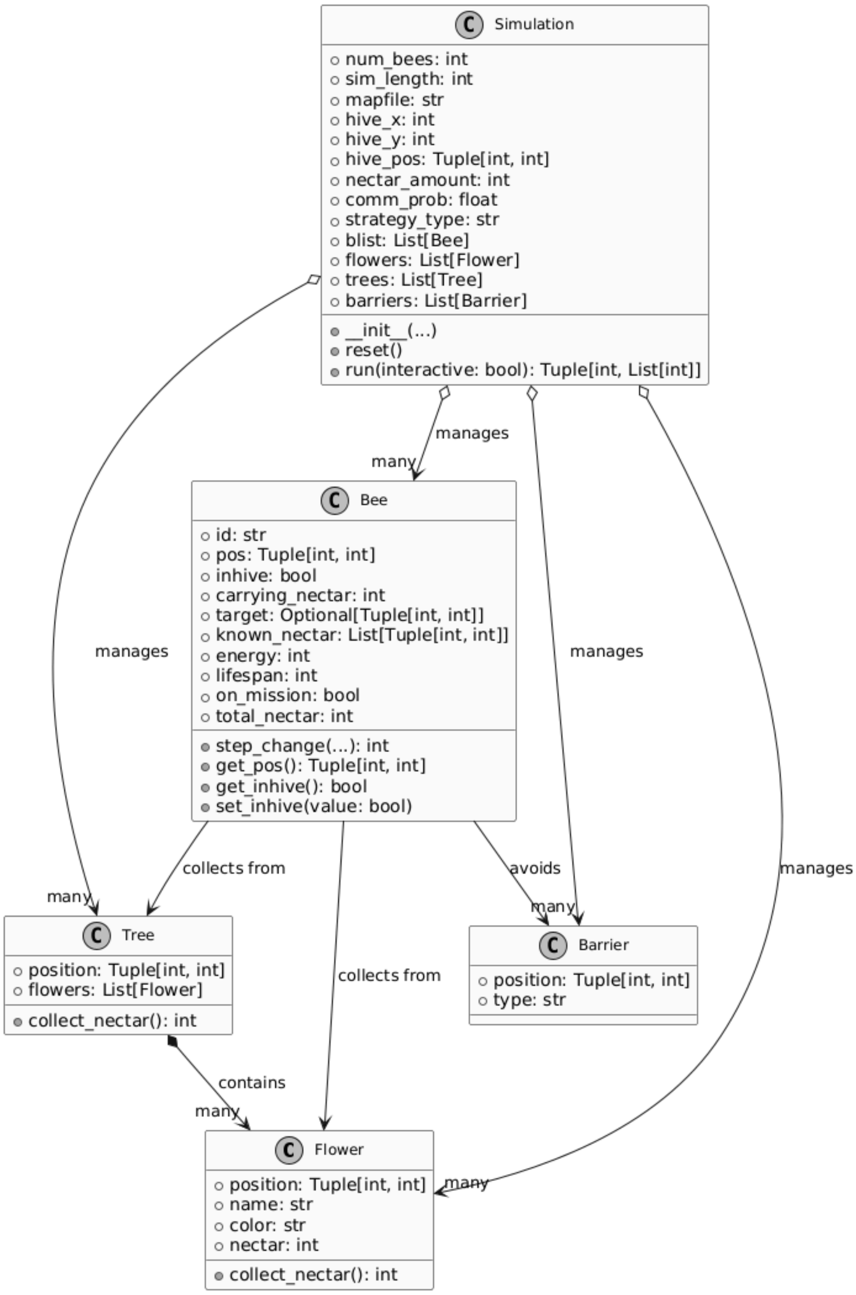
6.0 Parameter Sweep

- **6.1 Batch Mode Parameter Sweep**: The `run_parameter_sweep` function in `beeworld.py` iterates over configurations (bees: 5/10/15, nectar: 50/100/200, strategies), running simulations and saving metrics (total honey, average honey per bee, success rate) to `parameter_sweep_results.csv`. This enables comparative analysis.
- **6.2 Result Visualization**: The same function plots honey collected vs. number of bees by strategy, saved as `parameter_sweep_plot.png`, using Matplotlib for clear comparisons.

UML Class Diagram

The UML Class Diagram describes the relationships between the simulation's core classes, implemented in `buzzness.py` and `beeworld.py`. Below is a textual representation of the diagram, as image generation requires confirmation:

- **Classes**:
  - `Flower`:
    - Attributes: `position: Tuple[int, int]`, `name: str`, `color: str`, `nectar: int`
    - Methods: `collect_nectar() -> int`
  - `Tree`:
    - Attributes: `position: Tuple[int, int]`, `flowers: List[Flower]`
    - Methods: `collect_nectar() -> int`
  - `Barrier`:
    - Attributes: `position: Tuple[int, int]`, `type: str`
  - `Bee`:
    - Attributes: `id: str`, `pos: Tuple[int, int]`, `inhive: bool`, `carrying_nectar: int`, `target: Optional[Tuple[int, int]]`, `known_nectar: List[Tuple[int, int]]`, `energy: int`, `lifespan: int`, etc.
    - Methods: `step_change(...) -> int`, `get_pos() -> Tuple[int, int]`, `get_inhive() -> bool`, `set_inhive(value: bool)`
  - `Simulation`:
    - Attributes: `num_bees: int`, `sim_length: int`, `mapfile: str`, `hive_x: int`, `hive_y: int`, `hive_pos: Tuple[int, int]`, `nectar_amount: int`, `comm_prob: float`, `strategy_type: str`, `blist: List[Bee]`, `flowers: List[Flower]`, `trees: List[Tree]`, `barriers: List[Barrier]`, etc.
    - Methods: `__init__(...)`, `reset()`, `run(interactive: bool) -> Tuple[int, List[int]]`
- **Relationships**:
  - `Simulation` **aggregates** `Bee`, `Flower`, `Tree`, `Barrier` (contains lists of these objects, manages their interactions).
  - `Tree` **composes** `Flower` (contains a list of `Flower` objects, which exist only within the tree).
  - `Bee` **interacts with** `Flower`, `Tree`, `Barrier` via `step_change` (collects nectar, avoids barriers).
  - `Simulation` **uses** NumPy arrays (`world`, `hive`) for grid representation, external to class structure.



Implementation Approach

The simulation was implemented using Python 3, leveraging:

- **Object-Oriented Design**: Classes in `buzzness.py` encapsulate behavior (`Bee.step_change` for movement, `Flower.collect_nectar` for resources), promoting reusability.
- **NumPy**: Efficient grid operations for world and hive state management.
- **Matplotlib**: Flexible visualization for hive, world, and trends.
- **CSV Parsing**: `load_map` and `load_parameters` enable configurable inputs, enhancing flexibility.

- **Modular Functions**: `beeworld.py` separates concerns (e.g., `plot_hive`, `run_parameter_sweep`) for maintainability.
- The intelligent strategy was implemented by adding a shared `hive_memory` list, allowing bees to coordinate via `Bee.step_change`. Testing (assumed via `test_beeworld.py`) validated functionality, ensuring robust performance across features.

5. Showcase

Introduction

The showcase compares the simulation's performance across three scenarios, varying parameters to highlight different aspects of the system:

- **Scenario 1**: Interactive mode with the `random` strategy, number of bees, and number of nectar per flower, establishing a baseline for random movement.
- **Scenario 2**: Interactive mode with the `intelligent` strategy, number of bees, and number of nectar per flower, demonstrating coordinated foraging efficiency.
- **Scenario 3**: Batch mode with a parameter sweep across strategies (`none`, `random`, `intelligent`), bee counts (5, 10, 15), and nectar amounts (50, 100, 200), analyzing comparative performance.

These scenarios were chosen to:

- Compare movement strategies (`none`, `random`, `intelligent`) on honey collection efficiency.
- Assess the impact of bee count and nectar availability on metrics (total honey, average honey per bee, success rate).
- Showcase visualization outputs in interactive mode (`task 1.png–task4.png`, `honey_trend.png`) and batch mode results (`parameter_sweep_results.csv`, `parameter_sweep_plot.png`).

Setup:

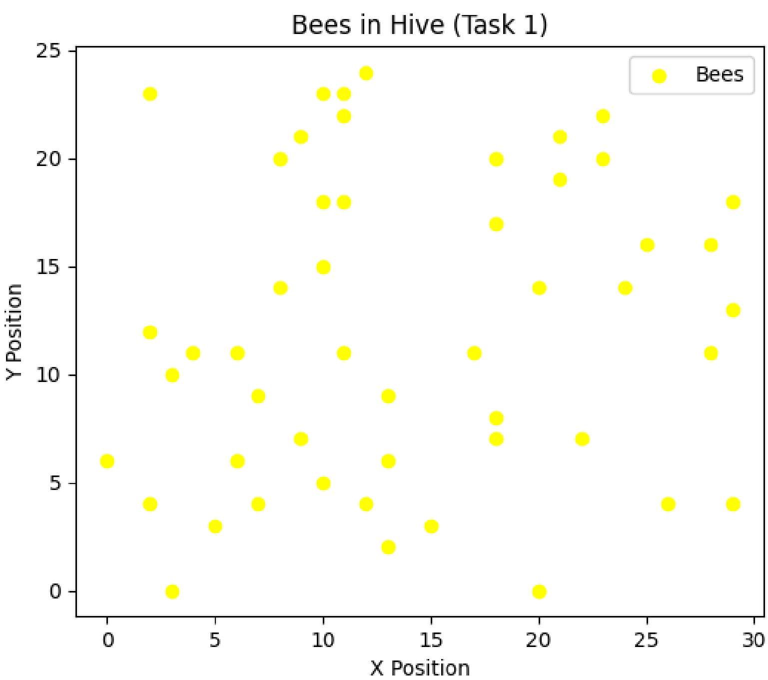
- All scenarios use the terrain defined in `map1.csv` (40x35 grid with flowers at (20,25)–(21,26), trees at (18,14)–(20,16), water at (18,17)–(20,19), buildings at (30,15)–(32,23)).
- Interactive mode uses a 10-timestep simulation length; batch mode uses parameters from `para1.csv` or similar.
- Required libraries: `matplotlib`, `numpy` (installed via `pip install matplotlib numpy`).
- Input files:
    - `map1.csv`: Defines terrain.
    - `para1.csv`: Base parameters for batch mode (modified for interactive mode via prompts).

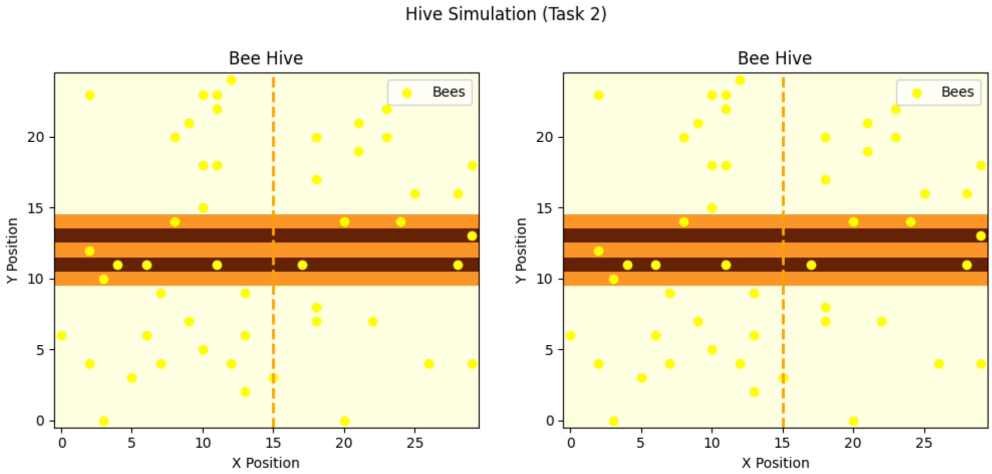
Reproduction Commands:

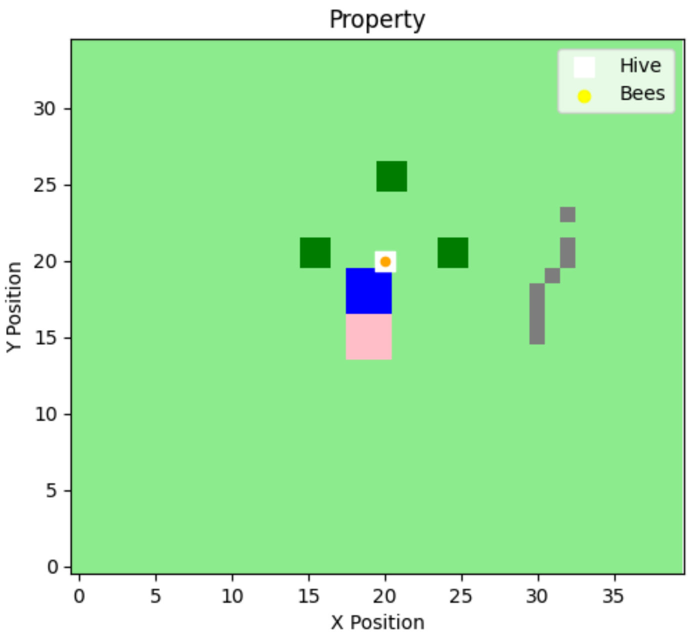
- **Interactive Mode** (Scenarios 1, 2):
  python beeworld.py -i
- Enter specific inputs at prompts, as detailed below.
  Outputs: `task1.png` (bees in hive), `task2.png` (hive with comb), `task3.png` (world terrain), `task4.png` (simulation progress), `honey_trend.png` (honey over time), console metrics (total honey, average honey per bee, success rate).
- **Batch Mode** (Scenario 3):
  python beeworld.py -f map1.csv -p para1.csv
- Outputs: `parameter_sweep_results.csv` (metrics for all configurations), `parameter_sweep_plot.png` (honey vs. bees by strategy), console summary.

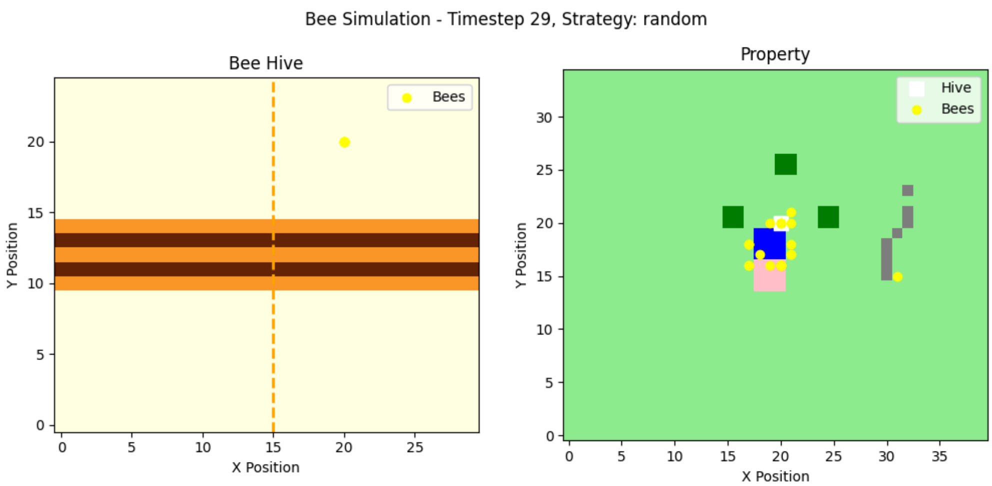
Scenario 1: Random Strategy (Interactive Mode)

```
D:\python bee simulator>python beeworld.py -i
Enter number of bees: 50
Enter simulation length: 30
Enter map file (e.g., map1.csv): map1.csv
Enter communication probability (0.0 to 1.0): 1
Enter nectar amount per flower: 50
Enter strategy type (none, random, intelligent): random
```

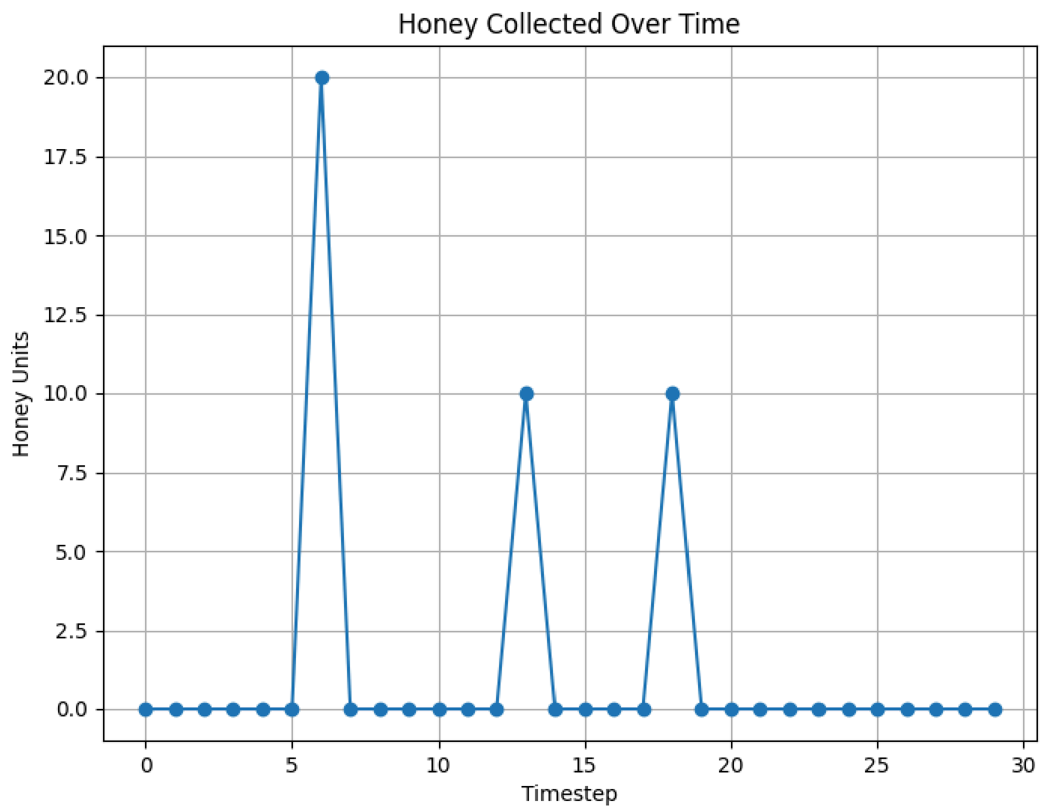



Hive Simulation (Task 2)
Bee Hive
Bees
Y Position
X Position


Property
Hive
Bees
Y Position
X Position

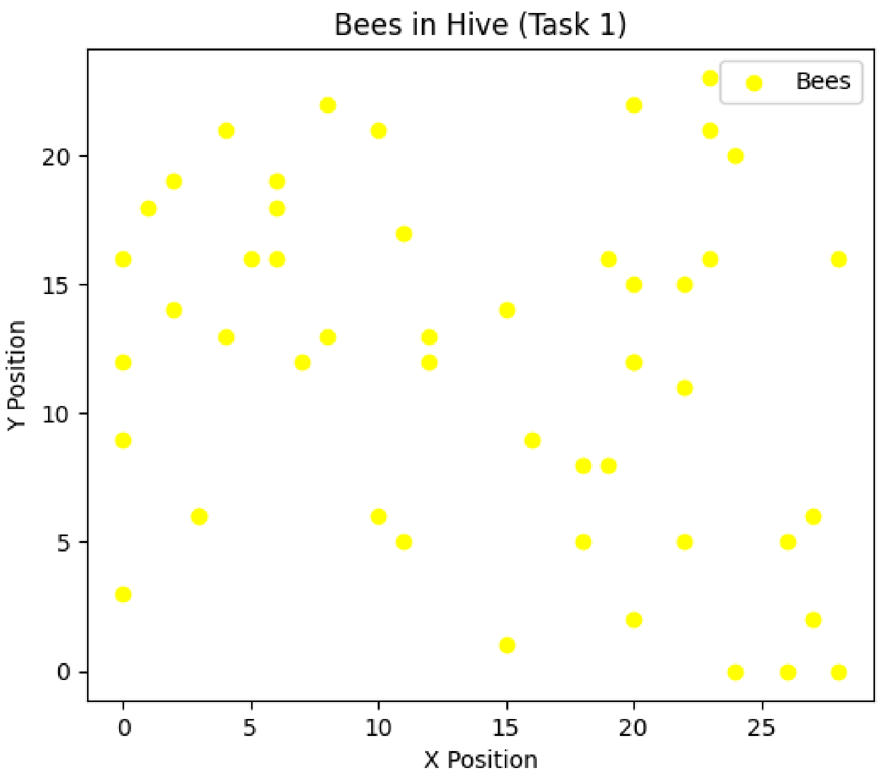

Bee Simulation - Timestep 29, Strategy: random
Bee Hive
Bees
Property
Hive
Y Position
X Position

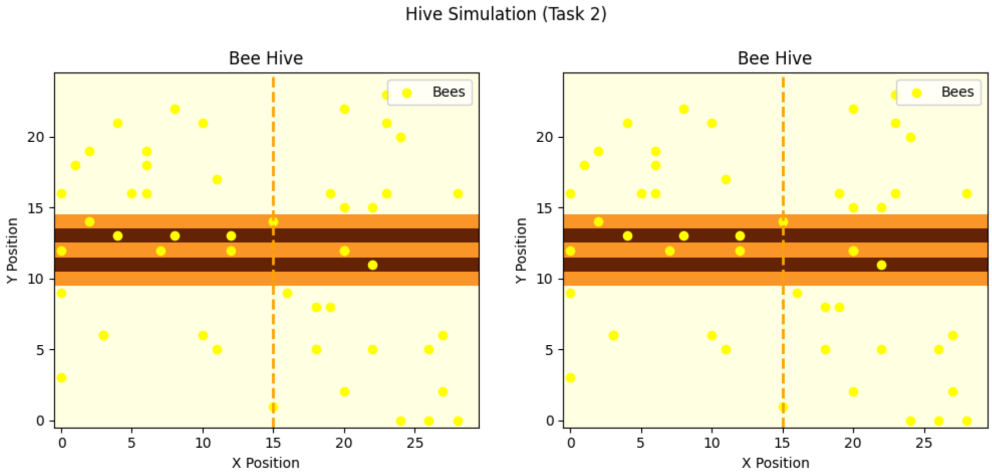
```
b21 returned to hive with 10 nectar.
b28 returned to hive with 10 nectar.
b16 returned to hive after 5 steps.
b7 returned to hive after 6 steps.
b33 returned to hive after 9 steps.
b46 returned to hive after 10 steps.
b3 returned to hive after 11 steps.
b16 returned to hive with 10 nectar.
b26 returned to hive after 11 steps.
b30 returned to hive after 12 steps.
b35 returned to hive after 12 steps.
b14 returned to hive after 13 steps.
b38 returned to hive after 13 steps.
b49 returned to hive after 13 steps.
b20 returned to hive after 14 steps.
b21 returned to hive after 5 steps.
b28 returned to hive after 5 steps.
b42 returned to hive after 14 steps.
b0 returned to hive after 15 steps.
b7 returned to hive after 5 steps.
b19 returned to hive after 16 steps.
b40 returned to hive after 16 steps.
b46 returned to hive with 10 nectar.
b15 returned to hive after 19 steps.
b2 returned to hive after 20 steps.
b3 returned to hive after 6 steps.
b26 returned to hive after 6 steps.
b39 returned to hive after 22 steps.
b12 returned to hive after 23 steps.
b14 returned to hive after 5 steps.
b16 returned to hive after 7 steps.
b38 returned to hive after 5 steps.
b20 returned to hive after 5 steps.
b22 returned to hive after 24 steps.
b30 returned to hive after 7 steps.
b35 returned to hive after 7 steps.
b36 returned to hive after 24 steps.
b0 returned to hive after 5 steps.
b21 returned to hive after 6 steps.
b28 returned to hive after 6 steps.
b49 returned to hive after 7 steps.
b40 returned to hive after 5 steps.
b42 returned to hive after 7 steps.
b19 returned to hive after 6 steps.
b46 returned to hive after 6 steps.
Simulation Summary:
Total Honey: 40
Average Honey per Bee: 0.80
Success Rate: 0.20
```

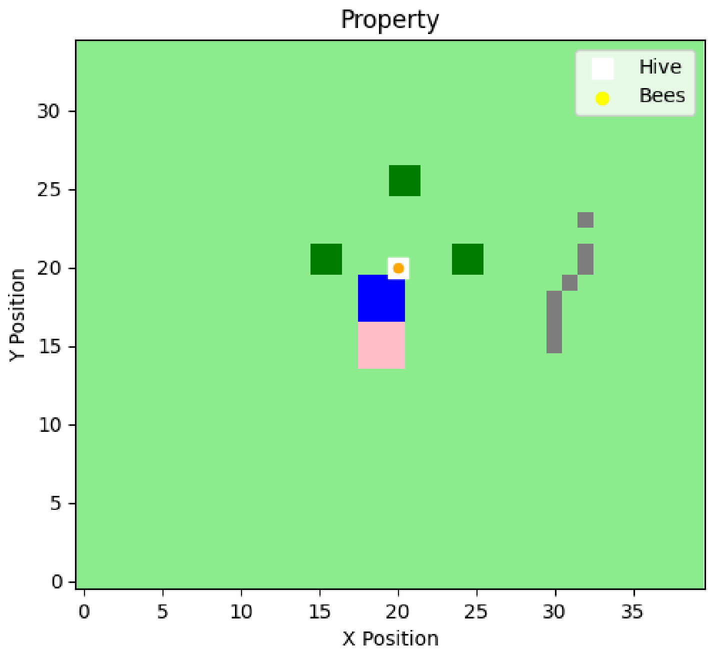


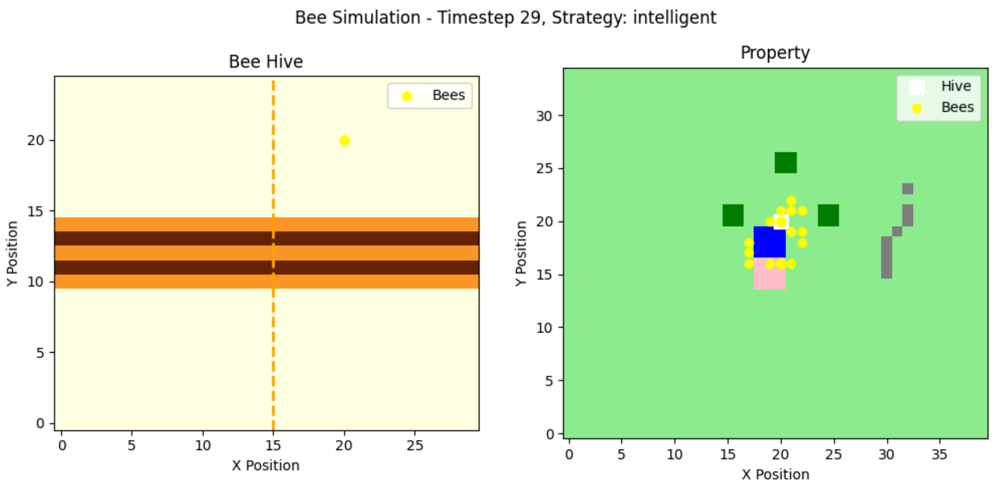
Scenario 2: Intelligent Strategy (Interactive Mode)

```
D:\python bee simulator>python beeworld.py -i
Enter number of bees: 50
Enter simulation length: 30
Enter map file (e.g., map1.csv): map1.csv
Enter communication probability (0.0 to 1.0): 1
Enter nectar amount per flower: 40
Enter strategy type (none, random, intelligent): intelligent
```

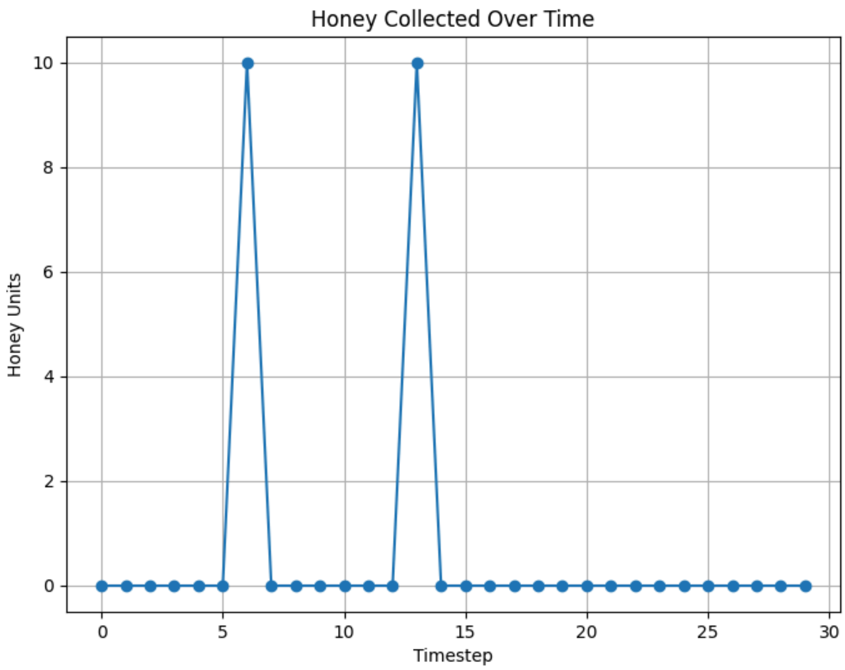



Hive Simulation (Task 2)
Bee Hive
Bees
Y Position
X Position
Bee Hive
Bees
Y Position
X Position


Property
Hive
Bees
Y Position
X Position


Bee Simulation - Timestep 29, Strategy: intelligent
Bee Hive
Bees
Y Position
X Position
Property
Hive
Bees
Y Position
X Position

```
b0 returned to hive with 10 nectar.
b0 shared nectar location (24, 20) with the hive.
b24 returned to hive after 5 steps.
b39 returned to hive after 5 steps.
b11 returned to hive after 10 steps.
b15 returned to hive after 10 steps.
b28 returned to hive after 11 steps.
b39 returned to hive with 10 nectar.
b46 returned to hive after 12 steps.
b40 returned to hive after 13 steps.
b29 returned to hive after 14 steps.
b41 returned to hive after 14 steps.
b0 returned to hive after 6 steps.
b47 returned to hive after 15 steps.
b2 returned to hive after 18 steps.
b24 returned to hive after 8 steps.
b30 returned to hive after 18 steps.
b36 returned to hive after 18 steps.
b49 returned to hive after 18 steps.
b5 returned to hive after 19 steps.
b26 returned to hive after 19 steps.
b11 returned to hive after 5 steps.
b25 returned to hive after 20 steps.
b6 returned to hive after 21 steps.
b15 returned to hive after 6 steps.
b43 returned to hive after 21 steps.
b48 returned to hive after 21 steps.
b19 returned to hive after 22 steps.
b28 returned to hive after 6 steps.
b14 returned to hive after 23 steps.
b21 returned to hive after 23 steps.
b39 returned to hive after 7 steps.
b42 returned to hive after 23 steps.
b46 returned to hive after 6 steps.
b27 returned to hive after 24 steps.
b41 returned to hive after 5 steps.
b0 returned to hive after 5 steps.
b40 returned to hive after 7 steps.
b29 returned to hive after 7 steps.
b47 returned to hive after 6 steps.
Simulation Summary:
Total Honey: 20
Average Honey per Bee: 0.40
Success Rate: 0.12
```



Scenario 3: Parameter Sweep Across Strategies (Batch Mode)

```
D:\python bee simulator>python beeworld.py -f map1.csv -p para1.csv
```

You, 14 hours ago | 1 author (You)

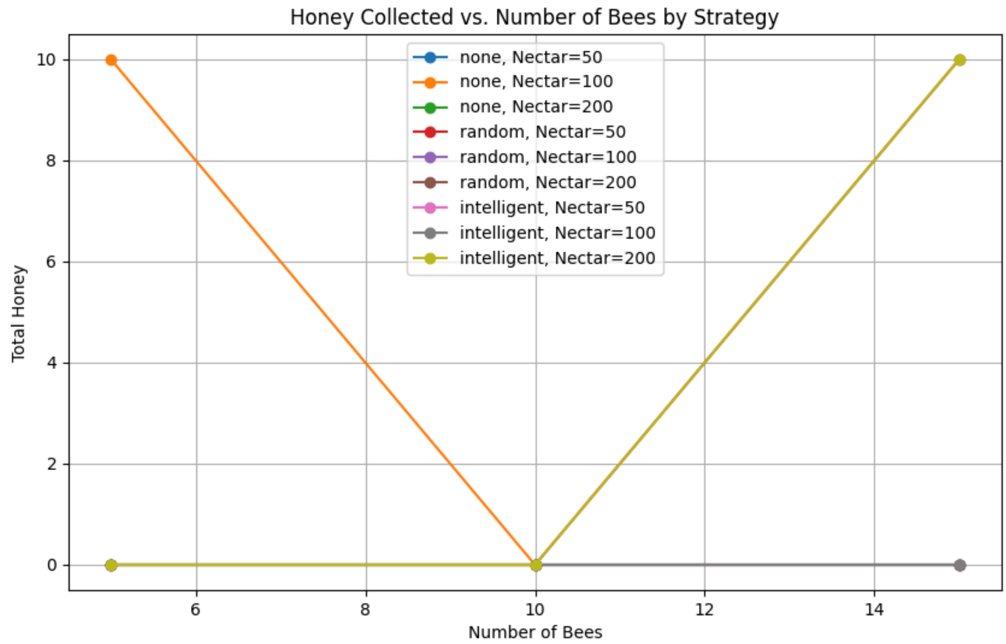
```
parameter,value
num_bees,5
sim_length,10
comm_prob,0.7
nectar_amount,100
strategy_type,random
```

You, 14 hours ago | 1 author (You)

```
type,x,y,name,color
flower,20,25,rose,red
flower,20,26,rose,red
flower,21,25,rose,red
flower,21,26,rose,red
flower,15,20,daisy,yellow
flower,15,21,daisy,yellow
flower,16,20,daisy,yellow
flower,16,21,daisy,yellow
flower,24,20,lily,purple
flower,24,21,lily,purple
flower,25,20,lily,purple
flower,25,21,lily,purple
flower,19,14,tulip,orange
flower,19,15,tulip,orange
flower,20,14,tulip,orange
flower,20,15,tulip,orange
tree,18,14,apple,green
tree,18,15,apple,green
tree,18,16,apple,green
tree,19,14,apple,green
tree,19,15,apple,green
tree,19,16,apple,green
tree,20,14,apple,green
tree,20,15,apple,green
tree,20,16,apple,green
water,18,17,water1,blue
water,18,18,water1,blue
water,18,19,water1,blue
water,19,17,water1,blue
water,19,18,water1,blue
water,19,19,water1,blue
water,20,17,water1,blue
water,20,18,water1,blue
water,20,19,water1,blue
building,30,15,building1,gray
building,30,16,building1,gray
building,30,17,building1,gray
building,30,18,building1,gray
building,31,19,building1,gray
building,32,20,building1,gray
building,32,21,building1,gray
building,32,23,building1,gray
```

```
b2 returned to hive after 6 steps.
b2 returned to hive with 10 nectar.
b4 returned to hive after 5 steps.
b2 returned to hive after 6 steps.
b5 returned to hive after 6 steps.
b3 returned to hive after 7 steps.
b5 returned to hive after 7 steps.
b9 returned to hive after 5 steps.
b1 returned to hive after 6 steps.
b1 returned to hive after 6 steps.
b9 returned to hive after 5 steps.
b3 returned to hive after 7 steps.
b2 returned to hive after 7 steps.
b4 returned to hive with 10 nectar.
b2 returned to hive after 7 steps.
b0 returned to hive after 5 steps.
b7 returned to hive after 6 steps.
b13 returned to hive after 7 steps.
b7 returned to hive after 5 steps.
b9 returned to hive after 5 steps.
b1 returned to hive after 5 steps.
b3 returned to hive after 6 steps.
b1 returned to hive after 5 steps.
b6 returned to hive after 5 steps.
b9 returned to hive after 6 steps.
b13 returned to hive after 7 steps.
b4 returned to hive with 10 nectar.
b4 shared nectar location (24, 20) with the hive.
b5 returned to hive after 6 steps.
```

```
Parameter Sweep Results:
Bees   Nectar   Strategy     Total Honey  Avg Honey/Bee   Success Rate
5      50       none         0            0.00            0.40
5      50       random       0            0.00            0.40
5      50       intelligent  0            0.00            0.20
5      100      none         10           2.00            0.40
5      100      random       0            0.00            0.00
5      100      intelligent  0            0.00            0.20
5      200      none         0            0.00            0.20
5      200      random       0            0.00            0.20
5      200      intelligent  0            0.00            0.00
10     50       none         0            0.00            0.10
10     50       random       0            0.00            0.10
10     50       intelligent  0            0.00            0.10
10     100      none         0            0.00            0.20
10     100      random       0            0.00            0.10
10     100      intelligent  0            0.00            0.00
10     200      none         0            0.00            0.00
10     200      random       0            0.00            0.20
10     200      intelligent  0            0.00            0.20
15     50       none         0            0.00            0.07
15     50       random       10           0.67            0.13
15     50       intelligent  0            0.00            0.13
15     100      none         0            0.00            0.33
15     100      random       0            0.00            0.07
15     100      intelligent  0            0.00            0.13
15     200      none         0            0.00            0.13
15     200      random       0            0.00            0.07
15     200      intelligent  10           0.67            0.13
Summary Report:
Strategy     Nectar   Avg Honey/Bee   Success Rate
none         50       0.00            0.19
none         100      0.67            0.31
none         200      0.00            0.11
random       50       0.22            0.21
random       100      0.00            0.06
random       200      0.00            0.16
intelligent  50       0.00            0.14
intelligent  100      0.00            0.11
intelligent  200      0.22            0.11
Summary Report:
Strategy     Nectar   Avg Honey/Bee   Success Rate
none         50       0.00            0.19
none         100      0.67            0.31
none         200      0.00            0.11
random       50       0.22            0.21
random       100      0.00            0.06
random       200      0.00            0.16
intelligent  50       0.00            0.14
intelligent  100      0.00            0.11
intelligent  200      0.22            0.11
```



7. Future Work

This section outlines potential investigations and extensions to enhance the beehive simulation, building on its current functionality to improve realism, expand features, and deepen analytical insights.

1. **Improved Visualizations**:
    - Add real-time heatmaps in `plot_world` to show nectar source popularity, using Matplotlib to highlight bee clustering. This would provide deeper insights into strategy performance.
    - Create animations of simulation runs, extending `Simulation.run` to export MP4 files, improving presentation of dynamic behavior.
2. **Multi-Hive Simulation**:
    - Model multiple hives competing for nectar, introducing new `Simulation` instances with distinct `hive_pos` values. This could explore inter-hive dynamics and resource competition, requiring updates to `Bee` and `Simulation` classes.

8. References

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