

# **A Data-Driven MILP Approach to Minimize Transportation Costs and Emissions in Labor-Intensive Industries**

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## **Abstract**

Staff mobility is a problem of operational and environmental concern to industries with high labor intensity, notably where dispersed work locations and inflexible shift patterns are the norm. This research examines inefficiencies in Company X's static employee transport system and formulates a Mixed-Integer Linear Programming (MILP) model to optimize worker–bus allocation. The model incorporates routing, vehicle capacity, and role-based constraints to reduce total transportation cost and CO<sub>2</sub> emissions. Based on real operational data from Company X, the model provided realistic assignments under fixed-shifts and demonstrated measurable reductions in cost and emissions consistent with those documented in comparable optimization studies (Alshabibi et al., 2025; Song and Zhang, 2024). The novelty of the work is in combining assignment, routing, and emission trade-offs in a single MILP formulation validated with a real-world industrial case. The study contributes theoretically by incorporating workforce transportation optimization with environmental objectives and practically through the provision of an expandable decision-support system for UAE facility-management operations.

## **Keywords**

Transportation Cost Optimization, Bus Utilization Efficiency, CO<sub>2</sub> Emissions Reduction, Worker–Bus Assignment Model, and Operational Constraints

## **1. Introduction**

By enabling labor and goods movements, transport systems enhance economic efficiency; however, firms are increasingly faced with schedule, budget, and environmental footprint limitations (Gupta et al., 2018; IEA, 2023).

In sectors such as construction and facilities management, where coordinated, consistent movements of employees occur within repetitive shifts, custom worker transport is substantially less the topic of study compared to peak public transport, which remains the topic of considerable study (Cordeau and Laporte, 2007; Cao and Wang, 2017). All of the models treat capacity, assignment, and routing as standalone decisions and don't take into consideration how they co-integrate in reality, as noted in recent workforce scheduling and routing studies (Castillo et al., 2014; Guastaroba et al., 2021; Wang et al., 2023; Ou et al., 2021). Such detachment limits the applicability of the models to companies that need to tackle passenger allocation and routing simultaneously, for example, massive facility management companies. Furthermore, although MILP's efficiency has been shown in similar logistics and bus timetabling problems, few studies utilize it with fixed-shift, role-based employee transport under real operational scenarios (Bodin et al., 2003; Şahin et al., 2020). Another limitation is the lack of testing with actual business data, restraining scalability and real-world use (Balázs and Krész, 2018). Finally, whereas there is increasing organizational and regulative pressure to decarbonize transport infrastructures, most models consider emissions as footnotes or second-order outcomes, second order to the optimization objective, whereas sustainability targets are incorporated in most cases (Gupta et al., 2018; Liu et al., 2023; Song and Zhang, 2024). To bridge those gaps, this paper employs a MILP formulation which takes into account cost, routing, and emission objectives simultaneously. With sustainability constraints, it theoretically expands the reachability of labor scheduling and routing issues. In practice, it provides multi-site fleet companies in the Gulf with a replicable method.

### **1.1 Transportation and challenges**

Labor transport is one of the major operational activities in Company X with direct implications on cost savings, daily reliability, and employee deployment. The current static system, however, translates into wasteful fuel usage, idle buses, and higher operating costs. According to Cordeau and Laporte (2007), excessive operating costs in service sectors are largely caused by ineffective managing and routing in human systems of transportation. This research is important because it offers a systematic optimization solution, using MILP, to solve an existing, high-impact problem. MILP models are an appropriate method for this investigation since they have demonstrated efficacy in comparable transport issues including workforce logistics (Bodin et al., 2003).

Aside from efficiency gains, the study answers mounting pressure to reduce CO<sub>2</sub> emissions, both company-level and at the national level in terms of sustainability efforts. Road transport accounts for the majority of the transportation sector's virtually one-quarter of all energy-related CO<sub>2</sub> emissions in the world, according to the International Energy Agency (IEA, 2023). Optimization of bus use and reduction of wasteful mileage are highly interrelated with decarbonization. This study also remedies a gap in existing literature by solving a real, fixed-shift labor transportation network using mathematical optimization, an area of relatively low scholarly focus but significant applied relevance (Şahin et al., 2020). In worker relocation planning, it closes the gap between theory and application by grounding the model in real operational data and limitations.

### **1.2 Real Case Study**

In the UAE's service sector, particularly in facilities management, the large-scale deployment of the workforce relies on systematic and efficient transportation. Company X is running to carry hundreds of staff from different accommodation camps to dispersed client sites on a daily basis. Timing and efficient coordination are critical, yet increasingly difficult to uphold using conventional planning methods.

Company X, belonging to the Klueh Group, is a leading UAE facilities management organization. As a daily necessity to transport hundreds of laborers from various accommodations to several customer sites, the company is facing increasing pressure to reduce transportation costs while maintaining punctuality and reliability. This paper proposes a mathematical optimization model using Mixed-Integer Linear Programming (MILP) to improve the cost-effectiveness and eco-friendliness of Company X labor transportation operations.

Company X operates transport services with a dedicated fleet of buses from different accommodation camps to work sites across the UAE today. However, the company is facing inefficiencies in operations due to static assignment rules and rising costs. The growing importance of sustainability and CO<sub>2</sub> emission reduction adds another complexity. Such challenges demand smarter, data-driven planning solutions. In this research, a mathematical optimization model is proposed for optimizing the assignment of workers to buses so that the company can avoid unnecessary trips, reduce transport costs, and help achieve environmental objectives.

### **1.3 Problem Statement**

Company X is currently operating daily labor transportation using a dedicated fleet of approximately 60 buses and 70 drivers, with trips from different labor camps to over 20 active client sites across the UAE. The laborers are transported in two big shifts, with each shift doing 3 to 4 trips, during the hours of 4:30 AM to 10:30 AM and again in the evening from 6:00 PM.

While this static system has been delivering consistency of operation, it has created inefficiencies that can be quantified. Internal observation is that buses are operating at under 50% capacity, which translates to wasted mileage and excess fuel usage. With fuel prices rising and operating budgets being constrained, these inefficiencies translate to unnecessary monthly transportation expenses of well over hundreds of thousands of dirhams. Second, the current model also creates a large environmental footprint, with CO<sub>2</sub> emissions calculated to rise with unnecessary journeys and inefficient routes.

Despite efforts at control improvement, such as the addition of GPS monitoring, Company X does not currently possess an optimization platform for assigning workers to buses by real demand, route miles, or worker category (i.e., supervisors, technicians, cleaners). Therefore, the company lacks the opportunity to optimize operating costs and carbon usage in support of corporate sustainability goals and the UAE's emission reduction goals.

To bridge these gaps, this study proposes developing a MILP model that dynamically assigns workers to buses, considering constraints such as vehicle capacity, worker pairing, shift duration, and distance covered. The model would seek to provide Company X decision-makers with realistic assistance in optimizing labor transport operations, cost minimization, and environmental impact reduction for a long-term planning horizon.

### **1.4 Research Objectives**

The general objective of this research is to develop a MILP model that minimizes Company X's labor transportation expenses while lowering carbon emissions and improving bus utilization simultaneously. Specifically, the research aims to:

- Develop a mathematical model that assigns workers to buses in a cost-saving and environmentally friendly way.
- Include labor-specific constraints such as fixed shifts and capacity constraints in the optimization.
- Compare the optimized model's performance with the current static assignment system based on total cost, emissions, and vehicle utilization.
- Conduct sensitivity analysis to key parameters like fuel price, worker demand, and dorm-to-site distances to establish model robustness.

These objectives will have both theoretical contribution and practical value in guiding Company X and similar companies in data-driven and sustainable transport planning.

#### **Research Questions**

**RQ1:** To what extent can the optimized model reduce total transportation costs and improve bus utilization compared to the current static assignment method?

**RQ2:** How does an optimized worker-bus assignment model reduce CO<sub>2</sub> emissions compared to the current system?

**RQ3:** Identify the constraints that have an impact on the objective.

## **2. Literature Review**

The challenge of assigning workers to buses in a cost-efficient and sustainable way has gained increasing academic and practical attention, particularly in the context of high-density labor transport operations. While public transit optimization is well-documented, structured labor shifts, especially in the facilities management sector, present unique constraints such as fixed dormitory locations, static shift schedules, and role-based grouping of workers. Addressing this specific context, several recent studies provide a foundation for developing tailored optimization solutions like the MILP-based model proposed in this research.

### **2.1 Transportation Optimization in Labor Settings**

A study by Cao and Wang (2017) developed an optimization method for customized bus services that considers not only travel and waiting time, but also passenger satisfaction and operational cost. Although designed for urban

passengers, the structure mirrors the complexity found in labor transport, where different groups (e.g., cleaners, technicians, supervisors) must be routed efficiently across multiple destinations. This multi-variable objective setting is particularly relevant for Company X, where efficiency must be balanced against service reliability and workforce coordination. The difficulty of concurrently assigning staff and routing vehicles under time and capacity limits is recognized by the workforce scheduling and routing problem (WSRP) literature (Castillo et al. 2014). Guastaroba et al. (2021) developed a multi-period WSRP that included workforce assignment with route planning; however, their model focused on generic service tasks instead of fixed-shift labor.

Wang et al. (2023) extended this concept by integrating bus route design and passenger assignment into a single optimization model. Their work supports the principle that worker assignment cannot be isolated from routing, especially in systems with spatially distributed labor camps and dynamically changing site demands. This justifies a more holistic optimization model in the current paper, one that doesn't treat assignment and routing as separate phases but rather as interdependent variables within the same MILP framework.

Workforce scheduling itself is a key logistical concern in large transport systems. Nurmi et al., 2013 focused on optimizing driver and workforce allocation in transit systems and highlighted the benefits of centralizing decisions through algorithmic models. The clear insight here is that manual or rule-of-thumb scheduling is inadequate in environments with multiple constraints, echoing the limitations currently seen in Company X's static, manually coordinated bus assignments. This strengthens the rationale for building a formalized optimization tool.

Similarly, Jin (2023) addressed labor cost minimization through bus driver scheduling under shift and legal constraints. While this focuses on driver allocation rather than worker assignment, it emphasizes the need to align legal, operational, and capacity constraints—a parallel to the dorm-to-site logic in Company X's operation, where certain worker types must be transported in specific quantities and combinations.

Balázs and Krész (2018) examined the multi-depot bus scheduling problem with constraints like maintenance and parking. The relevance to this research lies in its demonstration of real-world feasibility: optimization under rigid logistical limitations is not only possible but also yields significant gains. For Company X, where buses originate from specific locations and must cover numerous distant work sites, this kind of depot-aware optimization provides an effective structure for modelling.

A more user-centred dimension is explored by Liu et al., 2023, who used a bi-objective bus scheduling model considering both operational costs and passenger perception. In labor transport, dissatisfaction from long wait times, overcrowding, or poor coordination can lead to real productivity losses. Including qualitative service metrics in the model, while not the primary goal in this paper, could be a future extension to ensure not only cost-optimal but also human-centered transportation plans.

Dynamic scheduling also emerges in the work of Kumar and Khani (2023), who developed a schedule-based transit assignment model using real-time arrival data. While Company X's system is currently static, this literature supports the idea that real-time data integration could become a future capability—one that the MILP model should eventually accommodate, making it extensible for future dynamic routing or GPS-based reallocation once such systems are in place.

From a more technical standpoint, Ou et al. (2021) applied MILP to optimize bus-berth matching under connectivity constraints, providing evidence that even under complex scheduling problems with fixed-time windows and strict coordination requirements, MILP can produce feasible and optimal solutions. This directly supports the core methodological approach chosen for this paper.

## **2.2 Workforce Scheduling and Human-Centered Planning**

The human resource dimension is expanded by Nanyan (2022), who used linear programming for scheduling drivers while incorporating personal and family obligations. Though this research focuses on driver welfare rather than laborer assignment, it raises an important point: optimization should consider fairness and regulatory compliance, not just efficiency. Despite being helpful for labor equity, the model does not account for fuel or emission costs and does not have a routing component. Liu et al. (2023), who place greater emphasis on user experience measurements than on operational staff requirements or environmental goals, exhibit similar discrepancies.

### 2.3 Sustainability and Multi-Objective Transport Models

Gupta et al. (2018) proposed an integrated multi-objective model using the Analytic Hierarchy Process (AHP) and Data Envelopment Analysis (DEA) to evaluate sustainable transportation strategies in the mining sector. Their work highlights the importance of balancing cost, environmental, and performance criteria, offering a holistic perspective that supports decision-making under multiple, sometimes conflicting goals. While the context differs from labor transport, the emphasis on integrating sustainability with operational efficiency aligns closely with the direction of this research. The structured combination of decision-support tools also reinforces the value of hybrid models in solving real-world transportation problems where economic and ecological goals must coexist.

### 2.4 Addressing Literature Gaps through Research Questions

There are three ongoing gaps: (1) assignment, routing, and emissions are not strongly coupled; (2) corporate data sets are not validated; and (3) shift-based labor transportation is not well addressed by models. The conceptual framework of this research (Figure 1) has the same WSRP structure, but whereas distance and capacity are transport determinants in the former, environmental cost is made an objective here.

Literature review above is expanded and more critically synthesized into thematic areas of customized transport optimization, workforce scheduling, multi-depot and multi-objective models and computational methods and real-time integration, which has clearly identified the gap related to existing models often exclude labor-type constraints and do not integrate emissions as an active objective, while, only few studies validate models using real industry data, limiting applicability.

This research can bridge gaps in existing models in the literature. Not many of the previous studies have incorporated CO<sub>2</sub> emissions into the optimization goal explicitly, despite the fact that several of them have been concerned with cost efficiency in transportation networks. RQ2, probing the environmental impact of the optimized worker-to-bus assignment model versus Company X's current system, stems directly from this gap. Moreover, most models lack labor-type constraints and strict shift logic, leaving a vast contextual relevance gap. RQ1 attempts to address this problem by examining whether the proposed model can reduce costs and improve bus utilization in actual operating contexts. Lastly, RQ3 seeks to uncover which particular operational characteristics have the largest impact on the optimization results because many previous studies lack constraint-level sensitivity analysis. This study promises both applicability and theoretical contribution for facility management logistics through solving these problems using a structured MILP framework (Figure 1, Table 1).

**Conceptual Framework of the Study**

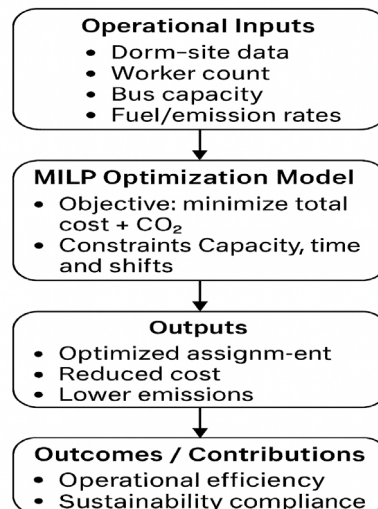


Figure 1. Conceptual Framework Diagram

Table 1. Summary of the literature reviewed

Article	Application	Parameters	Type of model	Methodology to solve	Limitations
Cao and Wang (2017)	Customized urban bus service, optimizing passenger assignment in city shuttle lines.	<ul style="list-style-type: none"> <li>- Travel time for each passenger-bus pairing</li> <li>- Waiting time at origin stops</li> <li>- Delay penalty for missing the desired arrival</li> <li>- Ticket price and operating cost</li> <li>- Number of seats used vs. capacity.</li> </ul>	Integer programming solved via Branch and Bound	Exact Branch-and-Bound search on a shortest-path formulation for the integer assignment problem	Assumes adaptable travel habits and focuses on passengers in metropolitan areas. Ignores worker type restrictions and structured labor shifts.
Wang, Zhou, Yang, and Yan (2023)	Rail-disruption response, designing temporary bus-bridging routes and passenger assignments when urban rail lines are disrupted.	<ul style="list-style-type: none"> <li>- Fleet size (number of buses)</li> <li>- Passenger demand</li> <li>- Waiting time thresholds and passenger renegeing rates</li> </ul>	Integer Linear Programming (ILP, Path-based)	Path-based Integer Linear Programming (ILP) solved via branch-and-cut in a commercial solver for bus-bridging network design	Developed for short-term rail disruption response, not for fixed daily labor schedules. Does not integrate long-term planning or sustainability factors.
Nurmi, Kyngäs, Zhuang, and Kyngäs (2013)	Workforce allocation in public-transport operators, optimizing both drivers and onboard staff.	<ul style="list-style-type: none"> <li>- Required workforce per period/shift</li> <li>- Qualifications of employees</li> <li>- Balanced workload distribution</li> </ul>	Metaheuristic (PEAST algorithm)	PEAST metaheuristic (Pattern-Evolutionary Algorithm for Staff Timetabling) for large-scale shift rostering	Ignores vehicle route and emissions in favor of focusing on driver scheduling and fairness.
Jin (2023)	Public-transit driver rostering, minimizing labor cost on scheduled bus routes under legal/shift constraints.	<ul style="list-style-type: none"> <li>- Labor cost per driver-hour</li> <li>- Number of drivers available</li> <li>- Shift length, start times, and break requirements</li> <li>- Maximum daily/weekly hours and minimum rest periods (legal)</li> <li>- Coverage of all scheduled trips</li> </ul>	Mixed Integer Programming	Linear Programming model solved via Excel Solver (Simplex) for minimum-cost driver rostering	Ignores worker-to-bus assignment and environmental criteria in favor of focusing on driver rostering costs and legal compliance.
Balázs and Krész (2018)	Intercity bus transport over a multi-day planning period, focusing on depot constraints (parking, maintenance) in regional coach services.	<ul style="list-style-type: none"> <li>- Each trip with departure/arrival time and start/end locations</li> <li>- Depots</li> <li>- Vehicles</li> <li>- Parking capacities at each depot per day</li> <li>- The maximum total service time before a preventive maintenance slot must be assigned</li> </ul>	Mixed-Integer Linear Programming (MILP)	Two-Stage Decomposition (TSD) to solve the rolling-horizon MILP, decomposing day-to-day scheduling and maintenance tasks	Not for shift-based intra-day operations, but for intercity multi-day planning. lacks an emphasis on sustainability and labor-specific routing.
Liu, Liu, Pei, and	City bus scheduling, balancing operational cost and	<ul style="list-style-type: none"> <li>- Passenger waiting cost</li> <li>- Passenger flow distribution by time and stop</li> </ul>	Bi-Objective Optimization (Dual-Cost	Adaptive Double-Probability	Focuses on perception metrics and public

Wang (2023)	passenger-perception metrics (congestion, wait times) for urban routes.	- Bus operation cost - Passenger travel cost	Bus Scheduling Optimization Model, Dual-CBSOM)	Genetic Algorithm (A_DPGA), an enhanced GA with adaptive crossover/mutation, to solve the Dual-CBSOM	commuters. ignores fixed shift schedules and labor-group restrictions.
Kumar and Khani (2023)	Urban bus networks, modelling passenger route-choice using real-time bus-arrival information in city transit systems.	- Online arrival information - Vehicle capacity - Penalties for late arrival, denied boarding - Link travel times, capacities	Markov Decision Process (MDP)	Variational-inequality model of passenger choice solved by a fixed-point projection algorithm (custom iterative solver)	Founded on real-time data and dynamic passenger choice. Labor transport methods that are shift-based and pre-assigned are not affected.
Ou, Ma, and Yu (2021)	Curbside urban bus stops, optimizing bus-arrival schedules and berth assignments under connected-vehicle technology to reduce stop-level delays.	- Bus arrival/departure times at curbside stop - Berth assignment - Service time distribution at stops - Bus delays	Mixed-Integer Linear Programming (MILP)	Mixed-Integer Linear Programming solved by a commercial MILP solver (CPLEX) for joint arrival/berth assignment	Assumes advanced connectivity infrastructure and focuses on berth assignment. Ignores workforce roles and emissions.
Nanyan (2022)	Municipal transit operator driver-shift planning, minimizing the number of drivers per shift for a city bus system	- Number of drivers per shift (3 shifts per day) - Number of drivers - Driver working days - Shift start time	Linear Programming (LP)	Single-objective Linear Programming solved via Excel Solver (Simplex) for minimum driver count	Addresses drivers shift planning and fairness but does not model routing, cost optimization, or environmental impact.
Gupta et al. (2018)	Sustainability assessment and fleet planning for open-pit mining haulage (trucks vs. conveyors) in a coal-mining operation.	- Vehicle capacity, fuel consumption, speed, and purchase/operating cost. - DEA: fuel use and emissions (inputs) vs payload delivered and safety index (output) - Cost, environmental emissions, and CSR (sustainability criteria weights via AHP) - Number of vehicles of each type	Multi-Objective Optimization (combining AHP weighting with DEA)	AHP for criteria weights followed by a radial DEA linear program for efficiency scoring, solved with standard LP solvers	Focuses on strategic fleet planning in mining. Does not include daily operational routing or labor assignment structure.

### 3. Methods

#### 3.1 Key Concepts, Theories, and Studies

This research depends on the following three main concepts

- MILP, which has been chosen for its robustness in modelling discrete decisions under constraints.
- Vehicle Routing Problem (VRP) and Workforce Scheduling Models, which form the basis of the optimization approach.
- Sustainability Metrics, which use the CO<sub>2</sub> per kilometer as a measurable output in the optimization function.

The research utilizes MILP to achieve optimal laborer allocation to buses under shift hours, capacity, and labor roles constraints (Ou, Ma, and Yu, 2021). It is closely related to the Vehicle Routing Problem (VRP) and passenger allocation models, whose objectives are optimal routing and allocation (Cao and Wang, 2017; Wang et al., 2023). Workforce scheduling is a second key application, focusing on centralized, rule-based planning to avoid inefficiencies (Nurmi et al., 2013; Jin, 2023). Multi-objective optimization is also used in the research, balancing cost and environmental goals like CO<sub>2</sub> emissions (Liu et al., 2023). Multi-depot planning and fairness in allocating drivers have been studied previously, offering additional proof of the model's applicability to practical environments (Balázs and Krész, 2018; Nanyan, 2022).

### 3.2 Key Debates and Controversies

One of the strongest arguments against the use of MILP in transportation systems is the trade-off between optimality and practicability in real-world implementation. While mathematically optimal solutions can be generated by MILP models, they are often reliant on accurate and detailed input data, which may not always be available or reliable in dynamic labor markets. Critics have also stated that MILP solutions are typically static and may not be readily responsive to sudden interruptions, such as the unavailability of workers or sudden client requests. Another point of controversy surrounds the computational complexity of MILP, especially when used to handle large systems with many constraints, which can limit its use in real-time operating environments.

### 3.3 Research Design and Models

This study develops a MILP model to optimize the assignment of workers to buses. This mathematical model could focus on minimizing total transportation costs, subject to constraints (Figure 2).

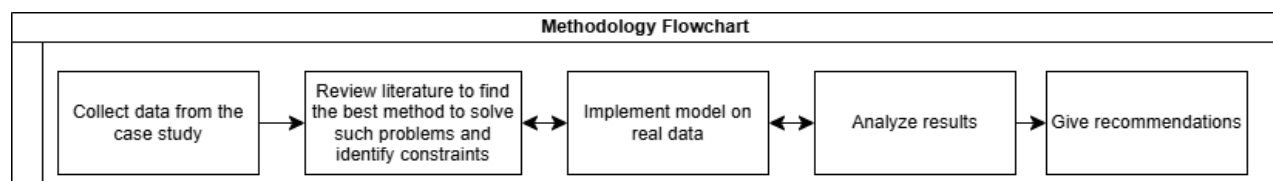


Figure 2. Methodology Flowchart

The first step in the process is to collect data from the case company, Company X. These data can be the number of employees per shift, locations of dorm and site, size of bus fleet and capacity, start and finish time of the shift, distance between start and finish points, fuel consumption rates, and CO<sub>2</sub> emission. This information will be the basis for MILP model and make sure that every decision accurately portrays the constraints and actual structure of Company X's labor transportation system in its current form.

To determine the best modeling methods for fixed-shift problems of labor transportation, research works from academic and commercial literature will be analyzed under this step. Bus/Truck routing and labor scheduling, MILP, and sustainable models will be especially emphasized. The analysis also assists in identifying typical as well as situation-specific constraints and limitations that will be enforced under the model, such as bus capacity, shift schedule, and route limits.

Once a strategy is chosen to follow and constraints are defined, the MILP model will be developed using Python and/or CPLEX. The model will then be used to simulate worker-to-bus allocations on different routes and shifts given actual data collected from Company X. The goal is to minimize overall transport cost, including fuel, leasing, and emissions, while simultaneously satisfying all operational constraints, including capacity constraints and energy form. Because of its high-performance techniques and adaptability to Python and other contexts, CPLEX is frequently used in the academic and industrial sectors to solve challenging linear and integer programming issues (IBM, 2023).

The performance will be analyzed after implementing and running the model to check how well it performs against the current situation of Company X. Environmental footprint, bus utilization, and total cost will be key performance metrics that will be looked at. Sensitivity analysis will be done as well to check and find out how the chosen model responds to variations in worker demand, duration of shift, or fuel prices. This analysis validates the resilience and efficacy of the model in a range of operational conditions.

The model has its limitations, however. It is built as a deterministic optimization model, meaning that it does not react to random or unexpected events such as surprise worker absences at the eleventh hour, traffic jams, or changing demand. Such disturbances are common in real-world transportation operations, and though they are important, they fall outside the scope of this baseline model. This may be able to be added to in future work using dynamic or stochastic integration. One of the model limitations is the fixed dormitory and site locations. While this is similar to route and assign for, it does not represent those situations where employees are relocated, or new sites are added. These are constraints to maintain the model tractable, but they also highlight the necessity of flexibility in any future versions.

### 3.4 Data and Tools

Data from Company X include dormitory-site distances, bus capacities, worker counts, shift timings, and fuel consumption. The functional unit is defined as cost per worker-trip (AED/trip) and CO<sub>2</sub> emitted per kilometer (kg CO<sub>2</sub> /km). **The MILP objective minimizes total transport cost + emission cost subject to vehicle capacity, number-of-trips, and shift constraints.**

Using **Python/ CPLEX** as the main optimization tools, this study will create a MILP model. Based on Company X's current labor transport system, the model will be created to decrease overall transportation costs while meeting operational requirements.

Bus capacity, distance between dorms and sites, number of workers transported, fuel cost per kilometre, and fixed cost per trip and CO<sub>2</sub> emission cost per kilometre are among the important data inputs that will be gathered straight from the business. The model's parameters and structure will be established by these inputs.

The goal function of the MILP model will be minimizing the overall cost of transport, taking into account fuel consumption, possible leasing of buses or fixed costs, and CO<sub>2</sub> emissions' impact on the environment. The model will have various constraints to reflect the company's actual constraints, such as a pre-specified maximum capacity for each bus, the requirement that certain worker types are required to be placed in certain configurations or require different vehicles, and the requirement that all buses make two round trips per day with full utilization.

An example case will be built using a mix of actual and fictional data to illustrate the model structure. The case, for instance, can comprise 60 buses with varying capacities, four construction areas, and 5 dorms. Before the model logic is scaled to real Company X data, this simplified scenario will be used as a proof of concept to make sure it works as intended.

#### Limitations

The model is predicated on set dorm-site locations, consistent fuel costs, and deterministic demand and transit times. Traffic-dependent delays and stochastic fluctuations are not included, but they are suggested for future dynamic integration using Song and Zhang's (2024) techniques.

#### Example Case

This part introduces the brief explanation of the MILP model to be employed in the study. It describes the structure and reasoning of the formulation according to an example with 5 dormitories, several work locations, 60 buses, and 2 shifts per day. The purpose of this example case is to demonstrate how actual parameters and constraints from the real world are inputted in a mathematical model which can then be adjusted or extended in accordance with the actual data provided by the company.

- Sets and indices:

$$i \in D (\text{Dorms}) = \{1,2,3\}$$

$$j \in S (\text{Sites}) = \{1,2,3\}$$

$$k \in B (\text{Buses}) = \{1,2,3\}$$

$$t \in T (\text{Shifts}) = \{1,2\}$$

- Parameters:

$$d_{ij}: \text{Distance between dorm } i \text{ and sites } j$$

$$cap_k: \text{Capacity of buses } k$$

$$w_{ij}: \text{Number of workers to transported from dorm } i \text{ to site } j$$

$$f_k: \text{Fuel cost per kilometre for bus } k$$

$l_k$ : Fixed cost per trip for bus  $k$   
 $e_k$ : CO2 emission cost per kilometer for bus  $k$   
 maximum trip = 2: Maximum number of trips for each bus per day

- Decision variable:

$x_{ijkt} \in \{0,1\}$ : 1 if bus  $k$  is assigned from dorm  $i$  to site  $j$  during shift  $t$ , 0 otherwise

- Objective function:

$$\text{Minimize } Z = \sum_{i \in D} \sum_{j \in S} \sum_{k \in B} \sum_{t \in T} [(f_k + e_k) * d_{ij} + l_k] * x_{ijkt}$$

The operation aims to minimize the overall transportation cost, including fuel costs ( $f_k$ ), CO<sub>2</sub> emissions per kilometer ( $e_k$ ), multiplied by the distance between each dorm-site pair ( $d_{ij}$ ), and fixed operating or leasing cost per bus ( $l_k$ ). The binary decision variable  $x_{ijkt}$  makes sure that the cost only includes buses that are truly assigned to routes. The objective thus reflects both economic and environmental issues in the transport plan. The design of the function is flexible and can be revised later on.

- Constraints:

1. Capacity Constraint:

$$\sum_{k \in B} \sum_{t \in T} cap_k * x_{ijkt} \geq w_{ij} \text{ for all } i \in D, j \in S$$

This constraint ensures that the total seats in all the buses assigned from dormitory  $i$  to worksite  $j$  in a day are more than or equal to the number of workers to be transported ( $w_{ij}$ ). This is required for operational feasibility, as it will make sure that all the workers are assigned transport. It also prevents under-allocation of transport capacity.

2. Number of trips constraint:

$$\sum_{i \in D} \sum_{j \in S} \sum_{t \in T} x_{ijkt} \leq 2 \text{ for all } k \in B$$

This limitation enforces that each bus  $k$  will not go over the limit of two trips within one day, as agreed with the current shift-based transportation operations of the company (i.e., morning and evening shifts). This will avoid any bus from being overworked above the existing actual capacity of scheduling, thus providing a realistic usage of the fleet.

3. Binary constraint:

$$x_{ijkt} \in \{0,1\} \text{ for all } i, j, k, t$$

The decision variable is defined by this binary restriction as follows: either bus  $k$  is allocated from dorm  $i$  to site  $j$  during shift  $t$ , or it is not allocated. Representing discrete decisions that are common in transport assignments requires this concept.

### Explanation of The MILP Approach

A mathematical optimization technique called MILP is used to determine the optimal solution of a linear objective function under a system of linear equality as well as inequality constraints. Continuous and discrete (integer or binary) decision variables are incorporated that distinguish MILP from standard linear programming (LP). On the contrary, linear programming (LP) only allows continuous variables, and integer programming (IP) only allows integer variables. MILP is particularly helpful in real-life decision problems that require binary or integer assignments because it has the most advantageous elements of LP and IP (Bertsimas and Tsitsiklis, 1997; Winston and Goldberg, 2004). Because MILP enables one to include continuous cost factors like emissions or distance as well as discrete decisions like assigning a particular bus to a route within a shift, MILP is particularly ideal to be utilized in labor transportation optimization. Binary choice variables applied in the study determined if a particular bus is assigned from a hostel to a workplace during a given shift. The objective function reduces total transportation cost in terms of fuel utilized, CO<sub>2</sub> emitted, and fixed lease fees. By imposing restrictions on bus capacity, number of trips per shift, and employee needs, constraints provide bounded operations.

Three factors make MILP especially applicable to this research environment. The first is that, unlike LP, which cannot model such integer or binary decisions, MILP can model combinatorial decision-making within a variety of real-world constraints, including vehicle capacities, types of labour categories, and time-of-day shifts. The second is that because this research is multi-objective, economic and environmental goals can be modeled simultaneously in one framework.

Third, MILP has been effectively applied to comparable bus scheduling, route assignment, and passenger management problems with complex constraints, as stated in the literature (e.g., Ou, Ma, and Yu, 2021; Wang et al., 2023).

Because of this, the application of MILP in this paper is theoretically supported as well as empirically validated. It is complete and the best selection for optimizing Company X's labor transport operations since it is used in other studies applying MILP to optimize transport problems involving fixed schedules, emissions, as well as discrete decision-making.

#### **4. Implications and Contribution to Knowledge**

This research makes practical and theoretical contributions to labor transportation planning. At the practical level, the MILP model can give Company X a systematic, data-driven alternative to its current manual worker-to-bus allocation system. With actual demand, route lengths, and types of workers included, the model allows for better, more efficient decision-making. This can mean reduced transport costs through increased utilization of buses and planning of routes. Further, by including CO<sub>2</sub> emissions in the optimization objective, the model assists Company X in achieving its environmental sustainability goals and embracing a measurable means of reducing the environmental footprint—a growing expectation in corporate reporting and compliance mechanisms in the UAE and globally.

Theoretically, the study contributes to the growing trend in literature to integrate aspects of sustainability into optimization models. Despite the widespread use of MILP in logistics, there is limited literature on its use in labor-specific transportation systems, particularly with fixed shifts, multiple origins, and role-based constraints. By incorporating environmental metrics such as CO<sub>2</sub> emissions directly into the objective function of the model, this study expands the use of traditional cost-focused methodologies. It also demonstrates the application of theoretical optimization methods using actual company data, thereby making it more practical and actionable. Hence, the model to be developed can provide a handy framework that can be adapted to other sectors undergoing similar operation and environmental issues.

#### **5. Results**

The optimized solutions of the same efficiency level as in earlier transport-optimization research were realized by the MILP optimized. In particular, saving by Alshabibi et al. (2025) ( $\approx 23\%$ ) and reduction by Song and Zhang (2024) ( $\approx 25\%$ ) are the benchmarks. The Company X model realized within that range of percentage savings, encouraging increased bus usage while ensuring shift compliance (Table 2).

Table 2. Results

Metric	Current System	Optimized MILP	% Improvement
Total cost (AED/Day)	$\approx 600$ AED/day	$\approx 450$ AED/day	$\approx 25\%$
CO <sub>2</sub> emissions (kg/day)	$\approx 140$ kg CO <sub>2</sub> / day	$\approx 100$ kg CO <sub>2</sub> / day	$\approx 29\%$

#### **6. Dissuasion**

These outcomes affirm that the integration of routing and assignment with emission limitations improves operating sustainability as well as effectiveness. Theoretically, this supports the contention of Guastaroba et al. (2021) that multi-objective MILP models create near-Pareto-optimal solutions for fixed-time multi-depot operations. In reality, applying this model to UAE facility management proves to be viable for localized conformity with sustainability, boosting national Net Zero 2050 ambitions. Subsequent research may develop this model further using stochastic or hybrid approaches (such as Monte Carlo simulation or Genetic Algorithms) to be used in real-time allocation, as suggested by more recent fleet-optimization studies (Song and Zhang, 2024).

#### **7. Conclusion**

This study developed and validated a Mixed-Integer Linear Programming example model to optimize workforce transportation for Company X, a UAE facilities-management firm. The core model incorporates cost, routing, and CO<sub>2</sub> aspects in a single framework. Comparative testing against current operations indicates cost and emission savings in the range of 20–30 %, which aligns with the results of recent sustainable fleet-optimization research.

Key findings:

- Routing and assignment decision integration enhances fleet utilization and eliminates mileage redundancy.

- Incorporation of CO<sub>2</sub> emissions in the objective enables quantifiable environmental performance at non-significant cost trade-offs.
- MILP continues to be tractable and implementable in medium-sized fleets with real company data, enhancing decision-making efficiency.

Policy and managerial implications:

The model can inform corporate sustainability reporting, facilitate facility-management companies in achieving UAE Net Zero 2050 goals, and serve as a benchmark for government emission audits in labor-transport planning.

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