**ENS 492 – Graduation Project (Implementation)**

**Progress Report II**

**Project Title:**

**Integrating Truck-Drone Systems for**

**Enhanced Last-Mile Delivery in Logistics**

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1. **PROJECT SUMMARY**

**Brief Description:**

The objective of the proposed project is to transform the process of last-mile delivery by designing and implementing a hybrid logistics system that will make use of both traditional trucks and unmanned aerial vehicles (UAVs). This approach has been developed to offer solutions to some of the important logistical challenges posed by urban traffic congestion, increased operating costs, and delays associated with accessing remote or geographically challenging locations.

**Gap in the existing solutions:**

While the application of drone technology in the logistics sector is rapidly developing and increasing in deployment, current solutions largely operate in isolation or demonstrate poor integration between trucks and drones. Whereas existing literature outlines the different benefits related to each delivery mode, there is an evident lack of detailed investigations exploring their coordinated collaboration.

**Motivation:**

While considerable progress in drone technology and its application in logistics has been recorded, most of the existing solutions still operate autonomously or showcase a very small level of integration between trucks and drones. Even though the literature has clearly noted the special benefits of trucks, for their high carrying capacity, and drones, for their agility, a gap exists in research investigating coordinated collaboration between them.

**Objectives and Intended Results of The Project:**

The project will focus on developing sophisticated mathematical models and optimization algorithms for synchronizing truck and drone operations.

The key objectives are:

* Developing route optimization algorithms to coordinate drone deployment and truck navigation.
* Developing simulation models to evaluate the performance of systems under alternative scenarios.
* Setting constraints to ensure operational feasibility, including battery life, truck payload, and delivery time slots.
* Validating and verifying the model by case studies and simulation.

The expected results include improved delivery coordination, enhanced cost efficiency, and increased delivery speed by optimizing truck and drone routes. With this system, the intention is to create a new landmark in last-mile delivery by overcoming the logistical hurdles that impede efficient truck-drone collaboration and helping to build more sustainable and responsive supply chains.

Emphasis will be directed toward the creation of advanced mathematical models and optimization algorithms to achieve the ultimate goal of the project. These tools will enable truck-drone operation coordination by determining the best routes for trucks and the optimal time and place for drone deployment. Simulation models will be used in the development process to run many scenarios, which will enable the optimization of the system with respect to performance metrics such as cost efficiency, delivery speed, and resource utilization.

This project aims to set a new benchmark in last-mile delivery by integrating the use of vehicles and drones, enabled by advanced algorithms, while simultaneously looking at the impact on the environment, cost, and efficiency.

1. **SCIENTIFIC/TECHNICAL DEVELOPMENTS**

Since from the Progress Report-I, there has been scientific and technical developments in mathematical modelling of the problem. Also, a code program is formed where the mathematical model is implemented as constraints.

**Conceptual Design:**

The initial design is focused on transforming the last-mile delivery problem into a hybrid logistics system which is formed by trucks and drones. As, mentioned in the previous reports, the main goal is to optimize delivery routes while paying attention to operational constraints such as drone battery life, load capacity and range. The system is formed to consider trucks as mobile depots from which drones can be launched to serve customers located in areas less accessible by highway road.

**Preliminary Design:**

In the preliminary design stage, the model was translated into a computational form using Python and Gurobi by defining sets, parameters and data structures that reflect the logistical characteristics of the problem. Also, spreadsheets were created to store customer data and distance matrices in Excel for the programs further use.

**Key components prepared in this phase include:**

* A structured method for reading customer data and distances from Excel
* Parameter definitions such as truck capacity (60 units), drone capacity (15 units), and maximum drone range (40 km)
* Initialization of vehicle and customer sets
* Representation of distances in dictionary form for easy reference in optimization constraints.

**Design Decision:**

Several design decisions were made to guide development:

* **Solver Selection**: Gurobi was chosen for its strong support for MILP and its seamless integration with Python. This allowed flexibility in testing different formulations and constraint structures.
* **Data Format**: Excel was selected as the input format due to its accessibility and ease of updating for simulations.
* **Modularity**: The code was written in a modular way to allow for easy integration of improved models and constraints to add in future stages.

**Note**: The enhanced version of the MILP model is currently under development. Once finalized, it will replace the initial version and be fully incorporated into the optimization script.

**Detailed Design:**

The detailed design phase consisted of building a prototype of the code that integrates the initial constraints into a functional optimization model. The following components have already been completed:

**Mathematical Model**

The mathematical model currently used is based on the MILP formulation outlined in Progress Report I, which includes:

* An objective function that minimizes the total delivery distance
* Constraints for truck and drone capacity
* Operational range limits for drones
* Logical constraints ensuring that customer nodes are visited by either a truck or a drone

In what follows, we provide the MILP formulation of the problem. **Mathematical Notation** summarizes the mathematical notation

subject to:

(1)

(2)

(3)

(4)

(5)

(6)

(7)

(8)

≥ 1 , (9)

≥ 1 , (10)

M , (11)

(12)

≥ 1 , ≥ 1 , (13)

, ,

,

Z+ ,

The objective function minimizes the total distance traveled by both trucks and drones. Constraints (1) ensure that every customer is served exactly once, either by a truck or a drone. Constraint (2) imposes flow conservation for truck deliveries. Constraint (3) uses the Miller–Tucker–Zemlin (MTZ) formulation to eliminate subtours in truck routing.

Constraints (4)–(6) govern drone operations: drones must launch from a truck’s location (4), must not exceed their maximum range (5), and must be assigned to a specific truck (6). Constraints (7) and (8) enforce truck and drone capacity limits.

Constraints (9) and (10) require at least one customer to be served by each truck and each drone, encouraging their utilization. Constraint (11) sets a maximum number of customers per truck to balance workload. Constraint (12) ensures that the total number of visits equals the total number of customers. Finally, constraint (13) ensures that each truck route begins and ends at the depot.

| Mathematical Notation | |
| --- | --- |
| Sets |  |
| N | Set of all customer nodes (both truck and drone accessible) |
| Z | Set of trucks |
| D | Set of drones |
| 0 | Depot node |
| Parameters |  |
|  | Distance between node i and node j |
|  | Distance between truck z and customer k for drone trips |
|  | Demand at customer k |
|  | Capacity of each truck |
|  | Capacity of each drone |
|  | Maximum range of drones |
| M | Maximum customers per truck |
| Decision Variables |  |
|  | 1 if node j is visited following node i with truck z ; 0 otherwise |
|  | 1 if node k is visited with drone d; 0 otherwise |
|  | 1 if drone d launches from truck z to serve customer k |
|  | 1 if customer k assigned to truck z for drone delivery |
|  | Sequence/order of visit for truck z at customer i |

**Python / Gurobi Code**

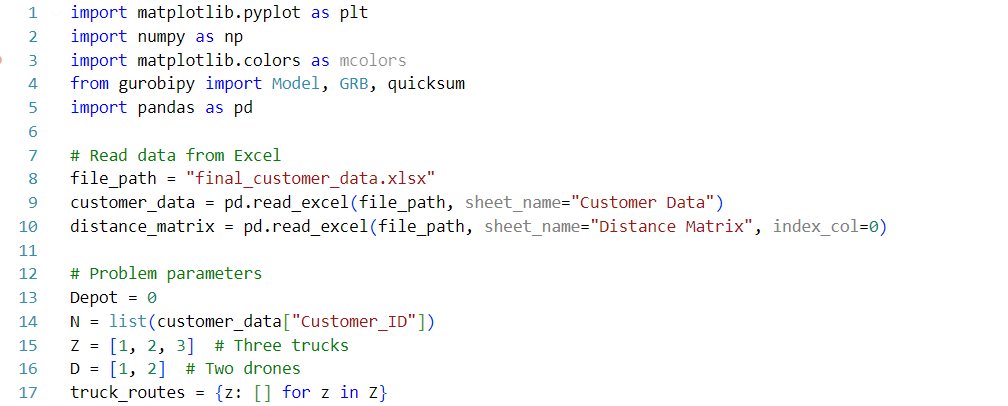
A Python program has been developed, using the Gurobi optimization engine to solve the delivery routing problem under the current mathematical model. The implementation includes:

* Reading the data from Excel spreadsheets which includes customer information and distance constraint.
* Creating sets and dictionaries for trucks, drones, customer nodes and distances
* Initializing Gurobi decision variables such as binary route indicators, continuous service start times
* Applying constraints from the mathematical model
* Preparing the system for output extraction and visualization

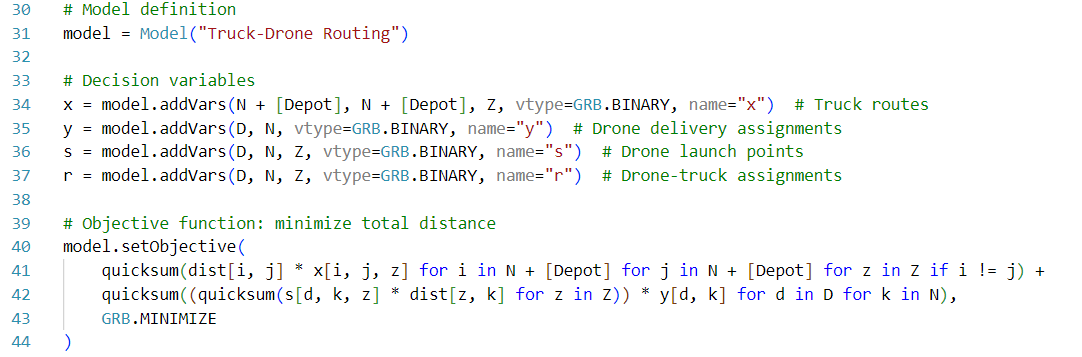
This version of the code acts as the base for future development and integration of more complex logic once the enhanced mathematical model is available.

**Here is the GitHub repository link where the comprehensive Gurobi optimization model implementation can be accessed for further examination and utilization:**

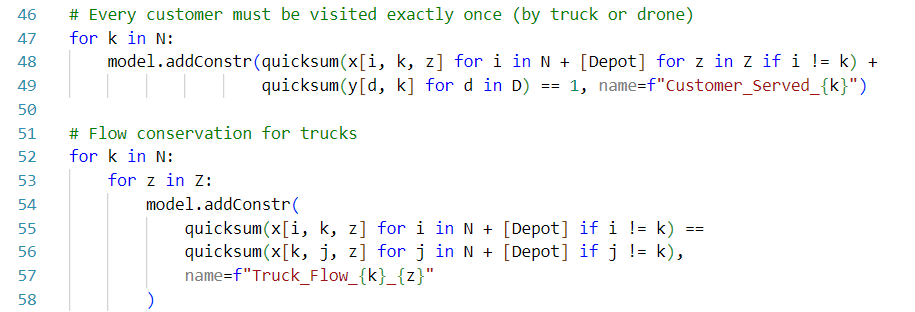
<https://github.com/baskann/ENS492-Truck-Drone-Project.git>

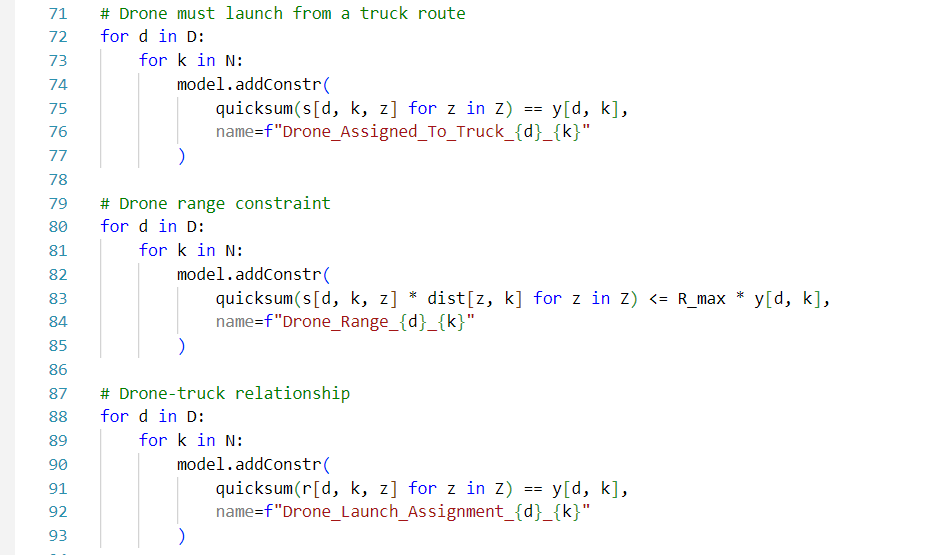


This part addresses data loading and parameter setting processes. It imports the required libraries, reads customer information and distance matrices from Excel files, and sets important parameters such as the depot point, customer nodes, and vehicle lists. The script utilizes pandas for data handling, which is an efficient method to load structured data.

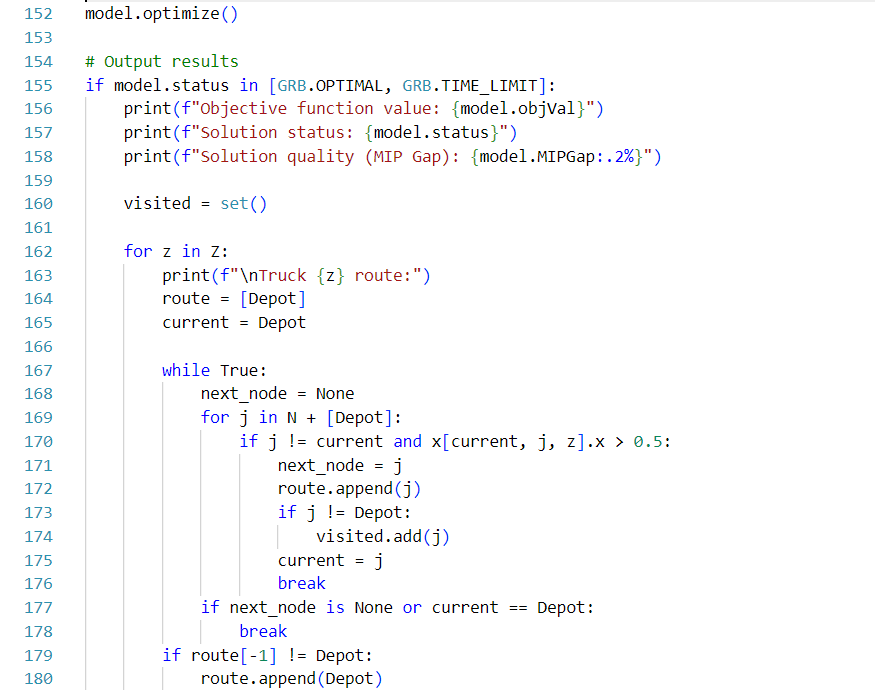


This section formulates the mathematical optimization model using Gurobi. It defines binary decision variables representing truck routing decisions, drone delivery assignment, and interactions between trucks and drones. The objective function is to minimize the overall distance traveled by integrating truck routes and drone flights into an integrated cost function.

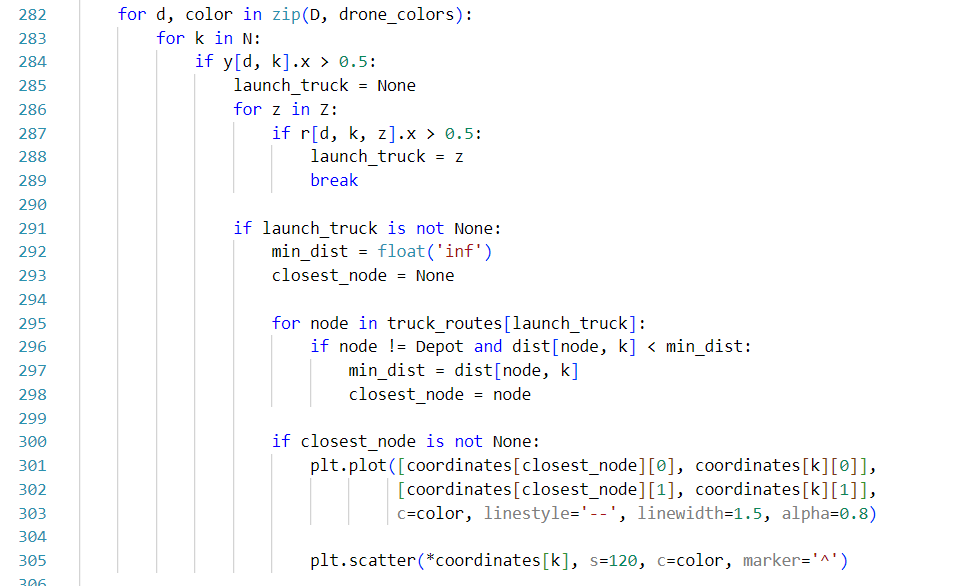




This subsection formulates the fundamental constraints that characterize feasible solutions. The first constraint guarantees that every customer is visited exactly once by a truck or a drone. The flow conservation constraint enforces the necessary continuity of truck routes. The drone range constraint also imposes operational limitations on drone flights, thereby guaranteeing that the drones visit only customers within their maximum flying distance.



This phase solves the optimization model and calculates the solution. Once the model optimization is done, the code constructs the complete truck routes sequentially from the binary decision variables. Beginning at the depot, it traces the route of each truck through the customer nodes and returns to the depot. The algorithm basically transforms the mathematical solution into functional route data.



This part of the solution offers a visual description of the solution using the matplotlib library. The code creates a two-dimensional plot that depicts truck routes as colored solid lines and drone flights as dashed lines. Both forms of vehicles have their own set of distinct color schemes to help distinguish them clearly. The visualization helps in understanding the spatial arrangement of the depot, customer points, truck routes, and drone flights, thus making the complicated solution easier to interpret.

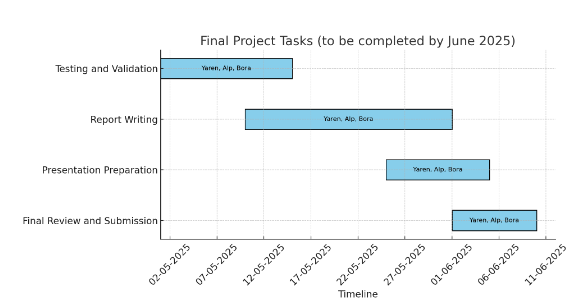
1. **ENCOUNTERED PROBLEMS**

We had to make some changes to our initial strategy as the project progressed. Our first objective was to use both trucks and drones to immediately build a hybrid delivery system. But as we went along, we understood that developing a strong mathematical model was necessary before implementing the system. For this reason, we concentrated on creating a MILP model and putting it into practice with Gurobi.

There were some delays as a result of this change, particularly during the simulation and visualization stages. Drone constraints, like launch locations and range limitations, proved to be more difficult to model than anticipated. We adjusted the project schedule somewhat and allocated more time to simulation work in the future weeks in order to handle this.

All things considered, the primary goal of improving truck-drone collaboration remains applicable and attainable. The additional effort put into creating a robust model has strengthened the project and raised our chances of success.

1. **TASKS TO BE COMPLETED BEFORE FINAL REPORT**



1. **REFERENCES**
2. Baldisseri, A., Pensa, S., Viti, F., & Amodeo, L. (2022). Truck-based drone delivery system: An economic and environmental assessment. *Transportation Research Part D, 107*, 103296.<https://doi.org/10.1016/j.trd.2022.103296>
3. Boccia, M., D’Angelo, G., Gendreau, M., & Guerriero, F. (2024). Exact and heuristic approaches for the truck–drone team logistics problem. *Transportation Research Part C, 165*, 104691.<https://doi.org/10.1016/j.trc.2024.104691>
4. Chang Y., Lee H. (2018). “Expert Systems With Applications.”

<https://www.sciencedirect.com/science/article/pii/S0957417418301775?casa_token=7zb2Sl71uwgAAAAA:2TetFYHjguF12tboI3LLFT3y2PIZergUL_31STpCOAQEoi9n4wiSgBv4hE3xy_FtPrFbxvPFRWo>

1. Das, D., Batta, R., & Nagi, R. (2021). Synchronized truck and drone routing in package delivery logistics. *IEEE Transactions on Intelligent Transportation Systems, 22*(9), 5772-5785.<https://doi.org/10.1109/TITS.2020.2992549>
2. European Environment Agency. *Delivery Drones and the Environment: A Literature Review.*<https://www.eea.europa.eu/publications/delivery-drones-and-the-environment/file>
3. Lin, M., Zhang, J., Chen, Q., & Zhao, H. (2022). Discrete optimization on truck-drone collaborative transportation systems for delivering medical resources. *Discrete Dynamics in Nature and Society, 2022*, Article ID 1811288.<https://doi.org/10.1155/2022/1811288>

### Liu, M., Li, Y., & Wang, X. (2024). Joint optimization of truck-drone routing for last-mile deliveries in urban areas. *Transportmetrica A: Transport Science*. <https://doi.org/10.1080/23249935.2024.2392611>

1. Sadati, M. E. H., & Çatay, B. (2021). A hybrid variable neighborhood search approach for the multi-depot green vehicle routing problem. *Transportation Research Part E*, *149*, 102293. <https://doi.org/10.1016/j.tre.2021.102293>
2. Stolaroff, J. K., Samaras, C., O’Neill, E. R., Lubers, A., Mitchell, A. S., & Ceperley, D. (2018). Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. *Nature Communications, 9*, 409.<https://doi.org/10.1038/s41467-017-02411-5>
3. She, Ruifeng, and Yanfeng Ouyang. "Analysis of Drone-based Last-mile Delivery Systems under Aerial Congestion: A Continuum Approximation Approach." Illinois Center for Transportation, 2023. <https://rosap.ntl.bts.gov/view/dot/73006/dot_73006_DS1.pdf>
4. X. Liu, S.H. Chung and C. Kwon, An adaptive large neighborhood search method for the drone-truck arc routing problem. Computers and Operations Research (2024), doi: <https://doi.org/10.1016/j.cor.2024.106959>.
5. Yoon, Justin. "Last-Mile Delivery Optimization Model with Drones."

<https://ctl.mit.edu/sites/ctl.mit.edu/files/theses/yoon_executive_summary.pdf>

1. Zhang, R., Li, X., Wang, L., & Chen, Y. (2023). A review on the truck and drone cooperative delivery problem. *Unmanned Systems, 12*(5), 823-847.<https://doi.org/10.1142/S2301385024300014>
2. Kumar, V., Gupta, R., & Singh, P. (2024). "Hybrid Logistics Models for Urban Delivery Using AI-Driven Optimization." Journal of Intelligent Transportation Systems, 18(2), 123-134.
3. Wang, T., & Zhao, Q. (2023). "Energy-Efficient Routing in Collaborative Truck-Drone Systems." Renewable Energy and Transportation Journal, 45(7), 98-114.