Optimal route management for mobile energy storage considering construction sites

Shamim Al Mamun.[1,2]. Sambeet Mishra. [1]. Thomas Oyvang.[1]. Chiara Bordin.[2]. Praveen Prakash Singh.[3]

[1] University of South-Eastern Norway, Porsgrunn, 3918, Norway.
[2] UiT- The Arctic University of Norway, Tromsø, 9019, Norway.
[3] Tallinn University of Technology (TalTech), Tallinn, 19086, Estonia.

Objectives

Develop a model of an optimized route plan for vehicles that minimizes idle time and operational cost, ensuring efficient management of mobile energy storage system (MESS) transportation to and from construction sites.

Sub-goals:

- Improve vehicle utilization.
- Trade-offs between travel distance and operational cost.
- Ensure the scalability of the model.
- minimize the carbon footprint of transportation by route optimization.

Country context: Norway

- One of the global leaders in renewable energy usage.
- According to the European Construction Industry Federation's statistical report, construction growth in Norway is projected to be 2 % in 2024 [1].
- This makes mobile energy storage essential for efficient construction and creates major logistical challenges.
- Road traffic emissions made up 17% of Norway's total emissions in 2022, impacting its efforts to meet the Paris Agreement targets [2].
- Optimizing MESS transportation helps to reduce road traffic emissions.

Knowledge gap and Contribution

- Utilization of vehicle routing problems in the area of mobile energy storage systems (MESS) transportation is significantly unexplored.

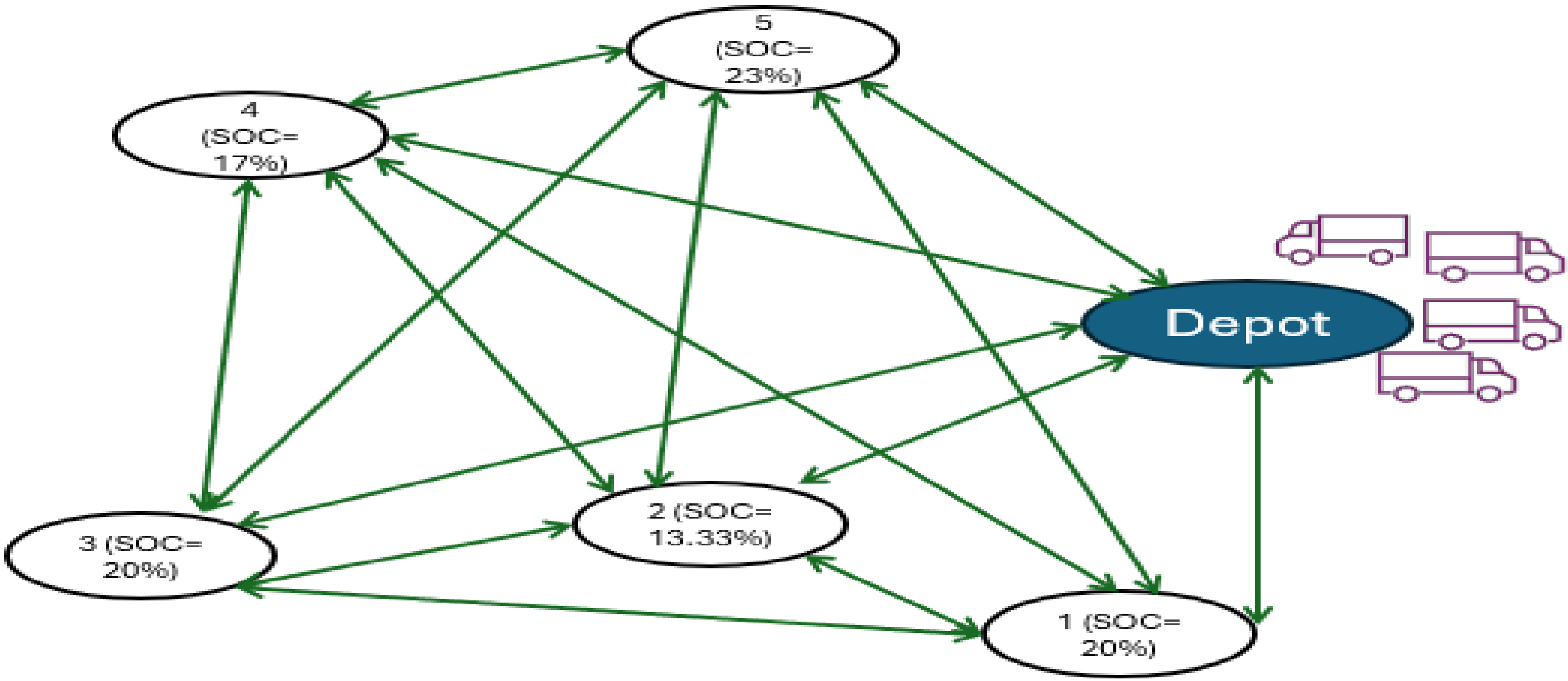
- The increasing demand for MESS on construction sites highlights the need for further research to address its unique challenges such as:
    - ensuring a consistent power supply
    - monitoring the state of charge (SOC) percentage of MESS units
    - Scheduling delivery times based on SOC to prevent power outages.

- This study aims to bridge this gap by proposing a dynamic programming optimization model for optimal route management of mobile energy storage systems (MESS) at construction sites.

Methodology

- The Investigate MESS transportation processes, gather data and identify operational limitations.
- Mathematical model development by the mixed integer linear programming (MILP) approach.
- Generate synthetic datasets that accurately replicate the variables and scenarios found at real-world construction sites.
- The Python programming language is used as the main computational tool.
- PuLP is used to fit the model, and the CBC solver (coin, branch, and cut) is used to solve the optimization problems primarily.
- Used dynamic programming techniques to improve solution quality.
- Evaluate the model and compare its applicability and scalability in different contexts.

Problem Description



SOC= State of Charge

How can operational costs and idle time be minimized for MESS transportation to construction sites by effectively monitoring and scheduling based on State of Charge (SOC) percentages to ensure a consistent power supply?

Mathematical Expression

Mixed Integer Linear Programming (MILP) approach

Decision Variable

X_{ij}^{k} = Binary Variable; 1 if lorry k travels directly from location i to location j .

S_i^k =Service start time at location i by lorry k

$deliv_i^k$= Integer variable, representing the amount of MESS delivered by vehicle k up to, in location i.

$Pick_i^k$= Integer variable, representing the amount of MESS picked by lorry k up to, in location i.

$LowSOC_i =$ Binary variable, 1 if the SOC at location i is below 20%, and 0 otherwise.

Objective Function:

The objective is to minimize the travel distance and operational costs:

Min $Z = \sum_{k\in K}\sum_{i\in N}\sum_{j\in N, i\neq j}(d_{ij} \cdot (FC + VMC) \cdot X_{i,j}^{k}) + \sum_{k\in K}\sum_{i\in N}\sum_{j\in N, i\neq j} MC \cdot (S_i^k + +p_i + T_{ij}) + \sum_{k\in K} RT \cdot \sum_{j\in N, j\neq 0} X_{0j}^{k}$

Constraints:

1. **Delivery and pickup demand fulfillment:**

   $deliv_i^k = D_i \quad \forall\, i\epsilon\, N\backslash\{0\}$

   $Pick_i^k = P_i \quad \forall\, i\epsilon\, N\backslash\{0\}$

2. **Vehicle routing constraint:**

   $\sum_{k\epsilon K}\sum_{j\epsilon N, j\neq i} X_{i,j}^{k} \geq D_i + P_i \quad \forall\, i\epsilon\, N\backslash\{0\}$

3. **Vehicle Capacity Constraint**

   $\sum_{k\epsilon K} deliv_i^k \leq \mathbf{Q} \quad \forall\, i\epsilon\, N\backslash\{0\}$

   $\sum_{k\epsilon K} pick_i^k \leq \mathbf{Q} \quad \forall\, i\epsilon\, N\backslash\{0\}$

4. **SOC Pickup Requirement**

   $\sum_{k\epsilon K} pick_i^k \geq LowSOC_i \cdot (1 - \frac{SOC_i}{100}) \times P_i \quad \forall\, i\epsilon\, N\backslash\{0\}$

5. **Service and travel time window constraint:**

   $e_i \leq S_i^k \leq l_i \quad \forall\, k\epsilon K \quad , \forall\, i\epsilon N$

   $S_i^k + p_i + T_{ij} \leq S_j^k \quad \forall\, k\epsilon K \quad , \forall\, i,j\epsilon N, i\neq 0$

6. **Depot start and end constraint:**

   $\sum_{j\in N, j\neq 0} X_{0j}^{k} = 1 \quad \forall\, k\epsilon K$

   $\sum_{i\in N, i\neq 0} X_{i0}^{k} = 1 \quad \forall\, k\epsilon K$

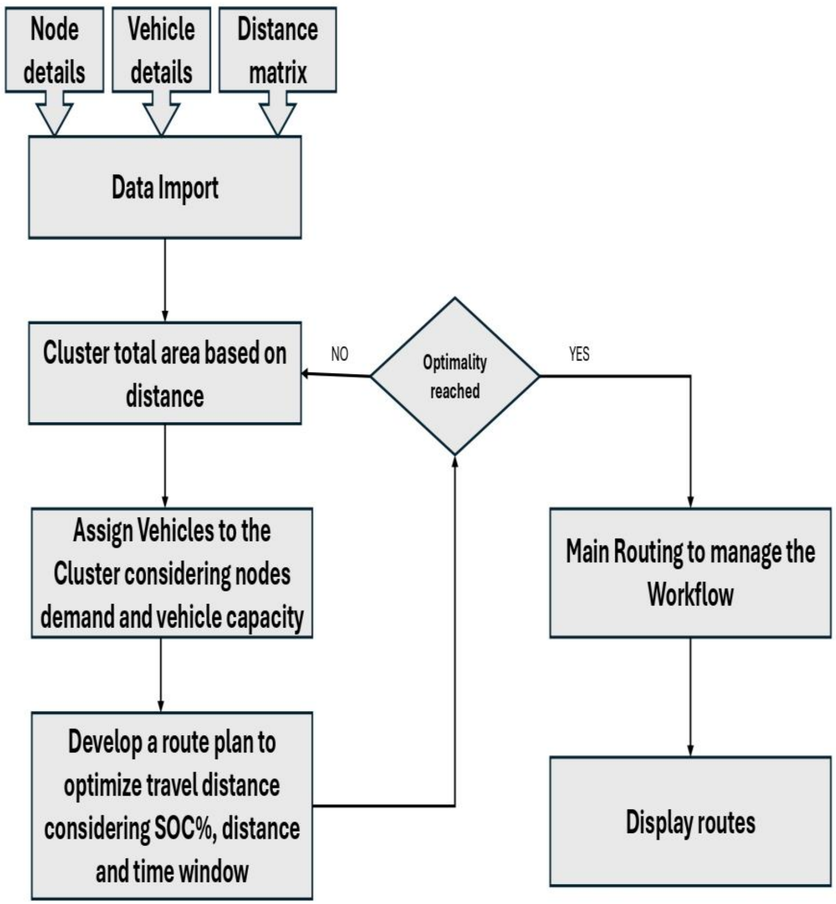
7. **Subtour elimination**

   $X_{i,j}^{k} + X_{j,i}^{k} \leq 1 \quad \forall\, k\epsilon K \quad , \forall\, i,j\epsilon N, i\neq 0$

8. **No loop between nodes**

   $\sum_{i\in \mathrm{N}} X_{ii}^{k} == \mathbf{0} \quad \forall\, k\epsilon K$

Dynamic Programming Approach



Procedure to solve the optimization model

- Guaranteed optimal solution.
- Can handle overlapping subproblems by using memorization or other approaches.
- Easily adapts to different problem sizes and constraints
- Highly effective for the shortest paths problem algorithms.
- High computational speed.

Dataset

Vehicle details

```
#Input data
vehicles = [{'id': 1, 'type': 'Small', 'capacity': 200, 'speed': 40, 'fuel_cost_per_km': 10, 'hourly_wage': 300},
            {'id': 2, 'type': 'Small', 'capacity': 200, 'speed': 40, 'fuel_cost_per_km': 10, 'hourly_wage': 300},
            {'id': 3, 'type': 'Medium', 'capacity': 250, 'speed': 35, 'fuel_cost_per_km': 12,'hourly_wage': 350},
            {'id': 4, 'type': 'Medium', 'capacity': 350, 'speed': 35, 'fuel_cost_per_km': 12,'hourly_wage': 350},
            {'id': 5, 'type': 'large', 'capacity': 500, 'speed': 30, 'fuel_cost_per_km': 14, 'hourly_wage': 400},
            {'id': 6, 'type': 'large', 'capacity': 500, 'speed': 35, 'fuel_cost_per_km': 14, 'hourly_wage': 400}]
```

- 7 nodes (6 customer + 1 depot)
- 2 customers SOC is heigher than 20%
- 6 vehicles with different speed, fuel cost and manpower wages.
- Similar time window for all the customers

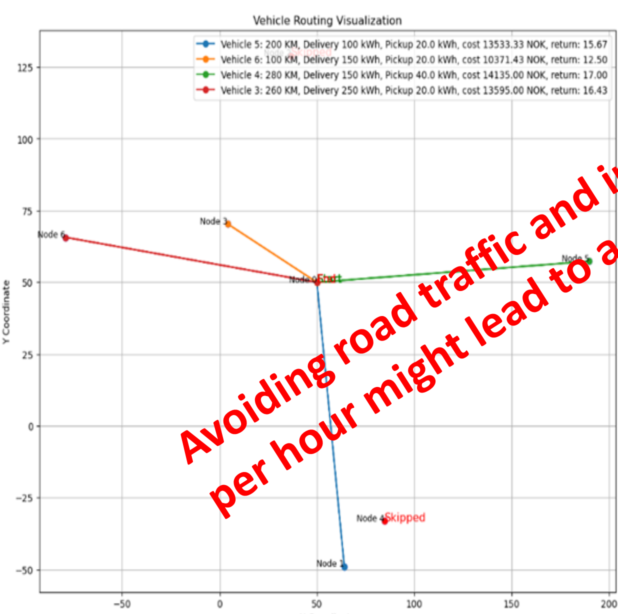
Customer details

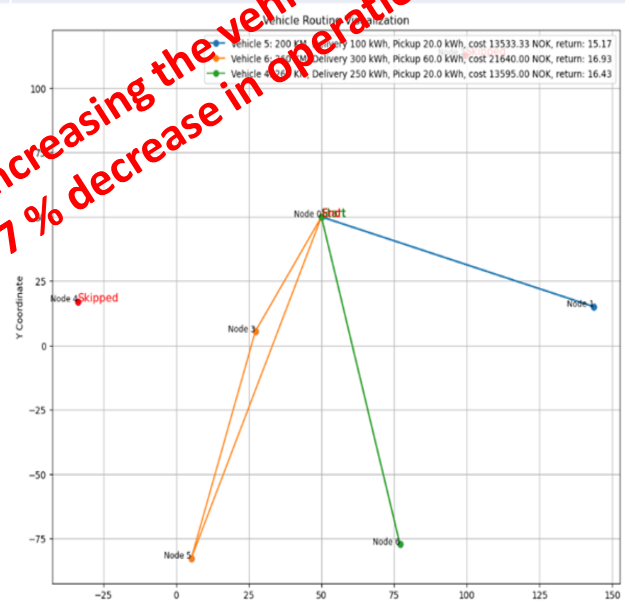
Nodes	Customers	Requirement of KWh	Present KWh	Present SOC	StartTime	EndTime
0	Depot	0	0			
1	building construction	100	20	20.00	8	16
2	pond construction	200	190	95.00	8	16
3	factory construction	150	20	13.33	8	16
4	bridge construction	100	30	30.00	8	16
5	road construction	200	40	20.00	8	16
6	power grid	250	20	8.00	8	16

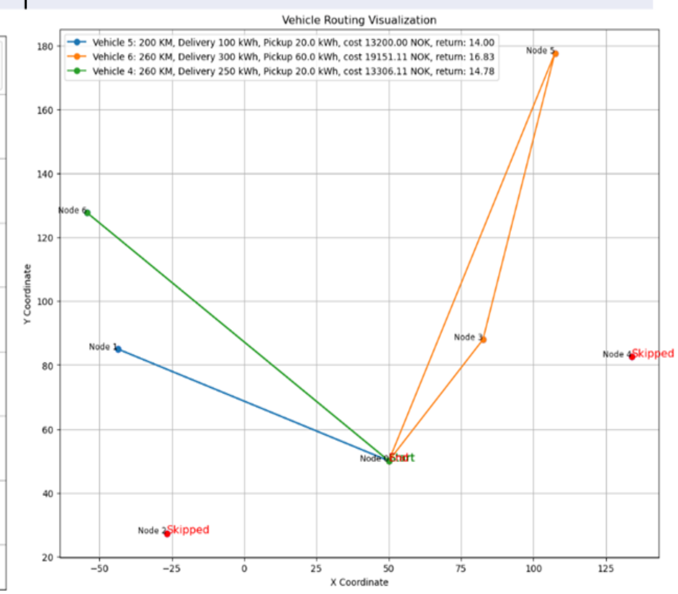
Model Validation Scenario: Time-window

Narrowing the time windows (8.00 – 14:00)	unique time window for customers with 4-Hour Intervals	Increasing vehicles speed to 10 KM/h with narrow time-window (8:00-14:00)
Skipped node: 2 and 4	Skipped node: 2 and 4	Skipped node: 2 and 4
4 vehicle assigned out of 6	3 vehicles assigned out of 6	3 vehicles assigned out of 6
Total travel distance: 840 KM	Total travel distance: 720 KM	Total travel distance: 720 KM
Total operation cost: 51634 NOK	Total operation cost: 48768 NOK	Total operation cost: 45657 NOK
Total delivery : 650 KWh	Total delivery : 650 KWh	Total delivery : 650 KWh
Total pickup:: 100 KWh	Total pickup:: 100 KWh	Total pickup:: 100 KWh

Avoiding road traffic and increasing the vehicle's average speed by 10 kilometers per hour might lead to a 7 % decrease in operational expenses.



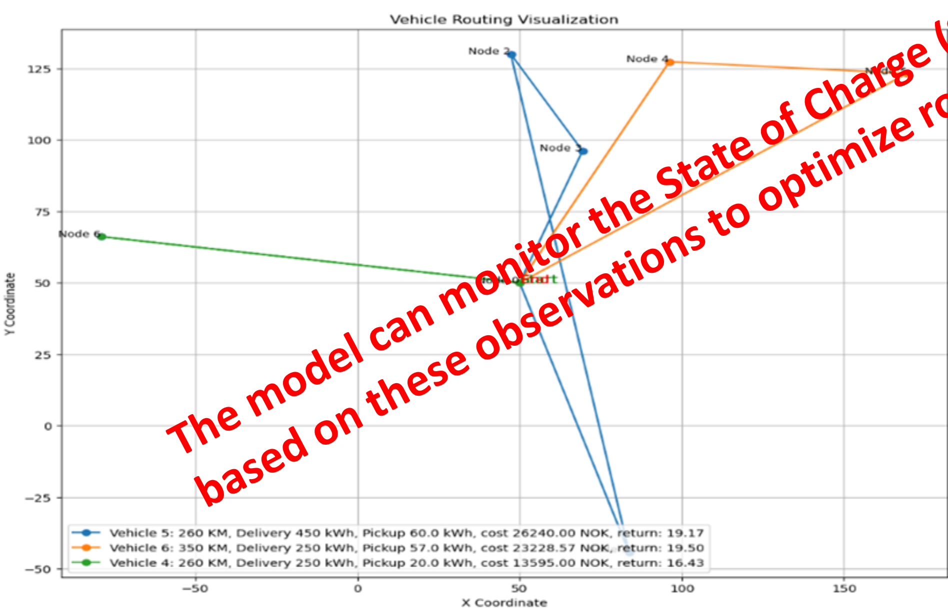


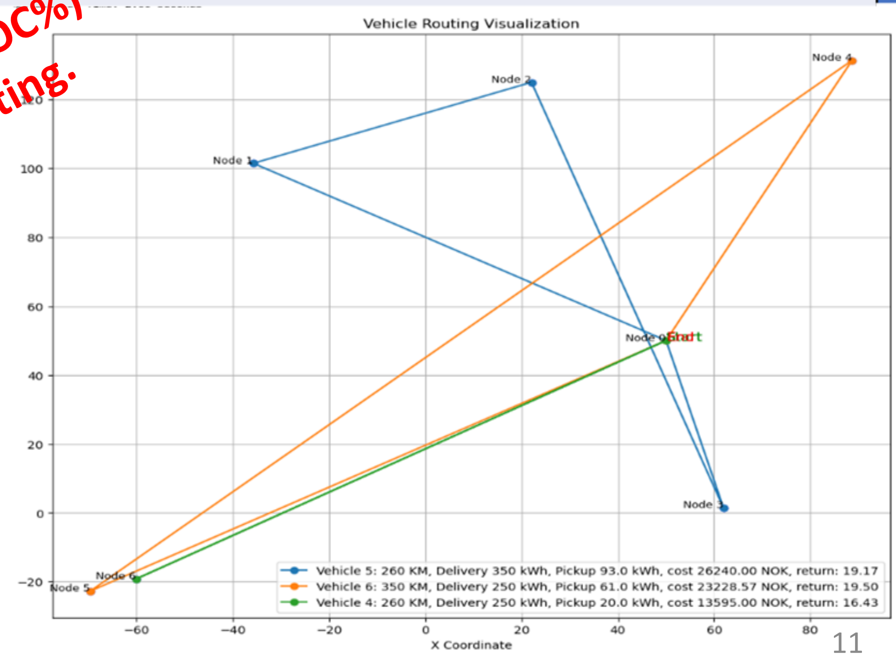


Model Validation Scenarios: SOC

all customers SOC <= 20%	Changed SOC =21% of Customer/node 1,2 & 4
Skipped node: No	Skipped node: No
3 vehicle assigned out of 6	3 vehicles assigned out of 6
Total travel distance: 870 KM	Total travel distance: 870 KM
Total operation cost: 63063 NOK	Total operation cost: 63063 NOK
Total delivery : 950 KWh	Total delivery : 950 KWh
Total pickup:: 137 KWh	Total pickup:: 137 KWh

The model can monitor the State of Charge (SOC%) of all MESS and make decisions based on these observations to optimize routing.

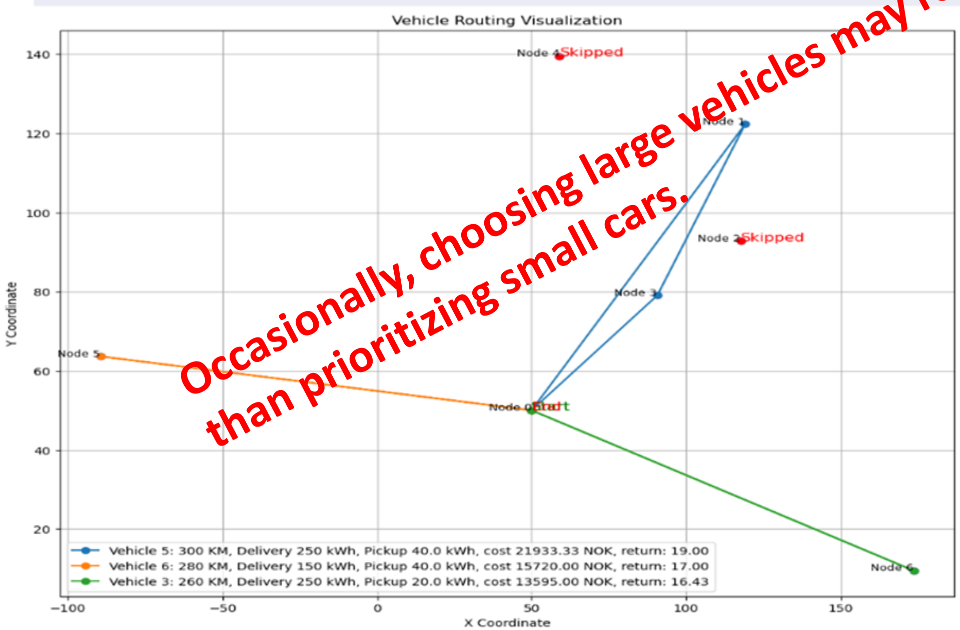


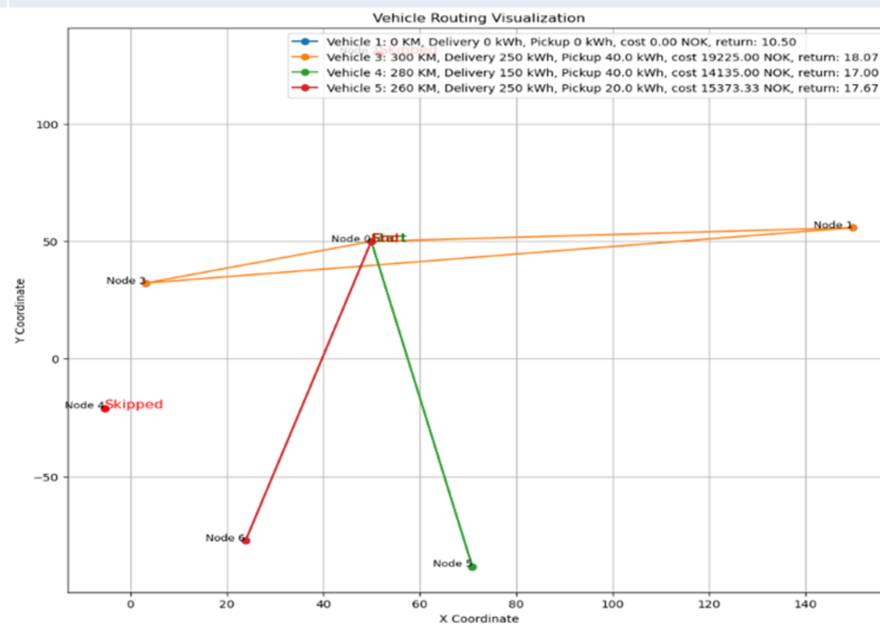


Model Validation Scenarios: Vehicles priority

Small Vehicle= 50KWh, Medium Vehicle= 250 KWh, Large vehicle = 300KWh (Large vehicle on priority)	Small Vehicle= 50KWh, Medium Vehicle= 250 KWh, Large vehicle = 300KWh (Small vehicle on priority)
Skipped node: 2 and 4	Skipped node: 2 and 4
3 vehicle assigned out of 6	4 vehicles assigned out of 6
Total travel distance: 840 KM	Total travel distance: 840 KM
Total operation cost: 51248 NOK	Total operation cost: 48733 NOK
Total delivery : 650 KWh	Total delivery : 650 KWh
Total pickup: 100 KWh	Total pickup:: 100 KWh

Occasionally, choosing large vehicles may result in greater operational expenditures than prioritizing small cars.





Check the Scalability of the Model (Large Scale Dataset)

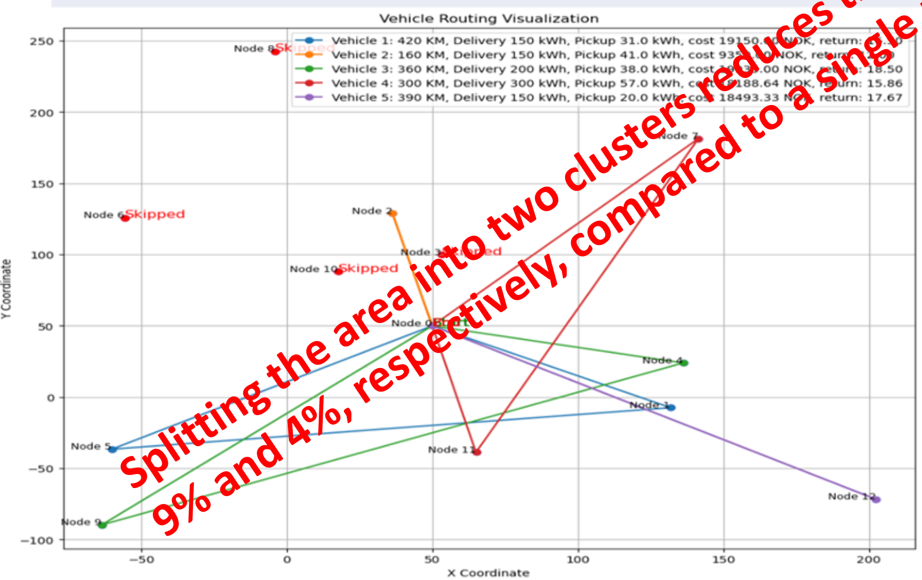
Node	Customers	Requirement of KWH	Present KWH	Present SOC	StartTime	EndTime
0	Depot	0	0			
1	building construction	100	21	21.00	8	16
2	pond construction	200	41	20.50	8	16
3	factory construction	150	100	66.67	8	16
4	bridge construction	100	17	17.00	8	16
5	road construction	50	10	20.00	8	16
6	power grid	50	40	80.00	8	16
7	building construction_2	250	40	16.00	8	16
8	pond construction_2	100	30	30.00	8	16
9	factory construction_2	100	21	21.00	8	16
10	bridge construction_2	50	46	92.00	8	16
11	road construction_2	100	17	17.00	8	16
12	power grid_2	150	20	13.33	8	16

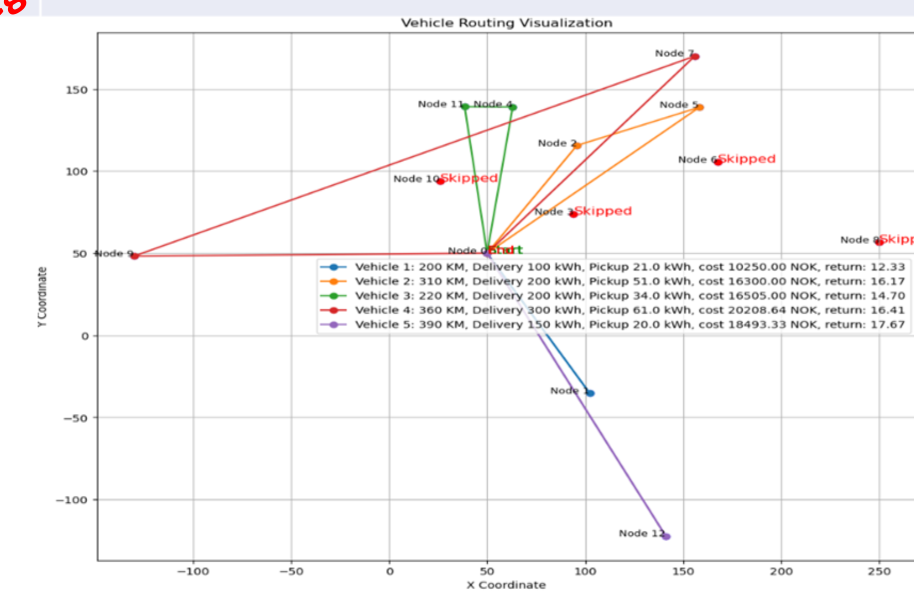
```
#Input data
vehicles = [{'id': 1, 'type': 'Small', 'capacity': 200, 'speed': 60, 'fuel_cost_per_km': 10, 'hourly_wage': 300},
            {'id': 2, 'type': 'Small', 'capacity': 200, 'speed': 60, 'fuel_cost_per_km': 10, 'hourly_wage': 300},
            {'id': 3, 'type': 'Medium', 'capacity': 250, 'speed': 50, 'fuel_cost_per_km': 12,'hourly_wage': 350},
            {'id': 4, 'type': 'Medium', 'capacity': 350, 'speed': 55, 'fuel_cost_per_km': 12,'hourly_wage': 350},
            {'id': 5, 'type': 'large', 'capacity': 500, 'speed': 45, 'fuel_cost_per_km': 14, 'hourly_wage': 400},
            {'id': 6, 'type': 'large', 'capacity': 500, 'speed': 45, 'fuel_cost_per_km': 14, 'hourly_wage': 400}]
```

Scenarios to check the model accuracy on large scale

12 customers in one cluster Cluster radius: 300 KM	Cluster Radius: 120 KM Cluster 0: Nodes [1, 2, 3, 4, 10, 11] Cluster 1: Nodes [5, 6, 7, 8, 9, 12]
Skipped node: 3, 6, 8 and 10	Skipped node: 3, 6, 8 and 10
5 vehicle assigned out of 6	5 vehicles assigned out of 6
Total travel distance: 1630 KM	Total travel distance: 1480 KM
Total operation cost: 85117 NOK	Total operation cost: 81757 NOK
Total delivery : 1010 KWh	Total delivery : 1010 KWh
Total pickup: 187 KWh	Total pickup:: 187 KWh

Splitting the area into two clusters reduces travel distance and operational costs by around 9% and 4%, respectively, compared to a single region.





Model Results and Future Work

During the validation of the model, several observations were recorded, including the computational time:

- Avoiding road traffic and increasing the vehicle’s average speed by 10 kilometres per hour might lead to a 7 % decrease in operational expenses.
- Occasionally, choosing large vehicles may result in greater operational expenditure than prioritizing small cars.
- Splitting the area into two clusters reduces travel distance and operational costs by around 9% and 4%, respectively, compared to a single region.
- The dynamic programming model took 3.27 seconds to 4.28 seconds to compute for different scenarios.

Scope of future work:

- Developing multi-objective evolutionary algorithms using co-optimization.
- Introducing real-time observations of MESS’s state of charge and considering battery degradation.
- Imposing constraints on traffic volume and meteorological conditions.

References

[1]. FIEC - European Construction Industry Federation. https://fiec-statistical-report.eu/norway#:~:text=Newly%20revised%20estimates%20show%20declining,growth%20each%20of%20the%20years.

[2]. Statistics Norway, Emissions to air. https://www.ssb.no/en/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft

[3]. S. Angel, A. Chabaeva, L. Gitlin, A. Kraley, J. Parent and M. Perlin: The dynamics of global urban expansion, World Bank Group. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/138671468161635731/the-dynamics-of-global-urban-expansion

[4]. IEEE:'Ieee draft guide for design, operation, and maintenance of battery energy storage systems, both stationary and mobile, and applications integrated with electric power systems, pp. 1–45. IEEE P2030.2.1/D9.0, February 2019.

[5.] Q. Z. Qingyou Yan: Discrete Dynamics in Nature and Society: The optimization of transportation costs in logistics enterprises with time-window constraints,'vol. 2015, no. 365367, p. 10, 2015. doi:10.1155/2015/365367

Thank You

Funded By:

- University of South-Eastern Norway
  - Prof. Sambeet Mishra
- UiT The Arctic University of Norway
  - Prof. Chiara Bordin

Collaborated By:

Praveen Prakash Singh, PhD candidate
Tallinn University of Technology (TalTech)

?