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(Autonomous), Kolkata

Department of Computer Science

Quantum Ridesharing

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# Abstract

The objective of Ridesharing is to satisfy clients travelling to various destinations while minimizing the cost of travel. The proposed task is to devise an efficient Ridesharing system that operates on quantum algorithms. This project attempts to emulate a Capacitated Vehicle Routing Problem (CVRP) having a variable number of passengers travelling to various destinations from a central hub with a fixed number of vehicles. The CVRP is a combinatorial explosion of possible solutions, which increases super-exponentially with the number of passengers. The goal of the model is to distribute the passengers amongst the vehicles available and to formulate the routes to their destinations such that the total distance covered is minimal. The model uses Quadratic Unconstrained Binary Optimization (QUBO) implemented via Quantum Annealing on D-Wave systems.

# Acknowledgement

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# introduction

## 1.1 Background

This project deals with solving the CVRP using a quantum annealer. Several approaches have been discussed to explore the work done in this domain. Laporte and Semet (2002) [1] presented a few heuristics for solving the CVRP namely construction heuristics, improvement heuristics, and metaheuristics.

Metaheuristics are top-level methods that assist local improvement operators in identifying a global solution. For the (C)VRP, Groër et al. (2010) [2] described a library of local search heuristics. Crispin and Syrichas (2013) [3] suggested a metaheuristic for vehicle scheduling based on classical-quantum annealing. They employed a stochastic variation dubbed Path-Integral Monte Carlo (PIMC) to replicate the quantum fluctuations of a quantum system on a classical computer to approximate quantum annealing. This is due to the quantum annealing hardware. The Sweep algorithm (Gillett and Miller, 1974) [4] is one of the most important classical 2-Phase-Heuristics, in which viable clusters are produced by rotating a ray centered at the depot. The TSP is then solved for each cluster. Fisher and Jaikumar (1981) [5] tried a cluster-first, route-second technique to solve the VRP. Instead of utilizing a geometry-based strategy to generate the clusters, they devised a Generalized Assignment Problem (GAP). The seeds were chosen by solving capacitated location problems, and the remaining vertices were gradually integrated in their allotted route in a second stage [6]. The efficiency of a quantum annealer in solving small instances inside families of hard operational planning problems under various mappings to QUBO issues and embeddings was investigated by Rieffel et al. (2015) [7]. While their research did not provide results that were competitive with state-of-the-art classical techniques, they did gain insights from the findings that can be used to program and construct future quantum annealers. A tree-search-based quantum-classical framework is described by Tran et al. (2016) [8]. To get strong candidate solutions, the authors utilize a quantum annealer to sample from the configuration space of a relaxed issue, followed by a classical processor that maintains a global search tree. They put their technique to the test and compare variants on minor problem examples from three scheduling fields. Many approaches have a hybrid structure, as can be seen in general. That is, traditional bottlenecks are delegated to quantum computing devices that perform local quantum searches iteratively [9][8][10].

Using the classical 2-Phase-Heuristic, the CVRP can be partitioned into smaller optimization problems. Laporte and Semet (2002) [1] divided the CVRP into two phases using this heuristic: the clustering phase and the routing phase. The clustering phase can be compared to the NP-complete Knapsack Problem (KP) (Karp, 1972) [11], which involved cramming various sized things (in this case, customers) into a limited number of knapsacks (here, vehicles). The sum of the objective values of the things in a knapsack should be maximized as a result, reducing the Euclidean distance between consumers assigned to a vehicle. Feld et al. (2019) [12] had provided an intuitive way to partition the problem into smaller subproblems.

## 1.2 Objectives

This project aims to develop a model for the CVRP such that:

* All the commuters are served while making the overall journey minimal.
* All the vehicles are utilized to their fullest.
* The model is no less efficient than other existing solutions.

## 1.3 Purpose, Scope and Applicability

* Purpose: The purpose of this project is to create a ridesharing system based on quantum methodologies. Many implementations of ridesharing have already been carried out using the classical setup. Quantum Computing is an upcoming research area of Computer Science. This field has till date been limited to theoretical and experimental aspects due to unavailability of quantum computers for practical use. Although quantum computers are now more widely available as compared to the past, they are still limited in terms of computing power, storage and usability. Despite these limitations, quantum computing has started to show promise in various fields, achieving results that are impossible for classical computers. This project tries to establish a groundwork in the domain of ridesharing using quantum computers with the vision that, in the future, when quantum computers become more suitable for practical applications, the foundations laid down by this project can be expanded for more extensive applications.
* Scope: This project considers a ridesharing ecosystem where there exists a particular location called hub, say H, where M vehicles (called shuttles) are present. There are N commuters at H who want to go to locations X1, X2, …, XN. The goal is to distribute the N commuters amongst the M shuttles and plan the routes of sending them to their destinations such that the overall journey undertaken by the shuttles is minimum.

To create this model the following assumptions have been made:

1. A commuter can board the vehicle only from the hub.
2. The total number of commuters is always less than the total combined capacity of the vehicles available.
3. The journey of a shuttle stops when it has dropped of its last onboard passenger.
4. All the destinations are within a radius of 50 km from the hub.

As current gate-based quantum computers have limited computing capability due to very limited number of qubits, they are only able to solve simplest versions of the VRP. According to the model used by this project, the number of commuters should not exceed 5 while the number of shuttles cannot be greater than 2.

* Applicability: The model described in this project can be adapted to many real-world use cases. A few of them are as follows:

1. The model can be extended to cater to any ridesharing application which provides carpooling services similar to Uber and Ola.
2. It can be used for a company carpool system for the employees.
3. It can be incorporated in a navigation application to route a journey with multiple stops.

# 2. survey of technologies

To successfully implement a project, apart from the programming language, suitable software development kits (SDKs) and runtime ecosystems needs to be chosen. A brief description about the relevant technologies that are available for quantum computing are as follows:

* **Programming Language:** Theprogramming language is a means of interaction between a developer and a computing device. Factors that affect the choice of a programming language include familiarity, ease of use, community, and availability of required functionality. The following languages have been surveyed while considering an appropriate choice for this project:
  1. **Python:** Python is a high-level object-oriented programming language. Python has an easy-to-understand syntax. It is easy to use and is currently one of the most popular programming languages. Python is open-source and has an enormous community support. It has an extensive library of modules and is greatly suitable for data analysis, processing, visualization, quantum programming and creation of APIs.
  2. **Q#:** Q# is an open-sourced programming language developed by Microsoft for developing as well as executing quantum algorithms. It enables inclusion of classical code inside a quantum program. During the implementation of an operation, Q# allows easy representation of algorithms in the circuit of quantum gates.
  3. **QCL:** Quantum Computing Language (QCL) is a high level, architecture independent programming language for quantum computers with C-like syntax. It allows the implementation and simulation of quantum algorithms.
* **Software Development Kit:** A software development kit is a collection of software development tools that facilitate the process of application creation. They come incorporated with advanced functionalities and greatly reduce the overhead work of a developer. The creation of certain platform-specific applications requires the use of SDKs. The following SDKs have been considered while choosing the apt ones for this project:

1. **Qiskit:** Qiskit is an open-source SDK founded by IBM Research for developing circuits, pulses, and algorithms. It uses Python and provides tools for creating, manipulating and running quantum programs. It has many well-defined quantum libraries, an active community, and modules for solving optimization problems.
2. **D-Wave Ocean:** D-Wave Ocean is an open-source suite of tools based on Python developed by D-Wave for solving hard problems with quantum computers. It has tools for the creation of quadratic models, constraint satisfaction, and various samplers and solvers.
3. **PennyLane:** PennyLane is a cross-platform Python library for differentiable programming of quantum computers. It enables the training of a quantum computer in a similar manner as a neural network. It is primarily focused on Quantum Machine Learning and supports a variety of machine learning development tools.
4. **Cirq:** Cirq is a Python library for writing, manipulating, and optimizing quantum circuits, and then running them on quantum computers and simulators. It includes abstractions for working with noisy intermediate-scale quantum computers, where details of the hardware are vital to achieving state-of-the-art results.

* **Runtime Ecosystem:** A runtime-ecosystem is a development environment that has the provision to build, test, run and analyse programs and algorithms. They include IDEs for building programs, simulators for testing, access to runtime systems, and tools for analysis. A few popular ecosystems for quantum programming are described below:

1. **Amazon Braket:** Amazon Braket is a fully managed quantum computing service designed for scientific research and software development for quantum computing. It has provisions for building, testing, running, and analysing quantum programs. It provides access to quantum computers via Amazon’s cloud service AWS.
2. **IBM Quantum Experience:** It is an online platform from IBM Quantum that provides cloud-based quantum computing services. It provides access to IBM's quantum processors, tutorials on quantum computation, and an interactive textbook. It can be used to run algorithms, experiments, and simulations on quantum computers.
3. **D-Wave Leap:** D-Wave Leap is a quantum cloud service that delivers real-time access to a quantum computer and a suite of quantum hybrid solvers. It also includes development kit, live editor, demos, learning resources, and a vibrant developer community. Its services are mainly suited to solve various business problems.

Based on the requirements of this project, **Python** was chosen as the preferred programming language. It is suitable for data analysis as well as quantum computing. It has well-defined quantum frameworks. The SDKs, Qiskit and D-Wave Ocean, both of which are integral for this project are based on Python. **Qiskit** is needed due to its ability to its ease-of-use and extensive tools for designing, altering, and executing quantum circuits. It has various modules for solving optimization problems which are required by the project. **Ocean** is integral to this project due to its extensive portfolio of solvers and support for quantum optimization. The **D-Wave Leap** ecosystem is considered appropriate for this project as their quantum computers have significantly larger number of qubits as compared to their compatriots.

# 3. requirements and analysis

## 3.1 Problem Definition

Let there be M shuttles at the Hub H. There are N passengers at H who want to go to locations X1, X2, …, XN. The input is provided to the system in the form of geographic coordinates of each node Xi, i =1, …, N.

The problem can be represented as a fully connected graph having N + 1 nodes with the hub being node 0 and the various destinations being nodes {1, 2, …, N}. Every edge (*i*, *j*) of this graph represents the cost of traveling from node *i* to node *j*. The cost is calculated as the Euclidean distance between the geographic coordinates of node *i* and node *j* and is represented as *Cij*. The objective is to find the optimal route, for each of the M vehicles, such that it can take all the commuters allotted to it to their destinations at minimal cost.

The problem can be divided into three subproblems:

1. **Binary Quadratic Model:** The cost matrix is calculated from the inputs provided and used to create a binary quadratic model of the problem.
2. **Clustering:** The commuters are distributed amongst the M available shuttles.
3. **Routing:** For each shuttle, the minimal route, to take the allotted commuters to their destinations, is found.

**Constraints:** The constraints are as follows:

* The maximum capacity of each shuttle is four commuters.
* There can be only one shuttle at any node (other than the hub) at any time instant.
* A shuttle must be at only one place at any time instant.

## 3.2 Requirement Specification

The system has the following requirements:

* The input for each destination Xi, i =1, …, N, is to be provided in the form of the geographic coordinates of that destination.
* The inputs are to be translated into a fully connected graph of N+1 nodes and a corresponding cost matrix is to be created.
* A binary quadratic model is to be created using the cost matrix.
* The output of the solver is to be represented in the form of a graph displaying the generated routes.

## 3.3 Software and Hardware Requirements

Hardware Requirements:

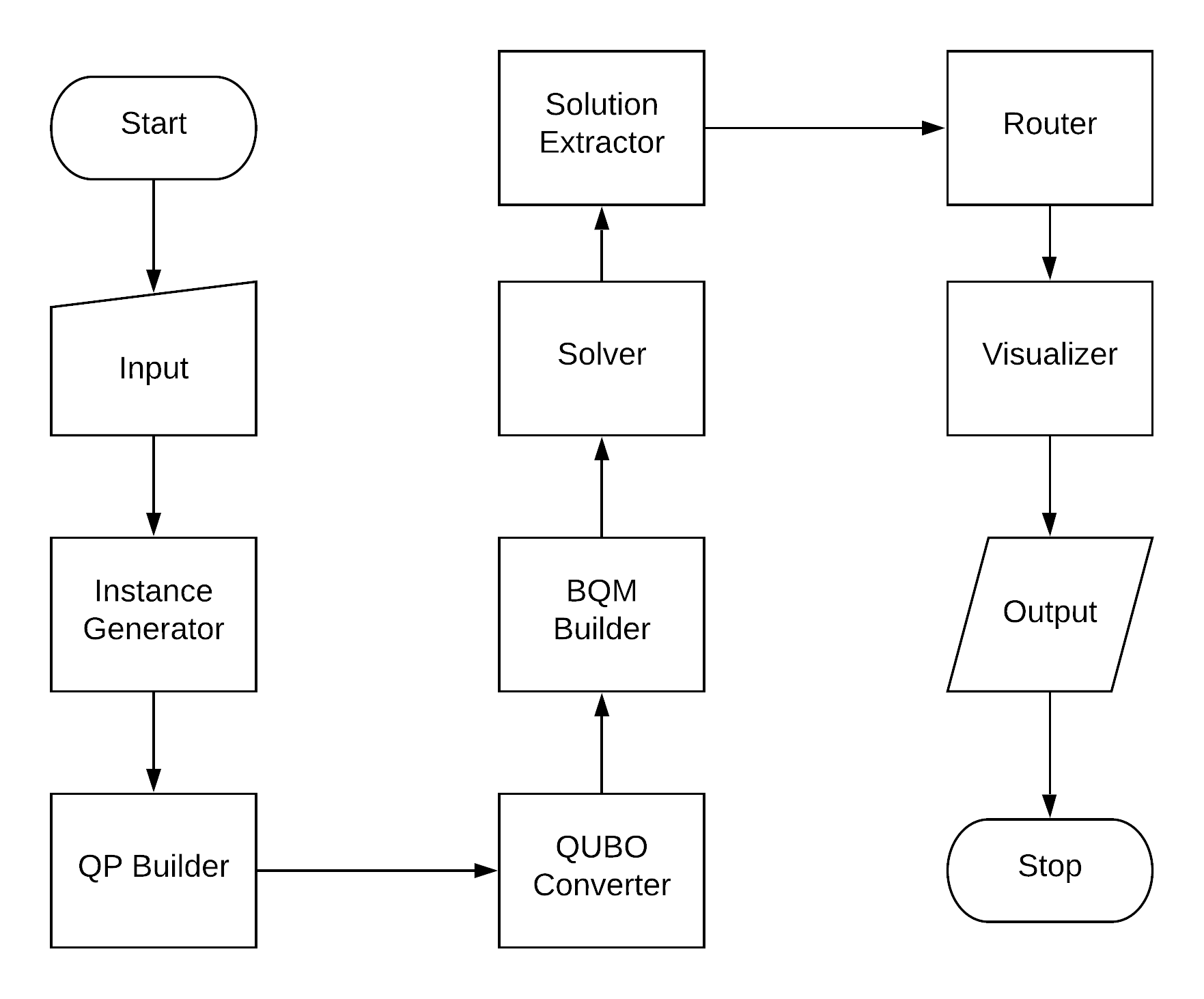
* Processor: Intel® Core 2 Duo E8400 or higher/ AMD® Athlon II X2 or higher
* Clock Speed: 2.2 GHz or higher
* System Architecture: 64-bit x86
* RAM: 4GB or higher

Software Requirements:

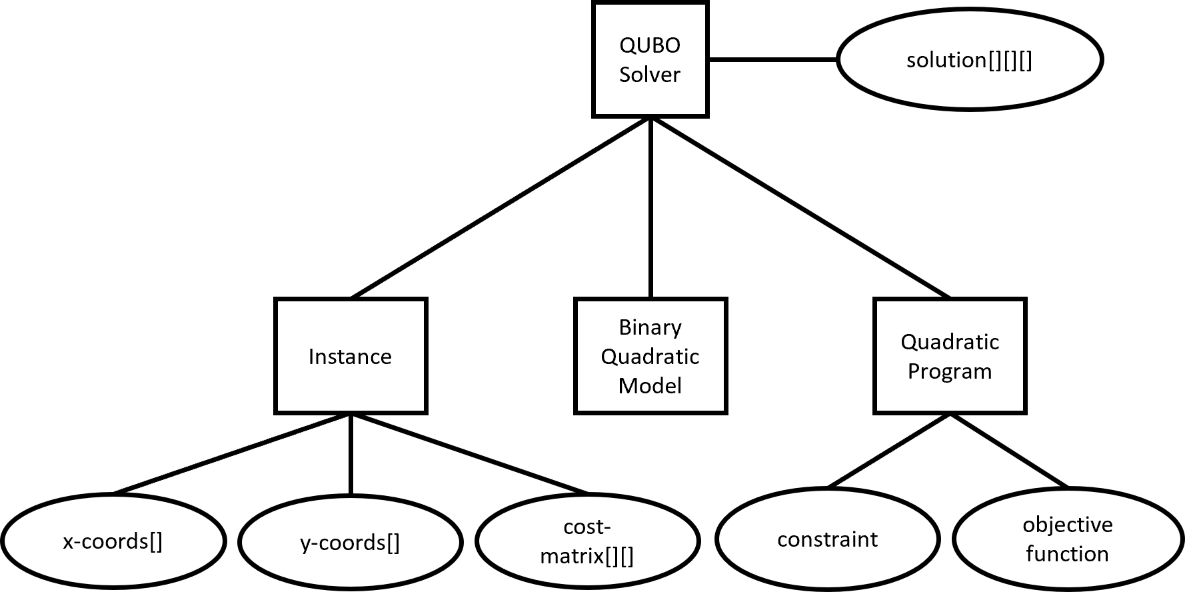
* OS: Windows 8 or higher / Ubuntu 16.04 or higher / mac OS X 10.13 or higher
* Python 3.6 or higher
* Qiskit
* D-Wave Ocean
* Jupyter Notebook

# 4. system design

## 4.1 Conceptual Model



**Figure 1. Data Flow Diagram of QUBO Solver**

****

**Figure 2. Object Model of QUBO Solver**

## 4.2 Basic Modules

The QUBO solver comprises of the following modules:

1. **Instance Generator:** Creates an instance that is used to build the Quadratic Program (QP). The instance comprises of two linear arrays containing the x and y coordinates of the various nodes and a 2-D matrix containing the cost to travel from one node to another.
2. **QP Builder:** Builds the QP from the instance and adds the corresponding constraints and the objective function.
3. **QUBO Converter:** Converts the QP to a QUBO instance by appending all constraints to the objective function in the form of penalties.
4. **BQM Builder:** Builds a Binary Quadratic Model (BQM) from the QUBO instance.
5. **Solver:** Solves the BQM.
6. **Solution Extractor:** Extracts the solution and maps it to a 3-D list.
7. **Router:** Using the distribution made by the solver, generates the appropriate routes.
8. **Visualizer:** Displays the generated routes in a graphical format.
9. **Simulator:** Using the distribution obtained from the solver, initializes a simulation which runs for a fixed number of iterations.
10. **Request Handler:** For a random request generated in an iteration, handles the request and either assigns it to a suitable shuttle or discards it.
11. **Map Drawer:** Draws the state of the simulation in every iteration on the map.

## 4.3 Data Design

**Object Model of the QUBO Solver:** TheQUBO Solver is a user-defined datatype. It acts as a wrapper for the entire solution model. It has the following components:

1. **Instance**: It is a user-defined datatype. It represents the problem space in the form of a graph. It has the following three attributes:
   * **x-coords:** It is an array that stores the x-coordinates of the nodes.
   * **y-coords:** It is an array that stores the y-coordinates of the nodes.
   * **cost-matrix:** It is a 2-D array that stores the cost to travel from one node to another.
2. **Binary Quadratic Model:** It is an imported datatype that is used represent a BQM instance.
3. **Quadratic Program:** It is an imported datatype that is used represent a QP instance. It has the following three attributes:

* **constraint:** It is an attribute that stores a constraint that binds the QP.
* **objective function:** It is an attribute that stores the objective function of the QP.

1. **solution:** It is an attribute that stores the solution obtained from the solver. It is in the form of a 3-D array.

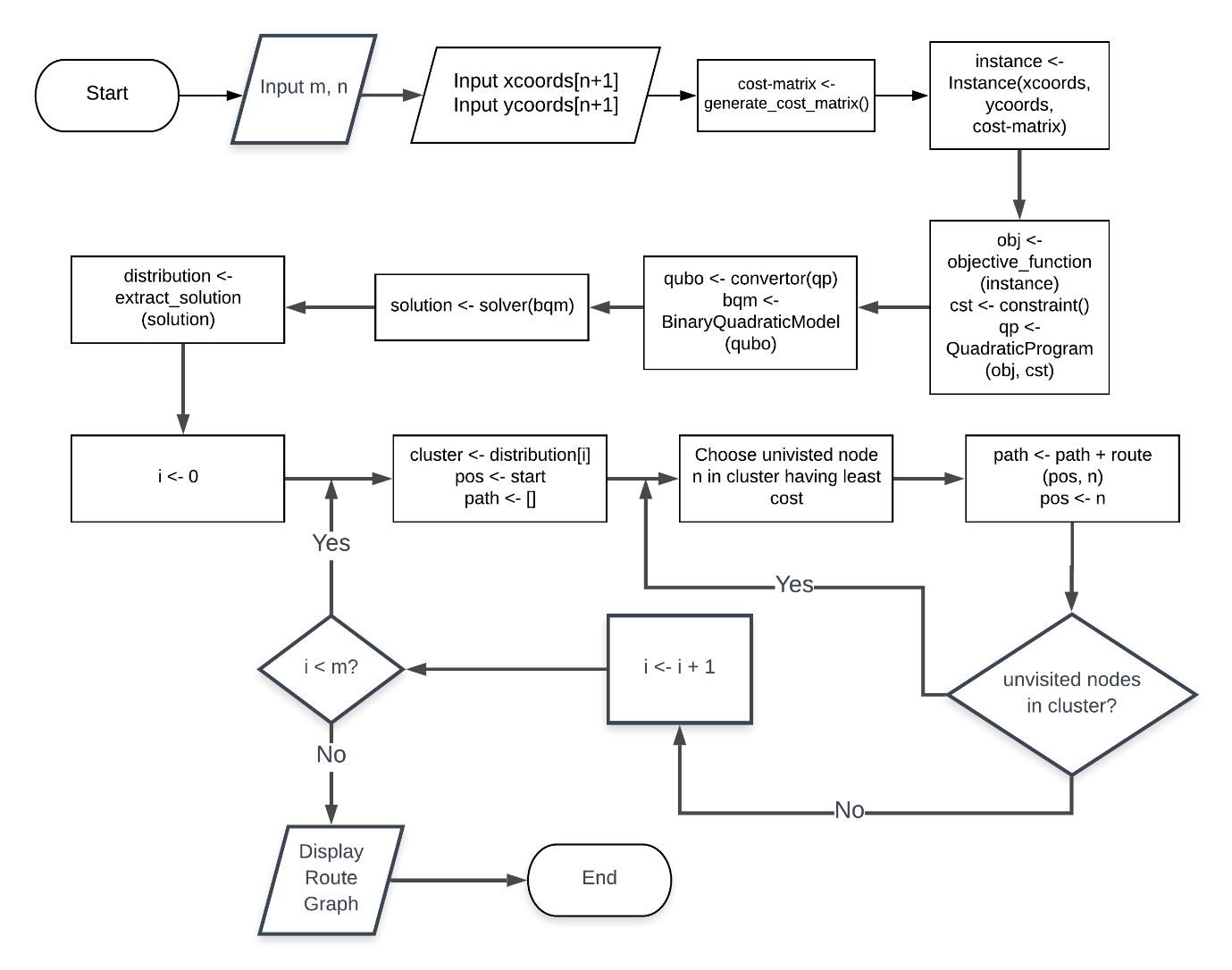
**Object Model of a Shuttle:** The Shuttle is a user-defined datatype that is used to represent the state of a shuttle at any instant. It has the following components:

* + 1. **Number:** A unique number identifying the shuttle.
    2. **Passengers:** A list containing the details of the current passengers.
    3. **Current Position:** Denotes the current position of the shuttle.
    4. **Route:** The current route that the shuttle is following.
    5. **Drop order:** Denotes the order in which the shuttle will service its passengers.
    6. **Occupancy:** The current occupancy of the shuttle.
    7. **Service:** Denotes whether the shuttle is servicing a pickup request or not.
    8. **Pickup:** The request of the passenger whom the shuttle is going to pick up.

**Object Model of Simulation:** The Simulation is a user-defined datatype that is used to represent the state of the simulation at any instant. It has the following components:

1. **m:** No. of vehicles available for service.
2. **n:** No. of initial passengers.
3. **Center:** Index of the hub.
4. **Total Nodes:** Total number of nodes in the problem.
5. **Clusters:** The clusters generated from the initial requests generated by the QUBO solver.
6. **Requests:** The list of initial requests.
7. **Shuttles:** The list of shuttle objects.

## 4.4 Procedural Design



**Figure 3. QUBO Solver Algorithm Flowchart**

The process starts by taking as input the values m and n which are the number of shuttles and the number of commuters respectively. For each commuter, the coordinates of their destination are taken as input. The x-coordinates and y-coordinates of all the nodes including that of the hub are stored in two arrays. A cost matrix is generated corresponding to the inputs. Next, an instance is created using the coordinates and the cost matrix. The instance is fed to the objective function generator to create an objective function. The necessary constraints are also generated. The objective function and constraints are used to create the QP which is then converted to a QUBO instance. The QUBO is transformed into a BQM. The BQM is then fed to the solver to obtain the distribution of commuters amongst the m shuttles. For each cluster in the distribution, the following steps are performed to generate the route for that cluster:

1. Choose the node having the least cost amongst the unvisited nodes.
2. Create a route between the current position and the chosen node.
3. Append the route to the existing path.
4. If there are any unvisited nodes left in the cluster, go to step 1.

After all the routes have been created for all the clusters, they are displayed in the form of a graph.

A simulation is created based on the above-obtained initial state. The initial state is shown in pictorial format by drawing the drop locations and the routes on the map. The simulation is run for a fixed number of iterations. For each iteration, a random request is generated and a request handler is used to determine whether the request is serviceable or not. If the request is not serviceable, the request is declined. Otherwise, suitable shuttles which can service the request are determined. If a shuttle is currently idle, and the pickup location is within a predefined radius of the current position of the shuttle, then it qualifies as a suitable shuttle. On the other hand, if a shuttle currently has passengers but its occupancy is not full, it is suitable for the request if the pickup location is within a predefined radius of the current position of the shuttle and the drop location of the request falls within the predefined radius of any node along its untraveled route. Among the suitable shuttles, the best fit is selected. The chosen shuttle is rerouted to accommodate the pickup and drop locations of the new passenger. It is set to service mode till the passenger is onboard. While in service mode, the shuttle does not entertain any further requests. The state of the simulation in every iteration is documented using logs as well as images of the map representing the current routes of the shuttles, the various drop locations, and the current positions of the shuttles.

## 4.5 Output Prototype

Diagram

Description automatically generated with low confidence

**Figure 4. Cluster graph**

Figure 4 shows a diagrammatical representation of the output as displayed by the visualizer. The nodes are distributed amongst the available shuttles (here, 2) and the routes are generated accordingly. Routes for each shuttle are represented by their respective colors. The total cost of journey for each shuttle is the sum of the costs of travelling to the nodes in accordance with their routes.

**5. IMPLEMENTATION AND TESTING**

**5.1 Source Code**

**constants.py**

*Contains the constant data used in the implementation of the application.*

import numpy as np

dist\_matrix = np.array([

    [0, 294, -1, -1, ………………………………………………………………., -1, -1, -1, -1],

    [294, 0, 348, -1, ……………………………………………………………..., -1, -1, -1, -1],

    [-1, 348, 0, 333, ..............................................................................................., -1, -1, -1, -1],

    [-1, -1, 333, 0, .................................................................................................., -1, -1, -1, -1],

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    [-1, -1, -1, -1, ...............................................................................………….... 0, 373, -1, -1],

    [-1, -1, -1, -1, ...............................................................................…………., 373, 0, 175, -1],

    [-1, -1, -1, -1, …………………………………………………………………., 175, 0, 436],

    [-1, -1, -1, -1, ............................................................................…………......, -1, -1, 436, 0],

])

[*Dimension: 122 rows x 122 columns*]

coordinates = [

{'latitude': 22.59257785, 'longitude': 88.39495508},

{'latitude': 22.59380613, 'longitude': 88.39813082},

{'latitude': 22.59582682, 'longitude': 88.40139238},

{'latitude': 22.59687855, 'longitude': 88.40372944},

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{'latitude': 22.56493018, 'longitude': 88.41030496},

{'latitude': 22.56208484, 'longitude': 88.40822695},

{'latitude': 22.56069259, 'longitude': 88.40911035},

{'latitude': 22.55804088, 'longitude': 88.41162285}]

[*Dimension: 122 items*]

image\_coordinates = [(143, 109), (180, 109), (220, 109), ……………………….

     ……………………………..., (58, 538), (58, 569), (59, 614)]

[*Dimension: 122 items*]

**utility.py**

*Contains functions to generate initial requests, to generate a VRP instance from the obtained requests, and to generate the optimal route for a particular cluster along with the service ordering.*

import numpy as np

import random

from constants import coordinates

from routes import Route, join\_route

def generate\_initial\_requests(n, center, total\_nodes):

    """Generate the initial set of requests.

    Args:

        n: No. of nodes excluding the hub.

        center: Index of the node considered as the hub.

        total\_nodes: Total number of nodes

    Returns:

        A numpy array of size n containing the initial requests.

    """

    requests = np.zeros(n, dtype=np.int8)

    i = 0

    while i < n:

        val = random.randrange(total\_nodes)

        if val != center:

            requests[i] = val

            i += 1

    return requests

def generate\_vrp\_instance(n, center, requests):

    """Generate a random VRP instance.

    Args:

        n: No. of nodes excluding the hub.

        center: Index of the node considered as the hub.

        requests: The initial batch of drop requests.

    Returns:

        A list of (n + 1) x coordinates, a list of (n + 1) y coordinates and an (n + 1) x (n + 1) numpy array as the cost matrix.

    """

    # Generate VRP instance

    xs = np.zeros(6)

    ys = np.zeros(6)

    ys[0] = 0

    xs[0] = 0

    for i in range(1, 6):

        ys[i] = (coordinates[requests[i - 1]]['latitude'] - coordinates[center]['latitude']) \* 500

        xs[i] = (coordinates[requests[i - 1]]['longitude'] - coordinates[center]['longitude']) \* 500

    instance = np.zeros((n + 1, n + 1))

    for ii in range(n + 1):

        for jj in range(ii + 1, n + 1):

            instance[ii, jj] = (xs[ii] - xs[jj]) \*\* 2 + (ys[ii] - ys[jj]) \*\* 2

            instance[jj, ii] = instance[ii, jj]

    # Return output

    return instance, xs, ys

def generate\_cluster\_route(center, requests, cluster):

    """Generate the route for a particular cluster.

    Args:

        center: Index of the node considered as the hub.

        requests: The initial batch of drop requests.

        cluster: The cluster for which the route is to be generated.

    Returns:

        A path for the cluster, and a list containing the order in which the requests belonging to the cluster are serviced.

    """

    path = []

    edge = []

    drop\_order = []

    dist = 0

    nodes = [requests[i - 1] for i in cluster]

    closest = nodes[0]

    start = center

    route = Route()

    while len(nodes) > 0:

        closest\_distance = 99999999  # Earth's cicumference: 40,075,000 m.

        for node in nodes:

            temp = route.generate(start, node)

            if route.distance < closest\_distance:

                closest\_distance = route.distance

                closest = node

                edge = temp

        join\_route(path, edge[:-1])

        dist = dist + closest\_distance

        start = closest

        nodes.remove(closest)

        drop\_order.append((center, closest))

    path.append(closest)

    return path, drop\_order

**backend.py**

*Contains solver that is used to solve the Vehicle Routing Problem*

from dwave.system import LeapHybridSampler

class Backend:

"""Class containing all backend solvers that may be used to solve the Vehicle Routing Problem."""

def \_\_init\_\_(self, vrp):

"""Initializes required variables and stores the supplied instance of the VehicleRouter object."""

# Store relevant data

self.vrp = vrp

# Initialize necessary variables

self.result\_dict = None

def solve(self):

"""Takes the solver as input and redirects control to the corresponding solver."""

# Call Leap Solver

self.solve\_leap()

def solve\_leap(self):

"""Solve using Leap Hybrid Sampler."""

# Solve

sampler = LeapHybridSampler()

self.vrp.result = sampler.sample(self.vrp.bqm)

# Extract solution

self.vrp.timing.update(self.vrp.result.info)

self.result\_dict = self.vrp.result.first.sample

self.vrp.extract\_solution(self.result\_dict)

**vehicle\_routing.py**

*Contains an abstract class to build and solve the VRP, a function to convert the VRP into a QUBO and eventually builds a BQM to be solved by a D-Wave solver*

import numpy as np

import dimod

import time

from functools import partial

from backend import Backend

from dwave.embedding.chain\_strength import uniform\_torque\_compensation

from qiskit\_optimization.converters import QuadraticProgramToQubo

from qiskit\_optimization.algorithms import OptimizationResult

class VehicleRouter:

    """Abstract Class for solving the Vehicle Routing Problem. To build a VRP solver, simply inherit from this class and override the build\_quadratic\_program function in this class."""

    def \_\_init\_\_(self, n\_clients, n\_vehicles, cost\_matrix, \*\*params):

        """Initializes the VRP by storing all inputs, initializing variables for storing the quadratic structures and results and calls the rebuild function to build all quadratic structures.

        Args:

            n\_clients: No. of nodes in the problem (excluding the hub).

            n\_vehicles: No. of vehicles available for service.

            cost\_matrix: (n\_clients + 1) x (n\_clients + 1) matrix describing the cost of moving from node i to node j.

            penalty: Penalty value to use for constraints in the QUBO. Defaults to automatic calculation by qiskit converters.

            chain\_strength: Chain strength to be used for D-Wave sampler. Defaults to automatic chain strength calculation via uniform torque compensation.

            num\_reads: Number of samples to read. Defaults to 1000.

        """

        # Store critical inputs

        self.n = n\_clients

        self.m = n\_vehicles

        self.cost = np.array(cost\_matrix)

        # Extract parameters

        self.penalty = params.setdefault('constraint\_penalty', None)

        self.chain\_strength = params.setdefault('chain\_strength', partial(uniform\_torque\_compensation, prefactor=2))

        self.num\_reads = params.setdefault('num\_reads', 1000)

        # Initialize quadratic structures

        self.qp = None

        self.qubo = None

        self.bqm = None

        self.variables = None

        # Initialize result containers

        self.result = None

        self.solution = None

        # Initialize timer

        self.clock = None

        self.timing = {}

        # Initialize backend

        self.backend = Backend(self)

        # Build quadratic models

        self.rebuild()

    def build\_quadratic\_program(self):

        """Dummy function to be overridden in child class. Required to set self.variables to contain the names of all variables in the form of a numpy array and self.qp to contain the quadratic program to be solved."""

        # Dummy. Override in child class.

        pass

    def build\_bqm(self):

        """Converts the quadratic program in self.qp to a QUBO by appending all constraints to the objective function in the form of penalties and then builds a BQM from the QUBO for solving by D-Wave."""

        # Convert to QUBO

        converter = QuadraticProgramToQubo(penalty=self.penalty)

        self.qubo = converter.convert(self.qp)

        # Extract qubo data

        Q = self.qubo.objective.quadratic.to\_dict(use\_name=True)

        g = self.qubo.objective.linear.to\_dict(use\_name=True)

        c = self.qubo.objective.constant

        # Build BQM

        self.bqm = dimod.BQM(g, Q, c, dimod.BINARY)

    def rebuild(self):

        """Builds the quadratic program by calling build\_quadratic\_program and then the QUBO and BQM by calling build\_bqm."""

        # Begin stopwatch

        self.clock = time.time()

        # Rebuild quadratic models

        self.build\_quadratic\_program()

        self.build\_bqm()

        # Record build time

        self.timing['qubo\_build\_time'] = (time.time() - self.clock) \* 1e6

    def extract\_solution(self, result\_dict):

        """Uses a result dictionary mapping variable names to the solved solution to build the self.solution variable in the same shape as self.variables and containing the corresponding solutions.

        Args:

            result\_dict: Dictionary mapping variable names to solved values for these variables.

        """

        # Extract solution from result dictionary

        var\_list = self.variables.reshape(-1)

        self.solution = np.zeros(var\_list.shape)

        for i in range(len(var\_list)):

            self.solution[i] = result\_dict[var\_list[i]]

        # Reshape result

        self.solution = self.solution.reshape(self.variables.shape)

    def evaluate\_vrp\_cost(self):

        """Evaluate the optimized VRP cost under the optimized solution stored in self.solution.

        Returns:

            Optimized VRP cost as a float value.

        """

        # Return optimized energy

        if type(self.result) == OptimizationResult:

            return self.result.fval

        else:

            return self.result.first.energy

    def evaluate\_qubo\_feasibility(self, data=None):

        """Evaluates whether the QUBO is feasible under the supplied data as inputs. If this data is not supplied, the self.solution variable is used instead.

        Args:

            data: Values of the variables in the solution to be tested. Defaults to self.solution.

        Returns:

            A 3-tuple containing a boolean value indicating whether the QUBO is feasible or not, a list of variables that violate constraints, and the list of violated constraints. If feasible, (True, [], []) is returned.

        """

        # Resolve data

        if data is None:

            data = self.solution.reshape(-1)

        else:

            data = np.array(data).reshape(-1)

        # Get constraint violation data

        return self.qp.get\_feasibility\_info(data)

    def solve(self):

        """Solve the QUBO using the selected solver."""

        # Solve

        self.backend.solve()

    def get\_clusters(self):

        """Retrieve the clusters from the solution.

        Returns:

            A 2-D list of lists where each list contains the indices of the requests in that cluster.

        """

        clusters = []

        for i in range(self.solution.shape[0]):

            var\_list = np.transpose(self.variables[i]).reshape(-1)

            sol\_list = np.transpose(self.solution[i]).reshape(-1)

            active\_vars = [var\_list[k] for k in range(len(var\_list)) if sol\_list[k] == 1]

            cluster = [int(var.split('.')[2]) for var in active\_vars]

            cluster = list(filter(lambda x: x != 0, cluster))

            clusters.append(cluster)

        return clusters

**qubo\_solver.py**

*Contains the class QuboSolver which inherits the VehicleRouter class and builds the quadratic program for capacitated QUBO solver.*

import numpy as np

import networkx as nx

import matplotlib.pyplot as plt

from collections import Counter

from matplotlib.colors import rgb2hex

from vehicle\_routing import VehicleRouter

from qiskit\_optimization import QuadraticProgram

class QuboSolver(VehicleRouter):

    """Capacitated Qubo Solver implementation."""

    def \_\_init\_\_(self, n\_clients, n\_vehicles, cost\_matrix, \*\*params):

        """Initializes any required variables and calls init of super class."""

        # Call parent initializer

        super().\_\_init\_\_(n\_clients, n\_vehicles, cost\_matrix, \*\*params)

    def build\_quadratic\_program(self):

        """Builds the required quadratic program and sets the names of variables in self.variables."""

        # Initialization

        self.qp = QuadraticProgram(name='Vehicle Routing Problem')

        # Designate variable names

        self.variables = np.array([[['x.{}.{}.{}'.format(i, j, k) for k in range(1, self.n + 1)]

                                    for j in range(self.n + 1)] for i in range(1, self.m + 1)])

        # Add variables to quadratic program

        for var in self.variables.reshape(-1):

            self.qp.binary\_var(name=var)

        # Build objective function

        obj\_linear\_a = {self.variables[m, n, 0]: self.cost[0, n] for m in range(self.m) for n in range(1, self.n + 1)}

        obj\_linear\_b = {self.variables[m, n, -1]: self.cost[n, 0] for m in range(self.m) for n in range(1, self.n + 1)}

        obj\_quadratic = {(self.variables[m, i, n], self.variables[m, j, n + 1]): self.cost[i, j] for m in range(self.m)

                         for n in range(self.n - 1) for i in range(self.n + 1) for j in range(self.n + 1)}

        # Add objective to quadratic program

        self.qp.minimize(linear=dict(Counter(obj\_linear\_a) + Counter(obj\_linear\_b)), quadratic=obj\_quadratic)

        # Add constraints - single client service

        for k in range(1, self.n + 1):

            constraint\_linear = {self.variables[i, k, j]: 1 for i in range(self.m) for j in range(self.n)}

            self.qp.linear\_constraint(linear=constraint\_linear, sense='==', rhs=1, name=f'single\_service\_{k}')

        # Add constraints - vehicle at one place at one time

        for m in range(self.m):

            for n in range(self.n):

                constraint\_linear = {self.variables[m, k, n]: 1 for k in range(self.n + 1)}

                self.qp.linear\_constraint(linear=constraint\_linear, sense='==', rhs=1,

                                          name=f'single\_location\_{m + 1}\_{n + 1}')

        # Add capacity constraints

        for i in range(self.m):

            constraint\_linear = {self.variables[i, j + 1, k]: 1 for j in range(self.n) for k in range(self.n)}

            self.qp.linear\_constraint(linear=constraint\_linear, sense='<=', rhs=4, name=f'capacity\_{i}')

    def visualize(self, xc, yc):

        """Visualizes solution.

        Args:

            xc: x coordinates of nodes.

            yc: y coordinates of nodes.

        """

        labels = {0: "O", 1: "A", 2: "B", 3: "C", 4: "D", 5: "E"}

        # Initialize figure

        plt.figure()

        ax = plt.gca()

        ax.set\_title(f'Vehicle Routing Problem - {self.n} Clients & {self.m} Cars')

        cmap = plt.cm.get\_cmap('Accent')

        # Build graph

        G = nx.MultiGraph()

        G.add\_nodes\_from(range(self.n + 1))

        # Plot nodes

        pos = {i: (xc[i], yc[i]) for i in range(self.n + 1)}

        #         labels = {i: str(i) for i in range(self.n + 1)}

        nx.draw\_networkx\_nodes(G, pos=pos, ax=ax, node\_color='b', node\_size=500, alpha=0.8)

        nx.draw\_networkx\_labels(G, pos=pos, labels=labels, font\_size=16)

        # Loop over cars

        for i in range(self.solution.shape[0]):

            # Get route

            var\_list = np.transpose(self.variables[i]).reshape(-1)

            sol\_list = np.transpose(self.solution[i]).reshape(-1)

            active\_vars = [var\_list[k] for k in range(len(var\_list)) if sol\_list[k] == 1]

            route = [int(var.split('.')[2]) for var in active\_vars]

            # Plot edges

            edgelist = [(0, route[0])] + [(route[j], route[j + 1]) for j in range(len(route) - 1)] + [

                (route[-1], 0)]

            G.add\_edges\_from(edgelist)

            nx.draw\_networkx\_edges(G, pos=pos, edgelist=edgelist, width=2, edge\_color=rgb2hex(cmap(i)))

        # Show plot

        plt.grid(True)

        plt.show()

**passenger.py**

*Contains a class passenger that defines an instance of a passenger.*

import random

class Passenger:

    def \_\_init\_\_(self, request, shuttle\_number):

        self.id = None

        self.request = request

        self.shuttle\_number = shuttle\_number

        self.generate\_passenger\_id()

    def details(self):

        print('ID: {}\tRequest Info: {}\t Shuttle Number: {}'.format(self.id, self.request, self.shuttle\_number))

    def generate\_passenger\_id(self):

        """ This function generates a random passenger id."""

        pid = 'P'

        for i in range(3):

            pid += str(random.randrange(10))

        for i in range(2):

            pid += chr(random.randrange(65, 91))

        for i in range(4):

            pid += str(random.randrange(10))

        self.id = pid

**shuttle.py**

*Contains a class Shuttle that defines an instance of a shuttle.*

import random

class Shuttle:

    def \_\_init\_\_(self, route, drop\_order=None):

        """Initializes a shuttle.

        Args:

            route: The initial route for the shuttle.

            drop\_order: A list containing the passenger requests in the order they will be serviced.

        """

        if drop\_order is None:

            drop\_order = []

        self.number = None

        self.passengers = None

        self.current\_position = route[0]

        self.index = 0

        self.route = route

        self.drop\_order = drop\_order

        self.occupancy = 0

        self.service = False

        self.pickup = None

        self.generate\_shuttle\_number()

    def set\_passengers(self, passengers):

        """Set the current passengers of a shuttle.

        Args:

            passengers: A list containing passenger objects.

        """

        self.passengers = passengers

        self.occupancy = len(passengers)

    def passenger\_details(self):

        """Display the details of a passenger."""

        for passenger in self.passengers:

            passenger.details()

    def details(self):

        """Display the details of a shuttle."""

        print('Number: {}\tNumber of Passengers: {}\t\tCurrent Position: {}\t Route : {} \tDrop order: {}'.format(

            self.number, self.occupancy, self.current\_position, self.route, self.drop\_order))

    def generate\_shuttle\_number(self):

        """This function randomly generates a car number.

        Returns:

            A string id of length 9.

        """

        number = 'WB'

        for i in range(2):

            number += str(random.randrange(10))

        number += chr(random.randrange(65, 91))

        for i in range(4):

            number += str(random.randrange(10))

        self.number = number

**routes.py**

*Contains methods to generate the most optimal route between start and end points.*

import numpy as np

from constants import dist\_matrix, coordinates

class Node:

    def \_\_init\_\_(self, parent=None, position=None):

        """Initializing a node.

        Args:

            parent: Parent of the node.

            position: Index of the node.

        """

        self.parent = parent

        self.position = position

        self.g = 0

        self.h = 0

        self.f = 0

    def \_\_eq\_\_(self, other):

        return self.position == other.position

def return\_path(current\_node):

    """Recreates the path from the current node to the starting node.

    Args:

        current\_node: The current node under consideration.

    Returns:

         A list containing the path from the starting node to the current node.

    """

    path = []

    current = current\_node

    while current is not None:

        path.append(current.position)

        current = current.parent

    path = path[::-1]

    return path

def join\_route(route1, route2):

    """Add the contents of the second list to the first list.

    Args:

        route1: List denoting the 1st route.

        route2: List denoting the route to be merged with the 1st route.

    Returns:

        A list with the 2nd route appended to the 1st route.

    """

    for i in route2:

        route1.append(i)

    return route1

def route\_distance(route):

    """Calculate the total distance of a route.

    Args:

        route: A list containing the route.

    Returns:

        An integer denoting the total distance of the route.

    """

    distance = 0

    for i in range(1, len(route)):

        distance += dist\_matrix[route[i - 1]][route[i]]

    return distance

class Route:

    def \_\_init\_\_(self):

        """Initialize the route object."""

        self.total\_nodes = dist\_matrix.shape[0]

        self.start = None

        self.end = None

        self.distance = None

    def neighbour(self, node):

        """List of neighbours of a node.

        Args:

            node: The index of the node in consideration.

        Returns:

            List containing the indices of the neighbours of the node.

        """

        nb = np.array([], dtype=np.int8)

        for i in range(self.total\_nodes):

            if dist\_matrix[node][i] > 0:

                nb = np.append(nb, i)

        return nb

    def astar(self):

        """This function finds the optimal route based on distance."""

        start = self.start

        end = self.end

        start\_node = Node(None, start)

        start\_node.g = start\_node.h = start\_node.f = 0

        end\_node = Node(None, end)

        end\_node.g = end\_node.h = end\_node.f = 0

        end\_node\_coordinates = (coordinates[end]['longitude'], coordinates[end]['latitude'])

        # Initialize the open set and closed set

        open\_set = []

        closed\_set = []

        # Add the start node to the open set

        open\_set.append(start\_node)

        x = 0

        # Loop till you reach the end node

        while len(open\_set) > 0:

            x += 1

            if x > 100000:

                print('Exceeded 100000 loops. Exiting.')

                break

            current\_node = open\_set.pop(0)

            closed\_set.append(current\_node)

            # Return the path if end point is reached

            if current\_node == end\_node:

                path = return\_path(current\_node)

                return path

            neighbours = self.neighbour(current\_node.position)

            for nb in neighbours:

                new\_node = Node(current\_node, nb)

                # Checking if child is in closed list

                flag = False

                for closed\_child in closed\_set:

                    if new\_node == closed\_child:

                        flag = True

                        break

                if flag:

                    continue

                new\_node\_coordinates = (

                    coordinates[new\_node.position]['longitude'], coordinates[new\_node.position]['latitude'])

                new\_node.g = current\_node.g + dist\_matrix[nb][current\_node.position] / 100

                new\_node.h = (new\_node\_coordinates[0] - end\_node\_coordinates[0]) \*\* 2 + (

                        new\_node\_coordinates[1] - end\_node\_coordinates[1]) \*\* 2

                new\_node.f = new\_node.g + new\_node.h

                # Checking if child is already in open list and the new path is larger

                flag = False

                for open\_child in open\_set:

                    if new\_node == open\_child and new\_node.g > open\_child.g:

                        flag = True

                        break

                if flag:

                    continue

                i = 0

                if len(open\_set) > 0:

                    while i < len(open\_set) and open\_set[i].f < new\_node.f:

                        i += 1

                open\_set.insert(i, new\_node)

        return False

    def generate(self, start, end):

        """Generate a new route between the start and end points.

        Args:

            start: The starting position of the route.

            end: The ending position of the route.

        Returns:

            A list containing the generated route.

        """

        self.start = start

        self.end = end

        route = self.astar()

        self.distance = route\_distance(route)

        return route

**visual.py**

*Contains methods to plot shuttle positions, pick-up and drop positions, and routes using different colors on the map.*

from constants import image\_coordinates

from PIL import Image, ImageDraw, ImageFont

class Visual:

    # Color constants used for drawing routes.

    start\_color = (255, 255, 255)

    branch\_color = [(0, 255, 0), (0, 255, 255)]

    current\_route\_color = [(173, 255, 47), (30, 144, 255)]

    old\_route\_color = [(8, 105, 114), (135, 206, 250)]

    drop\_node\_color = [(0, 100, 0), (180, 0, 180)]

    current\_position\_color = [(0, 250, 154), (123, 104, 238)]

    denied\_request\_color = [(255, 0, 0), (255, 0, 255)]

    def \_\_init\_\_(self, center, node\_size=5, folder=None):

        """Initialize the Map Drawer.

        Args:

            center: Index of the hub.

            node\_size: Size of the node to be drawn.

            folder: The name of the folder where the images are to be saved.

        """

        if folder is None:

            folder = 'random'

        self.center = center

        self.node\_size = node\_size

        self.folder = folder

        self.im = None

        self.draw = None

        self.initialize()

    def draw\_denied\_request(self, request):

        """Draw the nodes for a denied request.

        Args:

            request: A tuple containing the pickup and drop location.

        """

        node\_size = 10

        for i in range(2):

            self.draw.ellipse((

                image\_coordinates[request[i]][0] - node\_size, image\_coordinates[request[i]][1] - node\_size,

                image\_coordinates[request[i]][0] + node\_size,

                image\_coordinates[request[i]][1] + node\_size), fill=self.denied\_request\_color[i],

                outline=(0, 0, 0))

    def draw\_initial\_requests(self, requests):

        """Draw the nodes for the initial requests.

        Args:

            requests: The initial batch of drop requests.

        """

        for req in requests:

            self.draw.ellipse(

                (image\_coordinates[req][0] - self.node\_size, image\_coordinates[req][1] - self.node\_size,

                 image\_coordinates[req][0] + self.node\_size, image\_coordinates[req][1] + self.node\_size),

                fill=(255, 0, 0), outline=(0, 0, 0))

        self.draw.ellipse(

            (image\_coordinates[self.center][0] - self.node\_size, image\_coordinates[self.center][1] - self.node\_size,

             image\_coordinates[self.center][0] + self.node\_size, image\_coordinates[self.center][1] + self.node\_size),

            fill=(255, 255, 255), outline=(0, 0, 0))

    def draw\_nodes(self, shuttles):

        """Draw the nodes for a particular state of the shuttle.

        Args:

            shuttles: A list of objects containing the current shuttle objects.

        """

        for i in range(len(shuttles)):

            for req in shuttles[i].drop\_order:

                self.draw.ellipse(

                    (image\_coordinates[req[1]][0] - self.node\_size, image\_coordinates[req[1]][1] - self.node\_size,

                     image\_coordinates[req[1]][0] + self.node\_size, image\_coordinates[req[1]][1] + self.node\_size),

                    fill=self.drop\_node\_color[i], outline=(0, 0, 0))

            self.draw.ellipse((image\_coordinates[shuttles[i].current\_position][0] - self.node\_size,

                               image\_coordinates[shuttles[i].current\_position][1] - self.node\_size,

                               image\_coordinates[shuttles[i].current\_position][0] + self.node\_size,

                               image\_coordinates[shuttles[i].current\_position][1] + self.node\_size),

                              fill=self.current\_position\_color[i], outline=(0, 0, 0))

        self.draw.ellipse(

            (image\_coordinates[self.center][0] - self.node\_size, image\_coordinates[self.center][1] - self.node\_size,

             image\_coordinates[self.center][0] + self.node\_size, image\_coordinates[self.center][1] + self.node\_size),

            fill=(255, 255, 255), outline=(0, 0, 0))

    def draw\_request\_text(self, request):

        """Draw the current request text.

        Args:

            request: A tuple containing the pickup and drop location.

        """

        self.draw.text((30, 20), 'Request: ({}, {})'.format(request[0]+1, request[1]+1),

                       font=ImageFont.truetype("arial.ttf", 12), fill=(0, 0, 0, 255))

    def draw\_route(self, route, color):

        """Draw a route on the map.

        Args:

            route: A list containing the route.

            color: Color of the route.

        """

        for i in range(1, len(route)):

            self.draw.line((image\_coordinates[route[i - 1]][0], image\_coordinates[route[i - 1]][1],

                            image\_coordinates[route[i]][0], image\_coordinates[route[i]][1]), color, width=5)

    def draw\_state(self, shuttles):

        """Draw the nodes for a particular state of the shuttle along with the current routes of the shuttles.

        Args:

            shuttles: A list of objects containing the current shuttle objects.

        """

        for i in range(len(shuttles)):

            for j in range(1, len(shuttles[i].route)):

                self.draw.line((image\_coordinates[shuttles[i].route[j - 1]][0],

                                image\_coordinates[shuttles[i].route[j - 1]][1],

                                image\_coordinates[shuttles[i].route[j]][0],

                                image\_coordinates[shuttles[i].route[j]][1]), self.current\_route\_color[i], width=5)

            for req in shuttles[i].drop\_order:

                self.draw.ellipse(

                    (image\_coordinates[req[1]][0] - self.node\_size, image\_coordinates[req[1]][1] - self.node\_size,

                     image\_coordinates[req[1]][0] + self.node\_size, image\_coordinates[req[1]][1] + self.node\_size),

                    fill=self.drop\_node\_color[i], outline=(0, 0, 0))

            self.draw.ellipse((image\_coordinates[shuttles[i].current\_position][0] - self.node\_size,

                               image\_coordinates[shuttles[i].current\_position][1] - self.node\_size,

                               image\_coordinates[shuttles[i].current\_position][0] + self.node\_size,

                               image\_coordinates[shuttles[i].current\_position][1] + self.node\_size),

                              fill=self.current\_position\_color[i], outline=(0, 0, 0))

        self.draw.ellipse(

            (image\_coordinates[self.center][0] - self.node\_size, image\_coordinates[self.center][1] - self.node\_size,

             image\_coordinates[self.center][0] + self.node\_size, image\_coordinates[self.center][1] + self.node\_size),

            fill=(255, 255, 255), outline=(0, 0, 0))

    def initialize(self):

        """Load the image and create the draw object."""

        self.im = Image.open("test-img.png")

        self.draw = ImageDraw.Draw(self.im)

    def save(self, title):

        """Save the image in a folder.

        Args:

            title: Name of the saved file.

        """

        self.im.save('{}/{}.png'.format(self.folder, title))

    def show(self):

        """Create a temporary image file and show the image."""

        self.im.show()

**simulation.py**

*Contains methods to simulate a dynamic shared shuttle service for 30 iterations, along with a request handler.*

from shuttle import Shuttle

from passenger import Passenger

from utility import generate\_cluster\_route

from visual import Visual

from routes import Route, join\_route

import random

class Simulation:

    def \_\_init\_\_(self, m, n, center, total\_nodes, clusters, requests, folder=None):

        """Initializing the simulation. The simulation will create an initial state and then run 30 iterations. In each iteration, the state of the shuttles will be displayed. A random request will be generated for each iteration. The request will be checked for being serviceable. If serviceable, the state of the shuttles is modified to accommodate the request.

        Args:

            m: No. of vehicles available for service.

            n: No. of initial passengers.

            center: Index of the hub.

            total\_nodes: Total number of nodes in the problem.

            clusters: The clusters generated from the initial requests generated by the QUBO solver.

            requests: The list of initial requests.

            folder: The name of the folder where the images are to be saved.

        """

        if folder is None:

            folder = 'random'

        self.m = m

        self.n = n

        self.center = center

        self.total\_nodes = total\_nodes

        self.clusters = clusters

        self.requests = requests

        self.folder = folder

        self.shuttles = []

        self.shuttle\_index = {}

        self.initialization()

    def initialization(self):

        """Generating the initial state. In the initial state, the initial passengers are assigned to the shuttles available and the corresponding routes are generated.

        """

        for i in range(self.m):

            # Initial shuttle and passenger initiation

            current\_passengers = []

            path, drop\_order = generate\_cluster\_route(self.center, self.requests, self.clusters[i])

            shuttle = Shuttle(path, drop\_order)

            for drop\_request in drop\_order:

                current\_passengers.append(Passenger(drop\_request, shuttle.number))

            shuttle.set\_passengers(current\_passengers)

            self.shuttle\_index[shuttle.number] = i

            self.shuttles.append(shuttle)

            shuttle.details()

            for passenger in current\_passengers:

                passenger.details()

        # Displaying the initial state on map

        initial\_state = Visual(self.center, folder=self.folder)

        initial\_state.draw\_state(self.shuttles)

        # initial\_state.show()

        initial\_state.save('Initial state')

    def simulate(self):

        """A simulation is run for thirty iterations. At each iteration, every shuttle is considered to move to the next node in its route irrespective of the distance between the nodes. A single request is generated per iteration, which is handled accordingly.

Args: iterations: The number of iterations the simulation will run for.

        """

        print('\n\t###Simulation Starting###\n')

        for i in range(iterations):

            print('\nIteration ', i + 1)

            for shuttle in self.shuttles:

                if shuttle.route != [] and shuttle.index < len(shuttle.route) - 1:

                    shuttle.index += 1

                    shuttle.current\_position = shuttle.route[shuttle.index]

                for drop\_request in shuttle.drop\_order:

                    if drop\_request == shuttle.pickup:

                        continue

                    if drop\_request[1] == shuttle.current\_position:

                        shuttle.drop\_order.remove(drop\_request)

                        shuttle.passengers.pop(0)

                        shuttle.occupancy -= 1

                        print('Passenger dropped off at {} by car {}'.format(shuttle.current\_position, shuttle.number))

                if not shuttle.drop\_order:

                    shuttle.route = []

                    shuttle.index = -1

                if shuttle.service is True and shuttle.current\_position == shuttle.pickup[0]:

                    shuttle.passenger\_details()

                    shuttle.passengers.insert(shuttle.drop\_order.index(shuttle.pickup),

                                              Passenger(shuttle.pickup, shuttle.number))

                    shuttle.occupancy += 1

                    print('Passenger picked up at {} by car {}'.format(shuttle.pickup[0], shuttle.number))

                    shuttle.service = False

                    shuttle.pickup = None

            request = self.request\_generator()

            self.request\_handler(request, i)

            print('\n')

            for shuttle in self.shuttles:

                print(

                    'Number: {}\tNumber of Passengers: {}\t\tCurrent Position: {}\tRoute : {}\tDrop order: {}\t'

                    'Service: {}\tPickup: {}'.format(

                        shuttle.number, shuttle.occupancy, shuttle.current\_position, shuttle.route, shuttle.drop\_order,

                        shuttle.service, shuttle.pickup))

    def request\_generator(self):

        """Generate a random request."""

        src = random.randrange(self.total\_nodes)

        dest = random.randrange(self.total\_nodes)

        while src == dest:

            dest = random.randrange(self.total\_nodes)

        return src, dest

    def request\_handler(self, request, iteration):

        """Handle the servicing of a generated request. If a suitable shuttle is available, the request is assigned to the most suitable shuttle, and it's route is recalculated to accommodate the pickup and drop of the passenger. If no suitable shuttles are available, the request is denied.

        Args:

            request: A tuple containing the pickup and drop location.

            iteration: The current iteration of the simulation.

        """

        iteration\_state = Visual(self.center, folder=self.folder)

        iteration\_state.draw\_state(self.shuttles)

        print('Request generated: ', request)

        iteration\_state.draw\_request\_text(request)

        suitable\_shuttles = []

        route = Route()

        for shuttle in self.shuttles:

            occupancy = shuttle.occupancy

            src\_pt = -1

            dest\_pt = -1

            detour = 0

            pos = 0

            # Checking whether occupancy is not full and if the shuttle is already servicing another passenger.

            if shuttle.occupancy < 4 and shuttle.service is False:

                if shuttle.occupancy != 0:

                    pos = shuttle.route.index(shuttle.current\_position)

                    shortest\_distance = 999999

                    for i in range(pos, pos + 3):

                        if i >= len(shuttle.route):

                            break

                        point = shuttle.route[i]

                        route.generate(point, request[0])

                        print('{}\t{}\t{}\t{}'.format(i, point, request[0], route.distance))

                        if route.distance < 1000:

                            if route.distance > shortest\_distance:

                                continue

                            src\_pt = i

                            shortest\_distance = route.distance

                    detour += shortest\_distance

                    if src\_pt != -1:

                        shortest\_distance = 999999

                        for j in range(pos, len(shuttle.route)):

                            route.generate(shuttle.route[j], request[1])

                            if route.distance < 1000:

                                if route.distance > shortest\_distance:

                                    continue

                                shortest\_distance = route.distance

                                dest\_pt = j

                        detour += shortest\_distance

                    if src\_pt != -1 and dest\_pt != -1 and detour < 2000:

                        suitable\_shuttles.append((shuttle, (src\_pt, dest\_pt)))

                else:

                    route.generate(shuttle.current\_position, request[0])

                    if route.distance <= 3000:

                        suitable\_shuttles.append((shuttle, (0, 1)))

        if len(suitable\_shuttles) == 0:

            print('\nNo suitable shuttles')

            iteration\_state.draw\_denied\_request(request)

            # iteration\_state.show()

            iteration\_state.save('Iteration\_{}.png'.format(iteration + 1))

            return

        print('\nSuitable Shuttles: ')

        for shuttle in suitable\_shuttles:

            route.generate(shuttle[0].current\_position, request[0])

            print(

                'Distance: {}\t Number: {}\tNumber of Passengers: {}\t\tCurrent Position: {}\t Route : {} '

                '\tDrop order: {}'.format(

                    route.distance, shuttle[0].number, shuttle[0].occupancy, shuttle[0].current\_position,

                    shuttle[0].route, shuttle[0].drop\_order))

        route.generate(suitable\_shuttles[0][0].current\_position, request[0])

        closest\_dist = route.distance

        closest = 0

        # selecting the closest shuttle from the list of suitable shuttles.

        for i in range(1, len(suitable\_shuttles)):

            route.generate(suitable\_shuttles[i][0].current\_position, request[0])

            if route.distance < closest\_dist:

                closest\_dist = route.distance

                closest = i

        selected\_shuttle = suitable\_shuttles[closest]

        print('Selected Shuttle: ', suitable\_shuttles[closest][0].number)

        if len(selected\_shuttle[0].passengers) == 0:

            # Use spanning tree algo

            selected\_shuttle[0].drop\_order.append(request)

            temp = (route.generate(selected\_shuttle[0].current\_position, request[0]), route.generate(\*request))

            selected\_shuttle[0].route = join\_route(temp[0][:-1], temp[1])

            selected\_shuttle[0].index = 0

            if selected\_shuttle[0].current\_position == request[0]:

                selected\_shuttle[0].passengers.append(

                    Passenger(request, selected\_shuttle[0].number))

                selected\_shuttle[0].occupancy += 1

                print('Passenger picked up at {} by shuttle {}'.format(request[0], selected\_shuttle[0].number))

                # draw new route

                iteration\_state.draw\_route(temp[1],

                                           iteration\_state.current\_route\_color[self.shuttle\_index[

                                               selected\_shuttle[0].number]])

            else:

                selected\_shuttle[0].pickup = request

                selected\_shuttle[0].service = True

                iteration\_state.draw\_route(temp[0],

                                           iteration\_state.branch\_color[self.shuttle\_index[selected\_shuttle[0].number]])

                iteration\_state.draw\_route(temp[1],

                                           iteration\_state.current\_route\_color[self.shuttle\_index[

                                               selected\_shuttle[0].number]])

        else:

            src\_pt = selected\_shuttle[1][0]

            dest\_pt = selected\_shuttle[1][1]

            drop\_list = [node for node in selected\_shuttle[0].drop\_order]

            flag = False

            insert\_index = 0

            for i in range(len(drop\_list)):

                if dest\_pt < selected\_shuttle[0].route.index(drop\_list[i][1]):

                    drop\_list.insert(i, request)

                    insert\_index = i

                    flag = True

                    break

            if not flag:

                insert\_index = len(drop\_list)

                drop\_list.append(request)

            selected\_shuttle[0].drop\_order = [order for order in drop\_list]

            new\_route = selected\_shuttle[0].route[:src\_pt]

            # draw old route

            iteration\_state.draw\_route(selected\_shuttle[0].route,

                                       iteration\_state.old\_route\_color[self.shuttle\_index[selected\_shuttle[0].number]])

            branch\_route = route.generate(selected\_shuttle[0].route[src\_pt], request[0])

            new\_route = join\_route(new\_route, branch\_route[:-1])

            drop\_first = False

            for i in range(insert\_index):

                if selected\_shuttle[0].route.index(drop\_list[i][1]) > src\_pt:

                    drop\_first = True

                    break

            drop\_list = drop\_list[i if drop\_first else insert\_index:]

            join\_index = len(new\_route)

            new\_route = join\_route(new\_route, route.generate(request[0], drop\_list[0][1])[:-1])

            for i in range(1, len(drop\_list)):

                new\_route = join\_route(new\_route, route.generate(drop\_list[i - 1][1], drop\_list[i][1])[:-1])

            new\_route.append(drop\_list[-1][1])

            selected\_shuttle[0].route = new\_route

            # draw new route

            iteration\_state.draw\_route(new\_route[join\_index:],

                                       iteration\_state.current\_route\_color[self.shuttle\_index[

                                           selected\_shuttle[0].number]])

            if selected\_shuttle[0].current\_position == request[0]:

                selected\_shuttle[0].passengers.insert(insert\_index, Passenger(request,

                                                                              selected\_shuttle[0].number))

                selected\_shuttle[0].occupancy += 1

                print('Passenger picked up at {} by shuttle {}'.format(request[0], selected\_shuttle[0].number))

            else:

                selected\_shuttle[0].pickup = request

                selected\_shuttle[0].service = True

                # draw branch route

                iteration\_state.draw\_route(branch\_route,

                                           iteration\_state.branch\_color[self.shuttle\_index[selected\_shuttle[0].number]])

        iteration\_state.draw\_nodes(self.shuttles)

        # iteration\_state.show()

        iteration\_state.save('Iteration\_{}.png'.format(iteration + 1))

**main.py**

*The main program from which the different modules are called to execute the application.*

import numpy as np

import utility

import random

from qubo\_solver import QuboSolver

from routes import Route

from visual import Visual

from PIL import Image, ImageDraw

from simulation import Simulation

"""Definining the number of shuttles, the initial number of passengers, the central node, and the total number of nodes.

n: Initial number of passengers.

m: Number of shuttles.

center: Index of central node.

total\_nodes: Total number of nodes.

"""

n = 5

m = 2

center = 86

total\_nodes=122

# Generate the initial set of requests.

requests = utility.generate\_initial\_requests(n, center, total\_nodes)

print(requests)

# Show the requests generated on the map.

initial\_request\_view = Visual(center, node\_size=10)

initial\_request\_view.draw\_initial\_requests(requests)

initial\_request\_view.show()

# Generate the VRP instance

instance, xc, yc = utility.generate\_vrp\_instance(n, center, requests)

# Initialize the QUBO instance and solve

qs = QuboSolver(n, m, instance)

qs.solve()

# Visualize the solution as a graph

qs.visualize(xc, yc)

# Retrieve the clusters from the solution

clusters = qs.get\_clusters()

# Create the simulation instance

sim = Simulation(m, n, center, total\_nodes, clusters, requests, folder=’solution')

# Run the simulation for 30 iterations

sim.simulate(30)

**5.2 Unit Testing**

**5.2.1. Test Strategy**

The test strategy for this project involves manual testing during various stages of the development cycle. Since the iterative model of software development has been followed, where a relatively basic implementation of a subset of the requirement specification progresses through iterative improvisations until the entire system is completed, both unit testing and integration testing (functional testing) are required after each improvisation. Non-functional testing has been performed after the final deployment.

**5.2.2 Assumptions**

The capacitated shuttle routing problem is solved by keeping in mind the following constraints:

* The initial number of clients in the depot = 5
* Number of shuttles = 2
* The capacity of each shuttle = 4
* Only nodes marked in the map are considered.
* In a unit time instance, a shuttle moves from one node to the next node irrespective of the distance between the two nodes.
* While a shuttle is en route to service a passenger, it will not accept other service requests even if the boarding location is nearby.

**5.2.3 Unit Testing**

A brief description of different modules/components of the implementation is mentioned below, along with their input and output instances, as part of the project’s unit testing after the final iteration.

**VRP instance generation**

It generates an instance of the shuttle routing problem, in agreement with the constraints.

Function signature -

*generate\_vrp\_instance(n, center, requests) : instance, xc, yc*

where

n: No. of nodes excluding the hub.

center: Index of the node considered as the hub.

requests: The initial batch of drop requests.

Returns:

xc: a list of (n + 1) x coordinates,

yc: a list of (n + 1) y coordinates,

instance: an (n + 1) x (n + 1) NumPy array as the cost matrix.

Input:

n = 5

center = 86

requests = [ 24, 10, 40, 111, 121]

Output:

instance = [

[ 0. 50.0393134 92.0705667 50.1057419 60.81787326

179.56707486]

[ 50.0393134 0. 44.18660808 28.01566795 217.90432711

412.62742124]

[ 92.0705667 44.18660808 0. 6.33445004 282.73393999

404.26432554]

[ 50.1057419 28.01566795 6.33445004 0. 206.62493985

327.25651104]

[ 60.81787326 217.90432711 282.73393999 206.62493985 0.

57.82263815]

[179.56707486 412.62742124 404.26432554 327.25651104 57.82263815

0.]]

xc= [ 0. 1.90355 8.262975 6.1013 -3.85519 -0.11506]

yc= [ 0. 6.812915 4.87789 3.588855 -6.77904 -13.39977]

**Qubo instance generation**

It generates the QUBO form of a particular instance of the shuttle routing problem in order to make it solvable by a quantum annealer.

Function signature -

*qs = QuboSolver(n, m, instance)*

where

n: No. of nodes in the problem (excluding the hub).

m: No. of vehicles available for service.

instance: (n\_clients + 1) x (n\_clients + 1) matrix describing the cost of moving from node i to node j.

Input:

n = 5

m = 2

instance = [

[ 0. 50.0393134 92.0705667 50.1057419 60.81787326

179.56707486]

[ 50.0393134 0. 44.18660808 28.01566795 217.90432711

412.62742124]

[ 92.0705667 44.18660808 0. 6.33445004 282.73393999

404.26432554]

[ 50.1057419 28.01566795 6.33445004 0. 206.62493985

327.25651104]

[ 60.81787326 217.90432711 282.73393999 206.62493985 0.

57.82263815]

[179.56707486 412.62742124 404.26432554 327.25651104 57.82263815

0.]]

Output: Creates a QuboSolver object

**Qubo Solver**

Solves the QUBO problem corresponding to a particular instance of

the shuttle routing problem.

Function signature -

*qs.solve()*

This function redirects the control to the solver where it is solved using Leap Hybrid Sampler.

Input: Not Applicable

Output: A solution to the QUBO problem created.

[[[0. 0. 0. 1. 1.]

[0. 0. 1. 0. 0.]

[0. 1. 0. 0. 0.]

[1. 0. 0. 0. 0.]

[0. 0. 0. 0. 0.]

[0. 0. 0. 0. 0.]]

[[1. 1. 1. 0. 0.]

[0. 0. 0. 0. 0.]

[0. 0. 0. 0. 0.]

[0. 0. 0. 0. 0.]

[0. 0. 0. 0. 1.]

[0. 0. 0. 1. 0.]]]

For cluster 1, nodes A, B, and C are chosen.

For cluster 2, nodes D, and E are chosen.

Chart

Description automatically generated

**Figure 5. QUBO solution as Cluster graph**

**Route generation**

Generates the optimal route for a car instance given a starting point and ending point using A\* path search algorithm.

Function signature -

*generate(self, start, end): route*

where

start: the starting point of the journey

end: the ending point of the journey

route: the path between the start and end nodes

Input:

start = 13, end = 53

Output:

route = [13, 18, 43, 52, 53]

**Initial service ordering**

Determines the route and the drop order by which the commuters of each shuttle

will be serviced from the central hub, given a set of destinations.

Function signature -

*generate\_cluster\_route(center, requests, cluster): path, drop\_order*

where

center: the central hub

cluster: the set of destinations that will be serviced by a particular shuttle

requests: The initial batch of drop requests.

path: the sequence of nodes along which the shuttle moves

drop\_order: the ordered pair denoting the boarding point and alighting point of each passenger in the shuttle

Input:

center = 86,

cluster = [2, 3, 5, 4]

Output:

path = [86, 85, 90, 93, 103, 108, 112, 113, 114, 106, 105, 82, 74, 51, 52, 43, 18, 13, 12, 11, 10]

drop\_order = [(86, 93), (86, 113), (86, 13), (86, 10)]

**Request handler**

Assigns the most suitable shuttle amongst the available shuttles whenever a request is generated, and the state of the shuttle is changed to pick-up. If there is no such suitable shuttle, the request is denied.

Function signature -

*request\_handler(request, iteration)*

where

request: A tuple containing the pickup and drop location.

iteration: The current iteration of the simulation.

Case I:

Input:

request = (66, 28)

iteration = 2

Output:

Suitable Shuttles:

Distance: 420

Number: WB24S1026

Number of Passengers: 2

Current Position: 97

Route: [86, 87, 97, 100, 98, 99, 98, 65, 64, 31, 30, 29]

Drop order: [(86, 99), (86, 29)]

Selected Shuttle: WB24S1026

Number: WB78C2237

Number of Passengers: 4

Current Position: 90

Route: [86, 85, 90, 85, 84, 71, 55, 41, 20, 21, 10, 11, 12, 13]

Drop order: [(86, 20), (86, 21), (90, 10), (86, 13)]

Service: False Pickup: None

Number: WB24S1026

Number of Passengers: 2

Current Position: 97

Route: [86, 87, 97, 66, 65, 98, 99, 98, 65, 64, 31, 30, 29, 28]

Drop order: [(86, 99), (86, 29), (66, 28)]

Service: True Pickup: (66, 28)

Diagram

Description automatically generated

**Figure 6. Accepted request Map Representation**

Case II:

Input:

request = (77, 28)

iteration = 3

Output:

No suitable shuttles

Diagram

Description automatically generated

**Figure 7. Declined request Map Representation**

**Initial car state generator**

Generates the shuttle numbers and assigns passengers to shuttles.

Input: Not Applicable.

Output:

Number: WB95S4330

Number of Passengers: 3

Current Position: 86

Route: [86, 68, 69, 58, 37, 24, 37, 38, 39, 40, 21, 10]

Drop order: [(86, 24), (86, 40), (86, 10)]

ID: P759XV3663 Request Info: (86, 24) Shuttle Number: WB95S4330

ID: P852IO8829 Request Info: (86, 40) Shuttle Number: WB95S4330

ID: P881CY6956 Request Info: (86, 10) Shuttle Number: WB95S4330

Number: WB75Y6796

Number of Passengers: 2

Current Position: 86

Route: [86, 87, 97, 96, 95, 101, 110, 111, 119, 120, 121]

Drop order: [(86, 111), (86, 121)]

ID: P257TB1978 Request Info: (86, 111) Shuttle Number: WB75Y6796

ID: P958ZK9651 Request Info: (86, 121) Shuttle Number: WB75Y6796

**5.3 System Testing**

**Test Data**

This project uses the map of the Saltlake area to test the functional correctness of the proposed car routing algorithm. Some specific points on the map have been selected as drop locations, and these points are highlighted in the map given below.

Diagram

Description automatically generated

**Figure 8. Map**

**Legend**

The legend of the colors used to represent details on the map.

A picture containing table

Description automatically generated

**Figure 9. Legend**

**Test Case**

Initial requests: 30, 21, 14, 100, 22

Clusters: (21, 14, 22) and (30, 100)

Diagram

Description automatically generated

**Figure 10. Initial State**

**Initial State**

Number: WB78C2237

Number of Passengers: 3

Current Position: 86

Route: [86, 85, 84, 71, 55, 41, 20, 21, 20, 19, 18, 13]

Drop order: [(86, 20), (86, 21), (86, 13)]

Passengers:

ID: P019KP9860 Request Info: (86, 20) Shuttle Number: WB78C2237

ID: P504HM8618 Request Info: (86, 21) Shuttle Number: WB78C2237

ID: P009CS6541 Request Info: (86, 13) Shuttle Number: WB78C2237

Number: WB24S1026

Number of Passengers: 2

Current Position: 86

Route: [86, 87, 97, 100, 98, 99, 98, 65, 64, 31, 30, 29]

Drop order: [(86, 99), (86, 29)]

Passengers:

ID: P921TZ7006 Request Info: (86, 99) Shuttle Number: WB24S1026

ID: P376VI3525 Request Info: (86, 29) Shuttle Number: WB24S1026

Diagram

Description automatically generated

**Figure 11. Iteration 2 (Passenger pickup)**

**Iteration 2**

Passenger picked up at 90 by car WB78C2237

Request generated: (66, 28)

Suitable Shuttles:

Distance: 420 Number: WB24S1026

Number of Passengers: 2 Current Position: 97

Route: [86, 87, 97, 100, 98, 99, 98, 65, 64, 31, 30, 29]

Drop order: [(86, 99), (86, 29)]

Selected Shuttle: WB24S1026

Number: WB78C2237

Number of Passengers: 4

Current Position: 90

Route: [86, 85, 90, 85, 84, 71, 55, 41, 20, 21, 10, 11, 12, 13]

Drop order: [(86, 20), (86, 21), (90, 10), (86, 13)]

Service: False Pickup: None

Number: WB24S1026

Number of Passengers: 2

Current Position: 97

Route: [86, 87, 97, 66, 65, 98, 99, 98, 65, 64, 31, 30, 29, 28]

Drop order: [(86, 99), (86, 29), (66, 28)]

Service: True Pickup: (66, 28)

Diagram

Description automatically generated

**Figure 12. Iteration 3 (Denied Request)**

**Iteration 3**

Passenger picked up at 66 by car WB24S1026

Request generated: (83, 43)

No suitable shuttles

Number: WB78C2237

Number of Passengers: 4

Current Position: 85

Route: [86, 85, 90, 85, 84, 71, 55, 41, 20, 21, 10, 11, 12, 13]

Drop order: [(86, 20), (86, 21), (90, 10), (86, 13)]

Service: False Pickup: None

Number: WB24S1026

Number of Passengers: 3

Current Position: 66

Route: [86, 87, 97, 66, 65, 98, 99, 98, 65, 64, 31, 30, 29, 28]

Drop order: [(86, 99), (86, 29), (66, 28)]

Service: False Pickup: None

Diagram

Description automatically generated

**Figure 13. Iteration 8 (Passenger Drop)**

**Iteration 8**

Passenger dropped off at 20 by car WB78C2237

Request generated: (60, 9)

No suitable shuttles

Number: WB78C2237

Number of Passengers: 3

Current Position: 20

Route: [86, 85, 90, 85, 84, 71, 55, 41, 20, 21, 10, 11, 12, 13]

Drop order: [(86, 21), (90, 10), (86, 13)]

Service: False Pickup: None

Number: WB24S1026

Number of Passengers: 3

Current Position: 65

Route: [86, 87, 97, 66, 65, 98, 99, 98, 65, 64, 31, 30, 29, 28, 2]

Drop order: [(86, 29), (66, 28), (99, 2)]

Service: False Pickup: None

Diagram

Description automatically generated

**Figure 14. Iteration 19 (Passenger pickup from idle state)**

**Iteration 19**

Request generated: (26, 70)

Suitable Shuttles:

Distance: 308

Number: WB24S1026

Number of Passengers: 0

Current Position: 4

Route: []

Drop order: []

Selected Shuttle: WB24S1026

Number: WB78C2237

Number of Passengers: 0

Current Position: 21

Route: [40, 21, 22, 23, 24, 6]

Drop order: [(22, 6)]

Service: True Pickup: (22, 6)

Number: WB24S1026

Number of Passengers: 0

Current Position: 4

Route: [4, 26, 35, 60, 69, 70]

Drop order: [(26, 70)]

Service: True Pickup: (26, 70)

**Test Report Summary**

|  |  |
| --- | --- |
| **Project Details** | |
| Project Name | Quantum Ridesharing |
| Project Description | A capacitated vehicle routing algorithm implemented in a quantum system. |
| Project Duration | Start Date – 12/08/2021 End Date – 05/05/2022 |
| **Test Summary** | |
| Test Cycles | Unit Testing ✓ Integration Testing ✓ System Testing ✓ |
| Number of test cases executed | 30 |
| Number of test cases passed | 30 |
| Number of test cases failed | 0 |

**6. RESULTS AND DISCUSSION**

The capacitated vehicle routing problem (CVRP) is a VRP in which vehicles with restricted carrying capacity must pick up or deliver commuters/things at many locations. The objective is to pick up or transport the things at the lowest possible cost while never exceeding the capacity of the vehicles. This project tries to simulate a CVRP with a variable number of passengers travelling to different locations from a central hub with a fixed number of shuttles, using Quadratic Unconstrained Binary Optimization (QUBO) implemented via Quantum Annealing on D-Wave systems.

Given a CVRP problem instance, the proposed algorithm will help construct suitable clusters of passengers in a very short period of time. The algorithm further works on the clusters created to generate the most optimal routes. The clusters thus obtained are analyzed using a greedy approach to determine the service ordering. A simulation is initialized, and the service ordering is assigned to the respective shuttle. The simulation is executed for thirty iterations. For each iteration, a request is generated. A request handler is called to determine whether the request is serviceable or not. If the request is not serviceable, the request is declined. Otherwise, shuttles which can service the request are determined. Out of the suitable shuttles, the best-suited shuttle is chosen to service the request. The chosen shuttle’s path is modified to pickup the new passenger and the shuttle is set to pickup mode. While a shuttle is in pickup mode, it will not service any other incoming requests, whether it is suitable or not. The pickup mode is turned off once the passenger is picked up. The shuttle then continues its journey using the new route generated to accommodate the picked up passenger. For each iteration, the details of the corresponding state are displayed using logs as well as by drawing on the map.

The strength of the proposed algorithm is the utilization of QUBO for clustering the initial batch of requests. Although the simulation is run on limited capacity due to hardware limitations, with appropriate hardware, it would be possible to drastically reduce the time for clustering an overwhelming amount of data as compared to any classical approach.

**7. CONCLUSION**

Using a quantum approach from clustering is an efficient approach due to the capabilities of fasters calculations on overwhelming amounts of data. The project described is this paper is still in a preliminary research state due to limitations of quantum hardware. The true potential of this project can be measured when quantum computers are able to handle large amounts of data similar to modern classical computers. Till then, the effectiveness of the results proposed by this project will remain much abstract.

**7.1 Limitations**

* The project currently faces a hardware limitation in the form of the number of qubits available in contemporary gate-based quantum computers. They can only answer the simplest forms of the VRP. According to the model utilized by this project, the number of commuters should not exceed 5, and the number of shuttles should not exceed 2.
* Quantum run time is currently dominated by embedding time due to hardware constraints.
* Clustering as done by QUBO may not always be the most optimal one and may need to be further optimized.

**7.2 Future Scope**

* As quantum computers become mainstream in the upcoming few years, the project can be applied in practical scenarios to cater to thousands of service requests per instance of time, generating optimal routes and minimizing cost as well as waiting time of the commuters as well as drivers.
* The algorithm can be improved to handle multiple dynamic service requests in a particular instance of time.
* Improvisations can be made to make it possible to accept service requests from other passengers while in the process of picking up a passenger.

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# glossary

|  |  |
| --- | --- |
| API | Application Programming Interface |
| BQM | Binary Quadratic Model |
| CVRP | Capacitated Vehicle Routing Problem |
| GAP | General Assignment Problem |
| IDE | Integrated Development Environment |
| KP | Knapsack Problem |
| QP | Quadratic Program |
| QUBO | Quadratic Unconstrained Binary Optimization |
| SDK | Software Development Kit |
| VRP | Vehicle Routing Problem |