Hybrid Truck-Drone Delivery System

Group 22

Aman Khande, Hemant Bamb, Rishikesh Pandey, Saumya Sheth

Mentor: Aaditya Sakrikar

Guide: Prof. Avinash Bhardwaj

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Abstract

This report addresses the design and optimization of a Truck-drone hybrid delivery system to streamline last-mile logistics, cut delivery costs, and enhance package delivery efficiency. Urban delivery challenges, including traffic congestion and high costs, necessitate innovative solutions. By integrating drones with ground-based trucks, we aim to overcome these obstacles. Key challenges include coordinated route planning, energy consumption optimization, and algorithmic complexities. Addressing these challenges promises to revolutionize urban logistics, improve sustainability, and foster economic efficiency.

1 Problem Description

Design and optimize an innovative Truck-drone hybrid delivery system simplifying last-mile logistics, lowering total delivery costs, and increasing package delivery rate are the main objectives. With the help of this technology, which seamlessly combines drones with ground-based trucks, obstacles like traffic jams, long delivery distances, and high operating expenses may be addressed

2 Introduction

In urban environments, the efficient delivery of goods presents a formidable challenge due to the complex interplay of factors such as traffic congestion, extended delivery distances, and escalating operational costs. Conventional ground-based delivery methods often struggle to navigate through these challenges, resulting in increased expenses, prolonged delivery times, and environmental concerns. Recognizing the pressing need for a more effective solution, this report delves into the design and optimization of a Truck-drone hybrid delivery system.

The primary objective of this system is to streamline last-mile logistics, lower total delivery costs, and augment package delivery rates by seamlessly integrating drones with ground-based trucks. By leveraging the complementary strengths of both aerial and terrestrial modes of transportation, this hybrid approach aims to overcome the inherent limitations of each, offering a promising solution to the prevailing challenges in urban delivery networks.
This introduction outlines the importance of the problem at hand, identifies the key objectives of the proposed solution, and sets the stage for a comprehensive exploration of the formulation, algorithmic, computational, and logistical challenges that must be addressed in the development of this innovative delivery system.

3 System Design

3.1 Overview

The system integrates one truck and one drone in a coordinated delivery model. The truck serves as a mobile hub for the drone, launching and retrieving it at strategic nodes to optimize route efficiency and delivery speed.

3.2 Variables and Parameters

- n: Number of nodes
- s: Source node
- d: Destination node
- c_{ij}: Cost of traveling from node i to node j by truck
- t_{ij}: Time taken to travel from node i to node j by truck
- c'_{ij}: Cost of traveling from node i to node j by drone
- t'_{ij}: Time taken to travel from node i to node j by drone
- x_{ij}: Binary variable indicating if the truck travels from node i to node j
- y_{ij}: Binary variable indicating if the drone travels from node i to node j

4 Objective Function and Constraints

4.1 Objective Function

The objective function for the hybrid truck-drone delivery system is designed to minimize the overall delivery cost and time, which are crucial for efficient logistics operations. The function is a weighted sum of these two factors, allowing adjustments based on priority (cost vs. time). The mathematical expression for the objective function is:

Minimize:

$$w_c \left(\sum_{(i,j)} c_{ij} x_{ij} + \sum_{(i,j)} c'_{ij} y_{ij} \right) + w_t \left(\sum_{(i,j)} t_{ij} x_{ij} + \sum_{(i,j)} t'_{ij} y_{ij} \right)$$

Where:

- w_c: Weight factor for cost component
- w_t: Weight factor for time component

The objective function minimizes the weighted sum of total cost and total time.

4.2 Constraints

Variables:

$$x_{ij} \in \{0, 1\}, \quad y_{ij} \in \{0, 1\}$$

4.2.1 Flow Conservation

For every node k except s and d: This constraint ensures that each intermediate node k (i.e., nodes that are neither the source s nor the destination d) maintains flow equilibrium. The sum of flows (trucks or drones) into node k must equal the sum of flows out of node k. This is crucial for maintaining the conservation of flow across the network.

$$\sum_i x_{ik} - \sum_j x_{kj} + \sum_i y_{ik} - \sum_j y_{kj} = 0$$

For the source node s: This ensures that exactly one vehicle (either truck or drone) leaves the source node. It establishes the starting point for the transportation network.

$$\sum_j x_{sj} + \sum_j y_{sj} = 1$$

For the destination node d: Ensures that exactly one vehicle (either truck or drone) arrives at the destination node, marking the endpoint of the transport path

$$\sum_i x_{id} + \sum_i y_{id} = 1$$

4.2.2 Truck-Drone Coordination

- **Drone can be launched from a node where the truck is present:** This constraint dictates that a drone can only start its journey from any node i to j if there is at least one truck present at node i. It ensures the drone's dependency on the truck for deployment.

$$y_{ij} \leq \sum_k x_{ki} \quad \text{for all } i, j$$

- **Drone must return to the node where the truck is present:** Similar to the launch constraint, this ensures that a drone must end its journey at any node j only if there is at least one truck present at node j. It guarantees that drones return to a location where trucks are available, facilitating the coordination between the two modes of transport.

$$y_{ij} \leq \sum_k x_{kj} \quad \text{for all } i, j$$

4.2.3 Cost Constraint

This constraint imposes a maximum limit on the cost function so that it does not cross a particular amount

$$\sum_{(i,j)} c_{ij} x_{ij} + \sum_{(i,j)} c'_{ij} y_{ij} \leq c_{\max}$$

5 Methodology

5.1 Simulation Tools

The NetworkX library in Python was utilized to simulate the delivery routes and to calculate the minimum cost paths under various scenarios.

5.2 Optimization Techniques

The Gurobi optimizer was employed to handle more complex scenarios involving multiple destinations and dynamic constraints.

5.3 Problem Scenarios:

There are a total of four problem scenarios that are solved using methods like the brute-force approach, NetworkX solver, and Gurobi Solver. One source is defined for the scenarios.

5.3.1 One Truck, One Drone, One Destination:

- **NetworkX Library:** The destination is decided by the constraints. NetworkX library is used to simulate the graphs for truck and drone paths which are then combined to generate a graph that covers both of them with the least path of either. This combined graph is used to solve

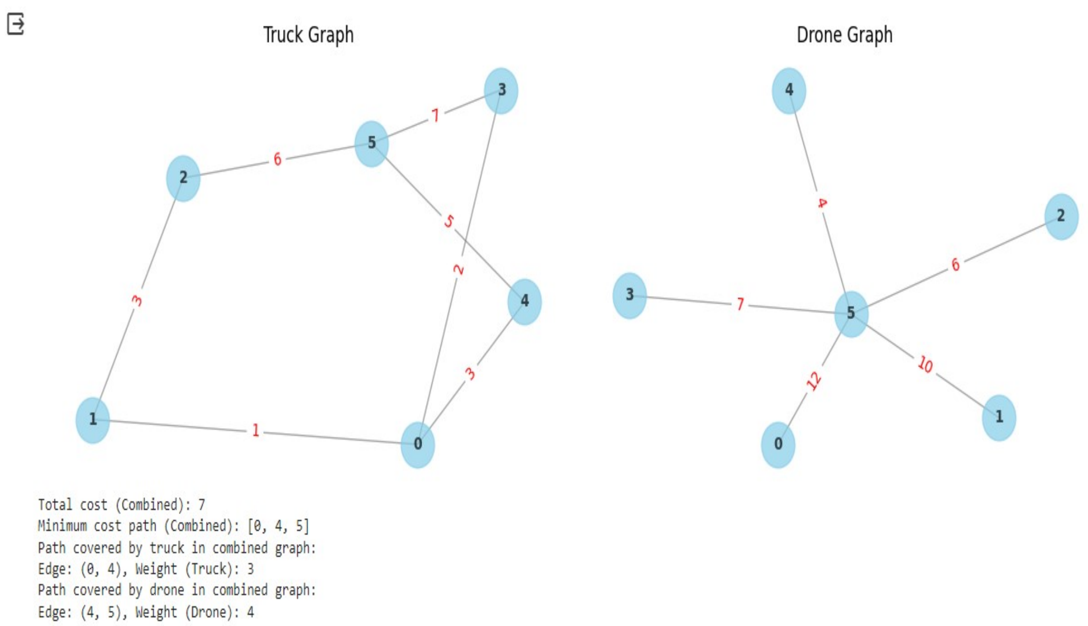


Figure 1: NetworkX Simulations

- **Gurobi Solver:** The Gurobi solver is fed with objective function and constraints and hence the solution is obtained

```
Optimal solution found (tolerance 1.00e-04)
Best objective 7.000000000000e+00, best bound 7.000000000000e+00, gap 0.0000%
Model solved optimally.
Truck Path: 0->4
Drone Path: 4->5
```

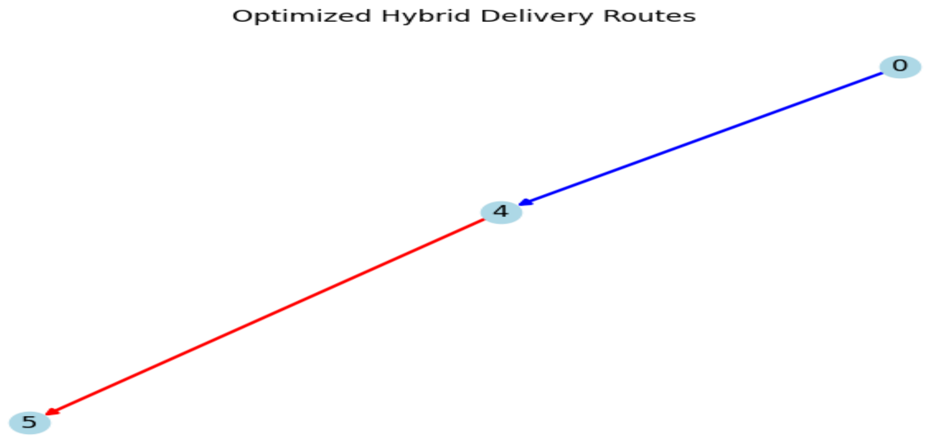
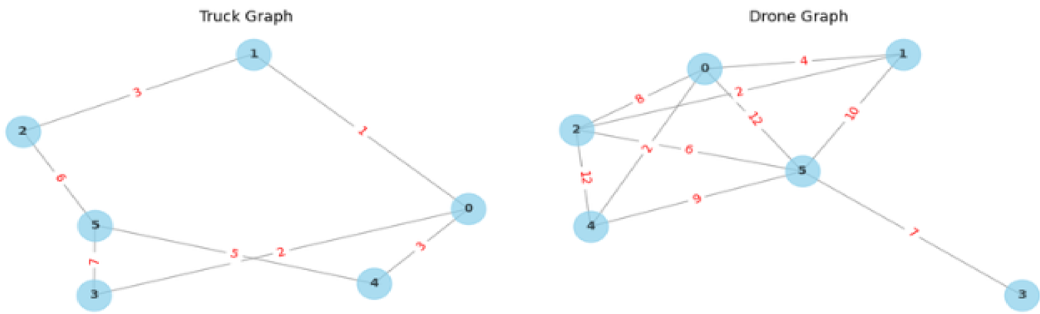


Figure 2: Gurobi Solution and Simulations

5.3.2 One Truck, One Drone, Two Destination:




```
Total cost (Combined): 8
Minimum cost path (Combined 0->2): [0, 1, 2]
Minimum cost path (Combined 2->4): [2, 1, 0, 4]
Path covered by truck in combined graph:
Edge: (0, 1), Weight (Truck): 1
Edge: (1, 0), Weight (Truck): 1
Path covered by drone in combined graph:
Edge: (1, 2), Weight (Drone): 2
Edge: (2, 1), Weight (Drone): 2
Edge: (0, 4), Weight (Drone): 2
```

Figure 3: NetworkX: Two Destination nodes 2 and 4

The two destinations D1 and D2 in this case are inputs. NetworkX library is used to simulate the graphs for truck and drone paths which are then combined to generate a graph that covers both of them with the least path of either. Firstly, the best path is chosen among Path1: Source to D1 and D1 to D2 and Path2: Source to D2 and D2 to D1.

5.3.3 One Truck, One Drone, Multiple Destinations

- **Brute - Force Approach:** In this case, the destinations are in the list in our code, by brute force method, the permutations of the required destinations are taken and then the minimum cost for each permutation is calculated, and the output for the optimal permutation is mentioned

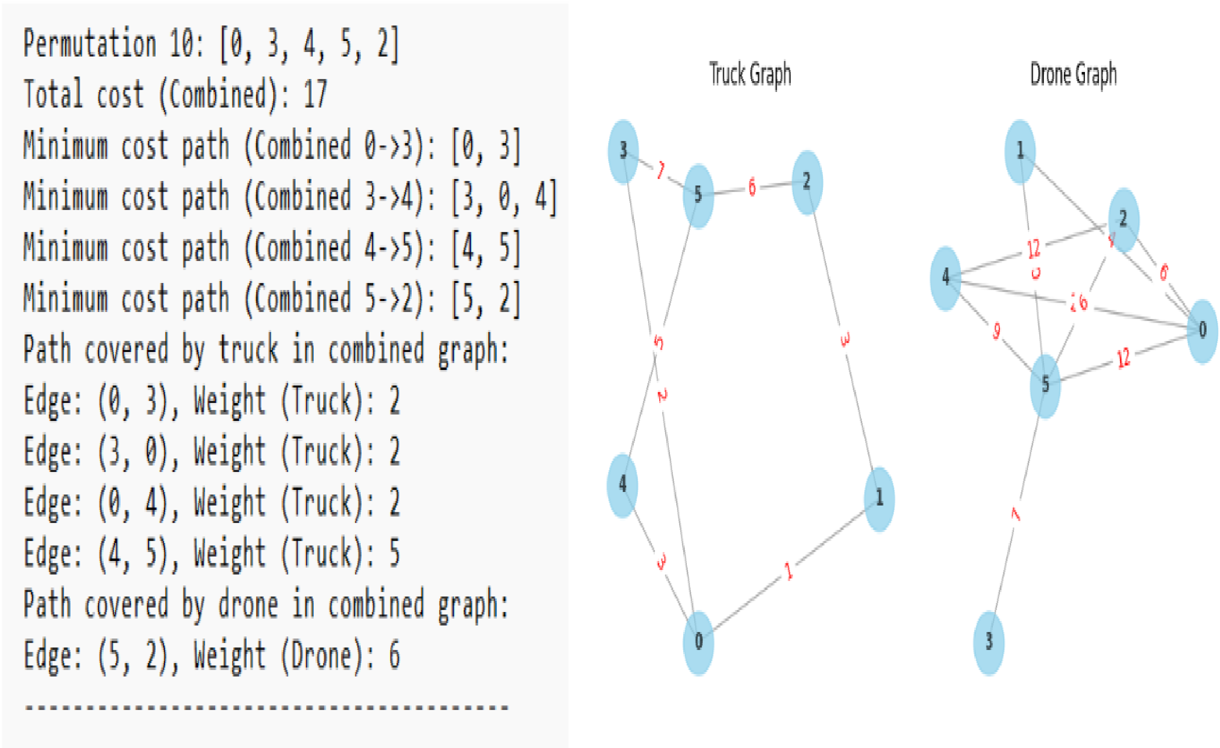


Figure 4: Multiple Destinations

- **Gurobi Method:** Gurobi Solver is used with added constraints by increasing the number of destinations.

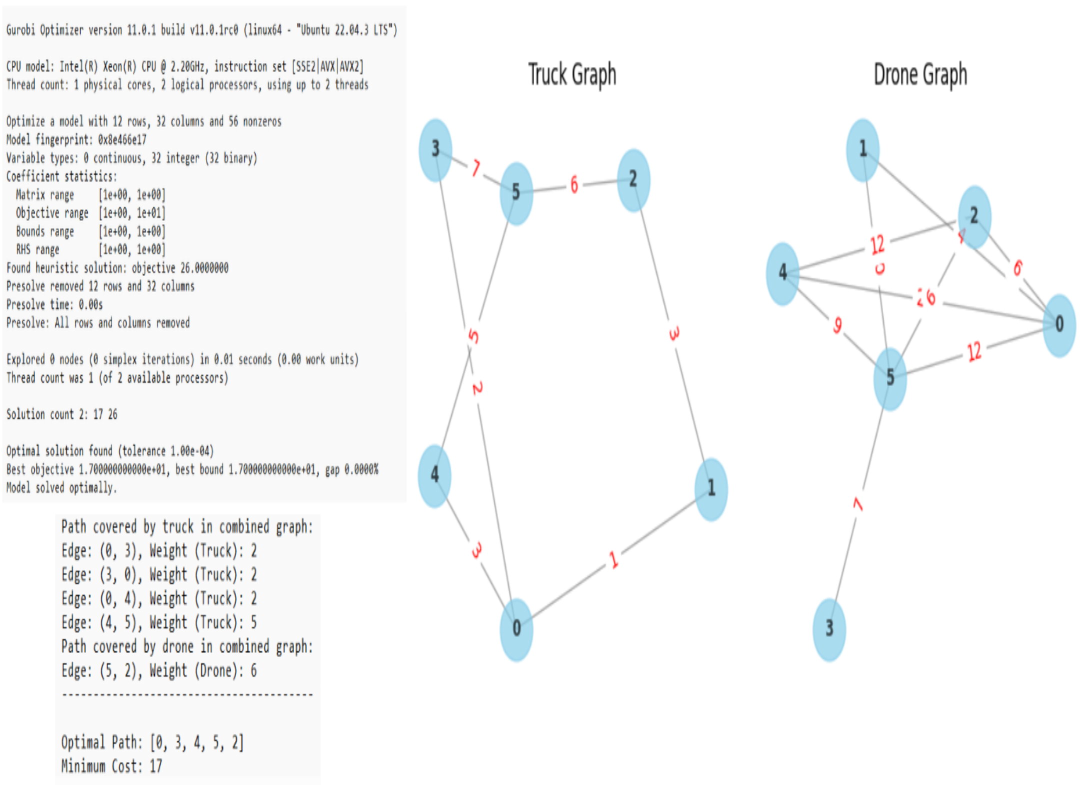


Figure 5: Gurobi Solver: Multiple Destination

5.3.4 Multiple Truck, Multiple Drone, Multiple Destination: Warehouse Approach

Few nodes are selected as warehouses. This scenario is particularly important considering hilly or remote places where only drones can deliver. Trucks travel to the warehouse and from there the drones take over to deliver. The number of drones traveling to a particular warehouse is decided by a clustering algorithm based on the number of destinations near it. This gives the most optimized solution for delivery.

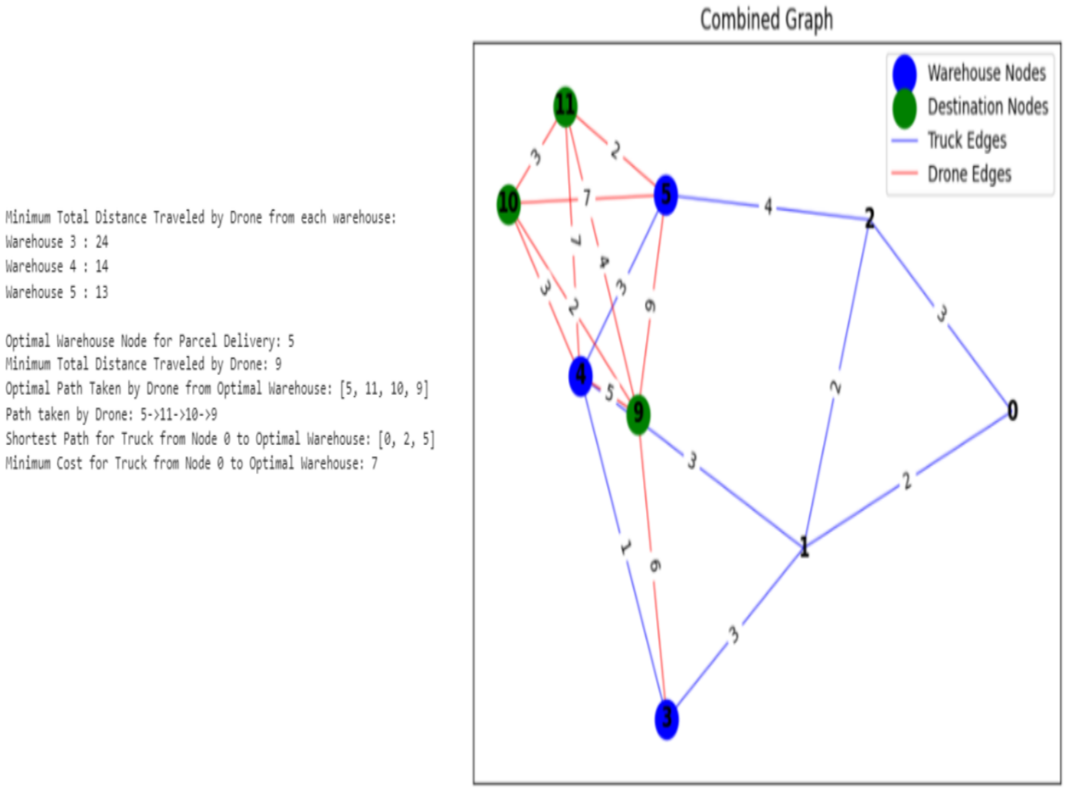


Figure 6: Gurobi Solver: Warehouse Approach

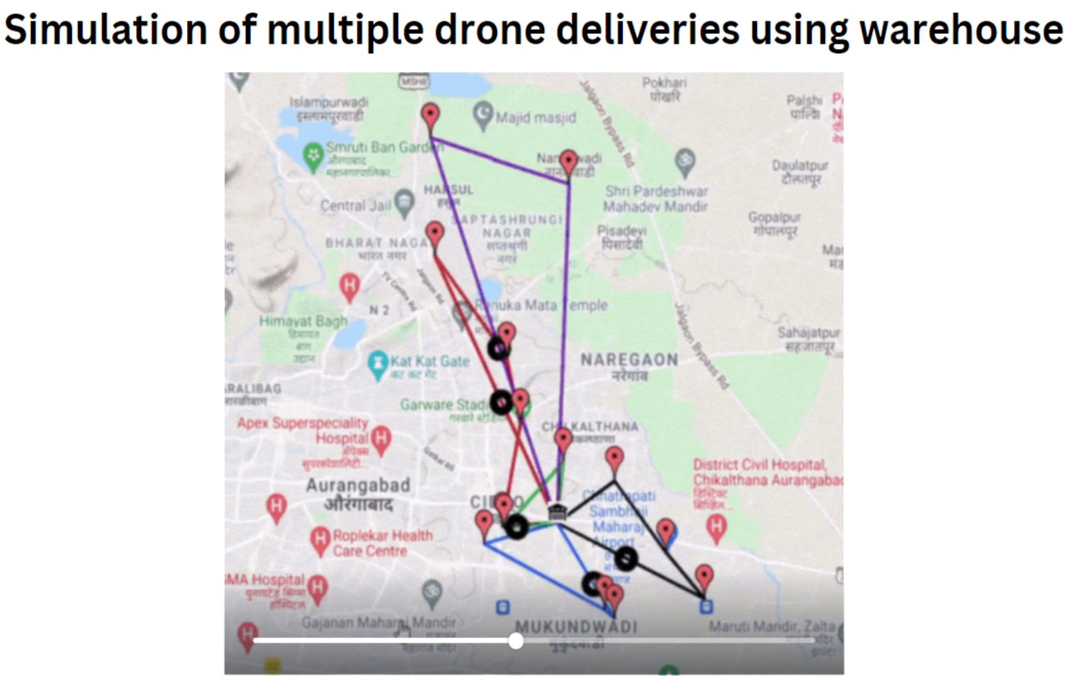


Figure 7: Multiple Drones Simulation

6 Results

6.1 NetworkX Simulations

The NetworkX simulations yielded optimized outcomes for the scenario involving multiple trucks, multiple drones, and multiple destinations. By leveraging NetworkX, an open-source Python library for graph theory and network analysis, our simulations provided valuable insights into route optimization and resource allocation.

6.2 Gurobi Solver

Utilizing the Gurobi solver, we further refined our optimization approach for the complex delivery scenario. By employing Gurobi, a powerful mathematical optimization solver, we were able to achieve highly optimized solutions for the distribution of goods using multiple trucks and drones across various destinations.

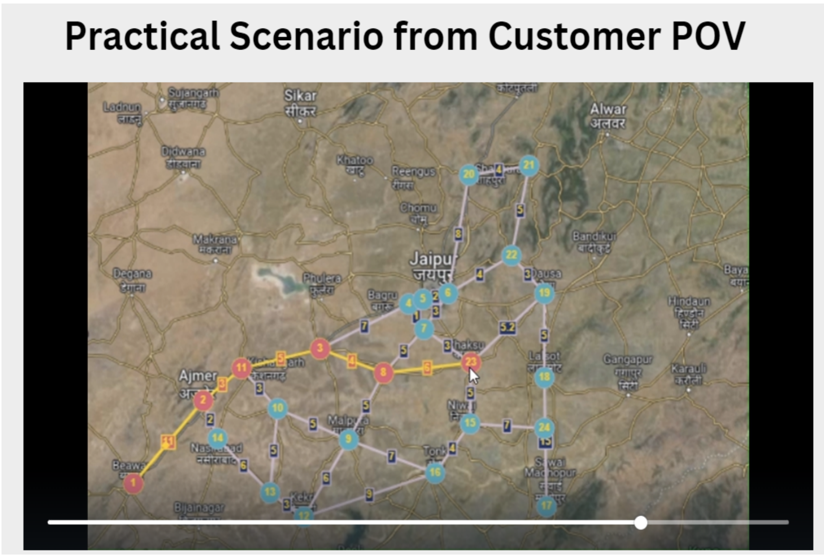
These descriptions emphasize the successful outcomes achieved through both NetworkX simulations and the Gurobi solver in optimizing the delivery system with multiple trucks, multiple drones, and multiple destinations.

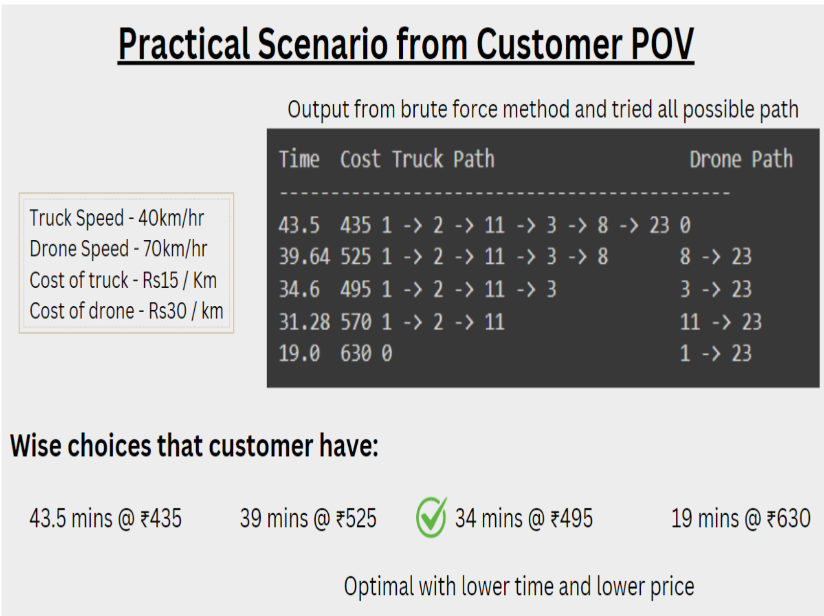
7 Practical Scenarios

7.1 Customer Perspective

From a customer's viewpoint, the hybrid system offers faster, cost-effective delivery options, thereby improving service satisfaction. The first image below shows the location of different nodes on the map of Jaipur. So considering our source to be 1 and destination to be 23, we have considered 5 possible ways to cover this path. Considering Truck speed to be 40 km/hr , Drone speed to be 70 km/hr , Cost of truck to be Rs 15/km and cost of drone to be Rs 30/km. So for the first case when we use just truck to reach the destination from the source, then the cost is the least that is Rs 435 but the time taken is the highest that is 43.5 mins. Whereas in the next 3 cases, we are using a combination of truck and drone for delivery wherein truck starts and then in midway from a point drone takes over and reaches the destination directly. So in the three cases drone takes over from points 8 , 3 and 11 respectively. So out of these we have achieved an optimal case where time taken as well as cost both are less, the optimal case is when truck starts from 1 goes on till 3 (truck path - 1,2,11,3) and then from 3 onwards drone reaches the destination that is 23 (drone path - 3,23). In this optimal case the time taken is 34.6 mins and cost is Rs 495. In the last case just drone is used to travel directly from source to detination that is drone from 1 to 23, in this case the time taken is least that is 19 mins but the cost is the highest that is Rs 630.

So in conclusion if the priority of the customer is just time and cost does not matter to him, then the last case which involves just drone for delivery is suitable for him. Whereas if for some other person just low cost is the highest priority and time does not matter to him, then the first case which involves just the truck is suitable for him. But the optimal solution which involves both less cost and less time can be achieved using the combination of both truck and drone as explained in the 2nd image below





7.2 Environmental and Social Impact

Environmental Sustainability:

1. **Decreased Emissions**: By integrating drones into the delivery system, we significantly reduce the reliance on traditional fuel-powered vehicles for last-mile logistics. This transition to more sustainable modes of transportation helps decrease harmful emissions, contributing to cleaner air quality and a healthier environment.

2. **Promotes Green Technologies**: The adoption of hybrid truck-drone delivery systems promotes the use of green technologies in the logistics industry. This shift towards eco-friendly practices aligns with global efforts to mitigate climate change and reduce carbon footprints.

3. **Reduces Urban Congestion**: Traditional delivery methods often exacerbate urban congestion, leading to traffic gridlocks and increased pollution. By employing drones for certain segments of the delivery process, we alleviate traffic congestion on roads, thereby minimizing environmental impact and improving overall traffic flow in urban areas.

Accessibility:

1. **Connects Remote Areas**: In addition to serving urban centers, the hybrid truck-drone delivery system extends its reach to remote and underserved areas. Drones are particularly effective in reaching locations that are geographically challenging or inaccessible by traditional road networks. This enhanced connectivity ensures that goods can be delivered to remote communities, promoting economic development and improving quality of life.

2. **Aid During Emergencies**: During emergencies such as natural disasters or medical crises, rapid delivery of essential supplies is paramount. The agility and versatility of drone technology enable swift response times, facilitating the timely delivery of critical supplies like medical aid, food, and water to affected areas. This capability can significantly enhance disaster relief efforts and save lives in times of crisis.

3. **Convenience for Vulnerable Populations**: The hybrid delivery system offers convenience and accessibility for vulnerable populations, including the elderly, individuals with disabilities, and those living in isolated communities. By providing efficient and reliable delivery services

directly to their doorstep, we improve accessibility to essential goods and services, enhancing the well-being and quality of life for these demographics.

Economic Benefits:

1. **Cost Savings**: In addition to its environmental and social benefits, the hybrid truck-drone delivery system also offers economic advantages. By optimizing delivery routes, minimizing fuel consumption, and reducing operational costs associated with traditional delivery methods, businesses can achieve significant cost savings over time. These savings can be reinvested in other areas of the business or passed on to consumers through lower prices, stimulating economic growth and competitiveness.

2. **Job Creation**: The adoption of innovative delivery technologies creates opportunities for skilled professionals in fields such as drone operations, logistics management, and technology development. As the industry continues to evolve, it generates employment opportunities and fosters innovation, contributing to economic prosperity and job creation in the logistics sector.

8 Discussion

8.1 System Efficacy

The design and simulations validate the efficacy of the hybrid truck-drone system in urban environments. By successfully integrating drones with ground-based trucks, the system demonstrates improved efficiency in last-mile logistics, reduced delivery times, and optimized resource utilization. The simulations conducted using tools like NetworkX and the Gurobi optimizer provide compelling evidence of the system's ability to streamline delivery operations and achieve cost-effective outcomes. Furthermore, the results indicate the scalability and adaptability of the system to varying delivery scenarios, reaffirming its efficacy in addressing the challenges of urban logistics.

8.2 Challenges and Limitations

While promising, the system's dependence on drone technology and regulatory environments presents challenges that must be carefully addressed. One of the primary challenges lies in the regulatory framework governing drone operations, including airspace regulations, safety standards, and privacy concerns. Navigating these regulatory hurdles requires collaboration with regulatory authorities and adherence to evolving legal frameworks to ensure compliance and operational safety.

Additionally, the integration of drones into existing delivery networks introduces technical complexities and operational challenges. These include battery life limitations, payload capacity, weather conditions, and obstacle avoidance mechanisms. Overcoming these challenges necessitates continuous innovation in drone technology, algorithm development, and operational practices to enhance reliability, efficiency, and safety.

Moreover, the system's effectiveness may be influenced by factors such as urban infrastructure, population density, and consumer behavior. Adapting the system to diverse urban landscapes and consumer preferences requires robust data analysis, predictive modeling, and stakeholder engagement to tailor solutions that meet local needs and preferences.

Despite these challenges, the ongoing advancements in drone technology, artificial intelligence, and data analytics offer opportunities to overcome existing limitations and further enhance the system's effectiveness. By addressing these challenges proactively and fostering collaboration across industry stakeholders, academia, and regulatory bodies, the hybrid truck-drone delivery system can realize its full potential as a transformative solution for urban logistics.

9 Future Work

The development of the hybrid truck-drone delivery system lays the groundwork for future research and advancements in urban logistics. Building upon the success of the current system, several avenues for future work and improvements can be explored:

1. **Relaxing Assumptions**: Further refinement of the delivery system can involve relaxing additional assumptions to better reflect real-world conditions. For instance, relaxing assumptions related to battery decay in drones and load capacity can provide a more accurate representation of operational constraints. By incorporating factors such as varying battery performance over time and dynamic adjustments in payload capacity, the system can better adapt to changing conditions and optimize resource utilization.

2. **Dynamic Adaptation**: Extending the system to handle dynamic changes in traffic conditions, weather patterns, and demand fluctuations is crucial for enhancing operational efficiency

and responsiveness. Leveraging real-time data streams from traffic sensors, weather forecasts, and demand analytics, the system can dynamically adjust delivery routes, mode selection, and scheduling to optimize performance. This proactive approach enables the system to anticipate and mitigate potential disruptions, ensuring reliable and timely delivery of goods.

3. **Advanced Routing Algorithms**: The development of advanced routing algorithms tailored to the hybrid truck-drone delivery system can further optimize route planning and resource allocation. Incorporating machine learning techniques, genetic algorithms, and reinforcement learning methods can enable the system to learn from past delivery experiences, adapt to evolving traffic patterns, and identify optimal routes in real time. By continuously refining routing strategies based on historical data and predictive analytics, the system can achieve higher levels of efficiency and reliability.

4. **Multi-Agent Coordination**: Investigating multi-agent coordination strategies can improve the coordination and collaboration between drones, trucks, and other delivery vehicles operating within the same urban environment. By leveraging techniques from multi-agent systems, game theory, and decentralized control, the system can optimize resource allocation, mitigate congestion, and enhance overall system performance. This collaborative approach enables vehicles to share information, coordinate actions, and adapt collectively to dynamic environmental conditions, thereby improving efficiency and reliability.

By addressing these research directions and exploring new avenues for innovation, the hybrid truck-drone delivery system can continue to evolve and deliver transformative benefits to urban logistics operations.

10 Conclusions

The hybrid truck-drone delivery system represents a significant advancement in urban logistics, offering a holistic approach to optimizing last-mile delivery operations. By seamlessly integrating traditional truck and drone delivery methods, the system achieves enhanced efficiency, cost-effectiveness, and sustainability while addressing the complexities of urban delivery networks.

Key conclusions drawn from the development and analysis of the hybrid delivery system include:

1. **Optimized Logistics**: The integration of truck and drone delivery methods optimizes logistics by leveraging the complementary strengths of each mode of transportation. By strategically coordinating truck routes, drone launch/retrieval nodes, and the interaction between trucks and drones, the system achieves streamlined delivery operations and maximizes resource utilization.

2. **Benefits**: The hybrid delivery system offers a range of benefits, including faster delivery times, reduced costs, lower emissions, and positive social impact. By enhancing delivery efficiency and reliability, the system improves customer satisfaction while promoting sustainability and accessibility in urban areas.

3. **System Design**: The design of the hybrid delivery system involves the optimization of variables such as truck routes, drone launch/retrieval nodes, and coordination mechanisms between trucks and drones. Through rigorous analysis and simulation, the system's design parameters are fine-tuned to achieve optimal performance across various delivery scenarios and operational conditions.

4. **Simulation Results**: Simulations conducted to evaluate the efficiency of the proposed system demonstrate its effectiveness across a range of scenarios, including single/multiple trucks, drones, destinations, and the use of warehouses. By simulating diverse delivery scenarios and assessing performance metrics such as delivery time, cost, and resource utilization, the system's efficacy and scalability are validated.

In conclusion, the hybrid truck-drone delivery system offers a transformative solution to the challenges of urban logistics, providing a scalable, efficient, and environmentally friendly alternative to traditional delivery methods. By harnessing the power of technology, innovation, and collaboration, the system paves the way for a more sustainable and accessible future in urban transportation and logistics.

11 Contributions

Name	Roll Number	Contributions
Aman Khande	210100009	Literature Review, Problem Statement Selection, Objective Function Formulation, One Destination Code (NetworkX), Multiple Destination Code (Gurobi), Practical Scenario Analysis, PPT Making, Report Making
Hemant Bamb	210040064	Literature Review, Problem Statement Selection, Objective Function Formulation, One Destination Code (Gurobi), Two Destination Code, Multiple Destination Code (Bruteforce), Warehouse Management Code, PPT Making, Report Making,
Rishikesh Pandey	210100105	Literature Review, Problem Statement Selection, Objective Function Formulation, One Destination Code(NetworkX), Multiple Destination Code (Gurobi), Practical Scenario Analysis, PPT Making, Report Making
Saumya Sheth	210020120	Literature Review Problem Statement Selection, Objective Function Formulation, One Destination Code (Gurobi), Two Destination Code, Multiple Destination Code (Bruteforce), Warehouse Management Code, PPT Making, Report Making

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13 Code Link:

Folder link: Code files

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