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Sustainable Vehicle Routing: Optimizing for Gender Equality

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Abstract. The lack of gender diversity has been a longstanding issue in the logistics industry. Female workers only account for a small percentage of the total workforce in the logistics industry, especially in the transport section. Despite the clear benefits of promoting gender diversity and equality, the research work examining the gender dimension of transport planning is still lacking. This study proposes a vehicle routing approach that helps reduce or limit the gender-differentiated impacts during delivery operations that may discourage women from labor force participation. While maintaining the traditional vehicle routing context, the proposed mixed-integer linear programming model can generate more preferable work conditions for female drivers by minimizing the penalty cost associated with the operational risk and the excessive energy expenditure. The proposed model can generate a route plan with a good balance between economic performance and motivating work conditions for female drivers., This research contributes to expanding the current sustainability vehicle routing literature by addressing the UN's sustainable development goal regarding gender equality.

Keywords: Gender equality, logistics, sustainability, sustainable development goal, vehicle routing, optimization.

1. Introduction

Gender equality and women's empowerment are the core components of fundamental human rights protection and sustainable development of society [1]. Recently, the strategic approach of how to achieve gender equality is defined in a more systematic way along with other UN sustainable development goals (SDGs) [2]. The need for comprehensive frameworks for evaluating gender equality is being addressed [3]. Global gender equality has progressed over multiple aspects according to the Women, Business, and the Law index [4], following the worldwide reformation of legislation and societal regulations concerning women's rights. At any rate, the global labor force participation rate for women has not improved much since 1990. Greater efforts are needed at every level to ensure greater access to employment and economic opportunities for women.

Gender equality is an important factor affecting logistics performance [5]. Possessing more female drivers in the workforce also results in greater flexibility to execute operations requiring female representatives. Broader gender diversity at the management level tends to result in the more successful implementation of logistic firms' eco-friendly practices and higher environmental performance [6]. However, the gender balance target in employment opportunities in logistics and supply chain management is still far from being reached [7]. The operational workforce of the logistics industry is quite male-dominated [8]. The gender equality issues are more pronounced in low and middle-income countries where the indicators and tools for measuring gender equality and women's involvement in the logistics workforce are still lacking [3].

In the transport and logistics industry, the factors that affect women's employment decisions are the lack of opportunities and support [9]. Women also have a poor perception of the working conditions in the logistics industry [10]. To promote gender equality and women's empowerment in the transport and logistics industry, work conditions with reduced gender-differentiated impacts need to be created first, allowing female drivers to engage in vocational activities in a more well-being conducive manner. The differences between groups of workers and their special needs must be recognized [11]. The less impact on female drivers is in line with the principle of gender equality principle which suggests that career advancement opportunities and compensation for disadvantages shall be given to the under-represented gender to stimulate broader gender diversity in the workforce [12]. In general, the gender-differentiated impacts are mainly caused by the gendered differentials in physical abilities and social orientation. In comparison to men, women have a lower energy expenditure limit [13, 14]. Women are also more likely to be assaulted or sexually abused [15].

In this study, we attempt to create work conditions where female drivers are less exposed to risks and excessive workload. The risks being considered are associated with the risk of becoming a victim of crimes such as sexual harassment, physical assault, and robbery. Regarding workload, the cumulative physical workload limitations in male and female drivers are considered in terms of allowable daily energy expenditure. A mixed-integer linear programming model is formulated to control the accumulated risk and energy expenditure over the working period. The major contribution of this paper is to be the first to develop a vehicle routing approach that promotes gender equality by achieving outcomes with reduced gender-differentiated impacts.

The remaining of this study is organized as follows. Section 2 presents the relevant literature on sustainable vehicle routing problems (VRPs). The social sustainability in VRP and the research gap related to gender equality consideration are discussed. Section 3 provides the problem description. Section 4 shows how the model is formulated. Section 5 presents the analysis results. In Section 6, the paper ends with a conclusion and discussion about the limitation of the research and future research direction.

2. Relevant Literature Review

Similar to other applied Operations Research problems, the sustainability performance of VRP is originally examined based on the three pillars: economic, environmental, and social. A large body of sustainable VRP and freight transport literature focuses on the economic and environmental aspects only [16, 17]. The amount of CO_2 emissions is commonly used as the environmental impact indicator. The main factors influencing the increase of transport-related CO_2 emissions are the sequence of customer visits and the vehicle and traffic conditions. Driving behavior has been examined as one of the driving factors of carbon emissions as well [18]. In some previous VRP studies, CO_2 emission is used as a proxy for social impact as it is assumed to be a negative contributor to society [19, 20].

The sustainable VRP literature has shown a trend in the improvement of social impact consideration that is more specific and diverse in terms of the definition of the stakeholders and the social impact involved. The VRP for a waste collection system proposed by Ramos et al. [21] focuses on improving the well-being of drivers by minimizing their working hours. The local community has also been shown to be another important stakeholder group that can be affected by vehicle routing decisions in terms of opportunities and health risks. Hanan and Malika [22] develop an optimization model for facility location and routing decision-makings that maximize the job opportunities in an urban freight distribution network. The sustainable VRP proposed by Grosso, R., et al [23] aims to limit the access of freight vehicles to certain urban areas during certain periods to avoid creating excessive congestion and pollution emissions. In the study by Yan Sun [24], the mixed-integer nonlinear programming model contains an objective of reducing the risk of the population's exposure to hazardous materials. Some recent studies show that previous sustainable VRPs tend to take into account public benefits and broader stakeholder interest for social impact evaluation. Dukkanci et al. [25] propose a sustainable VRP that ensures improved welfare for drivers and customers through equitable payment and delivery time. Their model also enhances the company's cost efficiency and environmentally conscious reputation. The sustainable waste collection approach by Tirkolaee et al. [26] simultaneously enhances job opportunities for local communities and a more balanced workload among the workers.

According to the current sustainable VRP literature, the social impact consideration has been more specific and refined [27]. At any rate, the examination of social impacts under the VRP context is still an evolving area of research that remains widely undiscovered. To our knowledge, the consideration of gender equality is still missing from the existing literature related to route planning and logistics optimization. To fill the gap, this study introduces the VRP model that strengthens gender equality and women's empowerment through improved work conditions for female drivers. The model can be used to find opportunities for reducing the gender-differentiated impacts on female drivers in a VRP.

3. Problem Description

Our numerical case of a two-tier goods distribution network is used. The distribution network comprises multiple customer locations that receive orders from a depot. The daily route of a fleet of the same type of vehicles is determined for 1) day-time delivery drivers (6 AM to 6 PM, 12 hours) and 2) night-time delivery drivers (6 PM to 6 AM, 12 hours). The gender of drivers is the only heterogeneity variable of interest. For both shifts, male and female drivers are entitled to their regular wage rates for work during the first 8 hours and overtime rates (1.5 times the regular rate) for every hour beyond that. The transportation risk for each route is specified on a scale from 1 to 5, with 1 being the lowest risk level and 5 being the highest risk level. In practice, the risk can be estimated based on various parameters that cause unfavorable working conditions such as accidence, sexual harassment, physical assault, and robbery. The risk during the night shift is generally higher than that during the day shift in general.

In the proposed model, wage and fuel costs are also taken into account to ensure the cost-effectiveness of the route planning outcomes. The social sustainability impact is assessed in terms of the risk penalty cost and over-workload penalty cost. The risk penalty cost is calculated from the accumulated risk value of drivers and the risk penalty cost coefficient. The workload associated with tasks; driving and unloading/loading products, performed by drivers is estimated in terms of energy expenditure (Kcal). The daily energy expenditure beyond the limits for male and female drivers is also translated into penalty cost using the excessive workload penalty cost coefficient. In this study, the penalty cost coefficient values are assumed to be significant but much less than the fuel and wage costs. In practice, the values of these coefficients can be estimated and adjusted according to their share of the firm's past expenses related to the loss of manhours, medical treatment, accidents, and the cost of insufficient gender diversity at the workplace.

4. Mathematical Model Formulation

The assumptions used to simplify the problem are presented in Section 4.1. The modeling details including the indices, parameters, decision variables, objective function, and constraints are presented in Section 4.2.

4.1. Assumptions

- The need to assign drivers 1) to handle excessive workload burden and 2) to work in high-risk areas negatively affects the well-being of drivers.
- Female drivers have a lower level of tolerance to the aforementioned negative factors.
- The demand and the location of customers are known.
- For some destinations, loading/unloading tasks need to be performed by drivers.
- Energy expenditure occurs when drivers engage in driving and loading/unloading tasks.

4.2. Model Formulation

4.2.1. Indices

D A depot ($D = D0$)
C Set of customers ($C = C1, C2 \ldots Cn$)
N Set of all nodes ($N = D \cup C$)
K Set of vehicles (or drivers) ($K = k1, k2, k3 \ldots kn$)
G Diver gender (f = female driver and m = male driver)
T Set of shifts (1 = day shift and 2 = night shift)

4.2.2. Parameters

d_{ij} Travel distance from nodes i to j (km)
ca_k The capacity of vehicle k (kg)
de_i Customer demand (kg)
R^t_{ijk} The level of risk of vehicle k associated with the usage of route (i, j) during shift t
B A big number

** Cost parameters ($)*
fc_k Fuel cost per km of vehicle k
tc_k The regular wage per hour of driver k (during the first 8 hours of each shift)
lc_k The extra payment for unloading/loading product of vehicle k
oc_k The hourly overtime wage of driver k
rc_k The risk penalty cost coefficient of driver k
ec_k The penalty cost coefficient of excessive energy expenditure for vehicle k

** Time parameters (hr)*
tt_{ij} Travel time from nodes i to j
st_k The starting time of vehicle k
at_i The time spent by a vehicle at node i
ut Unloading/loading time per unit (hr)

** Energy expenditure parameters*
E_k Daily energy requirement for driver k (Kcal)
co_k The number of calories spent for unloading/loading (Kcal/unit)
ce_k The number of calories spent for driving (Kcal/hr)

4.2.3. Decision Variables

X_{ijk} 1 if vehicle k travels from nodes i to j, 0 otherwise
RL_{ijk} The remaining load quantity while vehicle k travels from nodes i to j (kg)
PD_{ik} The number of units of product delivered to node i by vehicle k (kg)
RV^t_{ijk} The risk value when driver k travels from nodes i to j at shift t
SR_k The total transportation risk experienced by driver k
OT_k The number of overtime hours worked by driver k (hr)
TDT_k The total driving time of driver k (hr)
AT_{ik} The arrival time of vehicle k at node i (hr)
UW_k The number of calories spent by driver k when unloading products (Kcal)
CE_k The number of calories spent by driver k when driving (Kcal)
EN_k The total energy expenditure by driver k (Kcal)
$PC1$ The total penalty cost for excessive workload ($)
$PC2$ The total penalty cost for safety risk ($)

4.2.4. Objective Function

The objective function (A0) is to minimize the total cost including the salary of drivers (A1), fuel cost (A2), and the penalty cost associated with excessive workload burden (A3) and safety risk (A4).

Minimize $TC = SC + FC + PC1 + PC2$ (A0)

Wage cost

$$SC = \sum_{k\in K}(TDT_k - OT_k)\times tc_k + \sum_{k\in K} OT_k \times oc_k + \sum_{i\in C}\sum_{k\in K} PD_{ik}\times lc_k \quad (A1)$$

Fuel cost

$$FC = \sum_{i,j\in N}\sum_{k\in K} X_{ijk}\times fc_k \times d_{ij} \quad (A2)$$

The penalty cost for excessive workload

$$PC1 = \sum_{k\in K}(EN_k - E_k)\times ec_k \quad (A3)$$

The penalty cost for safety risk

$$PC2 = \sum_{k\in K} SR_k \times rc_k \quad (A4)$$

4.2.5. Constraints

Constraints (C1) and (C2) ensure that vehicles depart at the depot and return to the depot after finishing their trip.

$$\sum_{j\in C} X_{ijk} = 1 \quad \forall i\in D,\ \forall k\in K \quad (C1)$$

$$\sum_{i\in C} X_{ijk} = 1 \quad \forall j\in D,\ \forall k\in K \quad (C2)$$

Constraint (C3) is the flow conservation on each node.

$$\sum_{\forall j\in N, j\neq i} X_{ijk} - \sum_{\forall j\in N, j\neq i} X_{jik} = 0 \quad \forall i\in N, \forall k\in K \quad (C3)$$

Constraint (C4) ensures that each node is served by one vehicle.

$$\sum_{\forall j\in N, j\neq i}\sum_{k\in K} X_{ijk} = 1 \quad \forall i\in C \quad (C4)$$

Constraint (C5) ensures that vehicles can not revisit the same nodes on a route.

$$X_{ijk} = 0 \quad \forall i,j\in N,\ i=j, \forall\ k\in K \quad (C5)$$

Constraints (C6) and (C7) determine the remaining load quantity when vehicle travels between nodes.

$$X_{ijk}\times B \geq RL_{ijk} \quad \forall i,j\in N,\ i\neq j, \forall k\in K \quad (C6)$$

$$\sum_{\forall j\in N, j\neq i} RL_{jik} - \sum_{\forall j\in N, j\neq i} RL_{ijk} = PD_{ik} \quad \forall i\in C, \forall k\in K \quad (C7)$$

Constraint (C8) shows that the total number of products of all vehicles is equal to the customer demand.

$$\sum_{k\in K} PD_{ik} = de_i \quad \forall i\in C \quad (C8)$$

Constraints (C9) and (C10) define the vehicle capacity.

$$RL_{ijk} \geq de_i \times X_{ijk} \quad \forall i\in N, \forall j\in C, \forall k\in K \quad (C9)$$

$$RL_{ijk} \leq (ca_k - de_i)\times X_{ijk} \quad \forall i,j\in N,\ i\neq j, \forall k\in K \quad (C10)$$

Constraints (C11), (C12), and (C13) determine the arrival time of the vehicle at each node and the total driving time of the driver.

$$AT_{jk} = \mathrm{st}_k + \mathrm{t}_{ij} + de_j\times ut + a_i \times X_{ijk} \quad \forall i\in D, \forall j\in C,\ i\neq j, \forall k\in K \quad (C11)$$

$$AT_{jk} = \mathrm{AT}_{ik} + \mathrm{t}_{ij} + de_j\times ut + a_i \times X_{ijk} \quad \forall i\in C, \forall j\in N,\ i\neq j, \forall k\in K \quad (C12)$$

$$TDT_k = \sum_{i,j\in N, i\neq j} X_{ijk}\times t_{ij} \quad \forall k\in K \quad (C13)$$

Constraint (C14) calculates the overtime of driver.

$$OT_k = AT_{0k} - lt_k \times X_{i0k} \quad \forall i\in C, \forall k\in K \quad (C14)$$

Constraint (C15) calculates the calories spent when loading/unloading products.

$$\mathrm{UW}_{ik} = PD_{ik}\times co_k \quad \forall i,j\in C,\ i\neq j, \forall k\in K \quad (C15)$$

Constraint (C16) calculates the calories spent when driving.

$$CE_k = TDT_k \times ce_k \quad \forall k\in K \quad (C16)$$

Constraint (C17) calculates the total energy spent

$$EN_k = \sum_{i\in N} UW_{ik} + CE_k \quad \forall k\in K \quad (C17)$$

Constraints (C18), (C19), and (C20) determine the risk value when a driver travels between nodes at each shift and the total transportation risk

$$RV^{t=1}{}_{ijk} = X_{ijk}\times R^{t=1}{}_{ij(k=f)} + X_{ijk}\times R^{t=1}{}_{ij(k=m)} \quad \forall i,j\in N,\ i\neq j, \forall k\in K \quad (C18)$$

$$RV^{t=2}{}_{ijk} = X_{ijk}\times R^{t=2}{}_{ij(k=f)} + X_{ijk}\times R^{t=2}{}_{ij(k=m)} \quad \forall i,j\in N,\ i\neq j, \forall k\in K \quad (C19)$$

$$SR_k = \sum_{i,j\in N, i\neq j}\sum_{t\in T} RV_{ijk}{}^{t} \quad \forall k\in K \quad (C20)$$

Constraints (C21) and (C22) are used by the regular VRP model to calculate the penalty costs for excessive workload and safety risk, respectively.

$$PC1 = \sum_{k\in K}(EN_k - E_k)\times ec_k \quad (C21)$$

$$PC2 = \sum_{k\in K} SR_k \times rc_k \quad (C22)$$

Constraints (C23) and (C24) are the non-negative and binary variables.

$$RL_{ijk}, PD_{ik}, RV^{t}{}_{ijk}, SR_k, OT_k, TDT_k, AT_{ik}, UW_k, PC1, PC2, CE_k, EN_k \geq 0 \quad \forall i,j\in N, \forall k\in K, \forall t\in T \quad (C23)$$

$$X_{ijk} = \{0,1\} \quad \forall i,j\in N,\ i\neq j, \forall k\in K \quad (C24)$$

Table 1. The wage and fuel costs of regular VRP and proposed VRP.

Cost ($)	Regular VRP	Proposed VRP
Fuel	760.86	763.02
Wage	354.71	357.13
Total	1115.57	1120.15

Table 2. The penalty cost of the proposed VRP.

Penalty Cost ($)		Regular VRP	Proposed VRP
Penalty	Workload	197.15	185.04
	Risk	176.85	135.06
	Total	374.00	320.64

5. Analysis Results

The proposed mixed-integer model is coded in Python 3.8 platform and solved using Gurobi. The results of the proposed model are compared and contrasted against those of the regular VRP. As shown in Table 1, the fuel and wage costs of the proposed model are slightly higher than those offered by the regular model. However, the proposed model yields lower penalty costs, as shown in Table 2. This means that the proposed VRP model can reduce the excessive workload and risk burden for the entire workforce. It must be noted that the penalty costs are not part of the cost minimization objective of the regular VRP. The penalty costs associated with the regular VRP's optimal solution are shown in the constraints (C21), and (C22), allowing the direct comparison to the solution of the proposed model.

In Table 3, the average workload (Kcal) and average (accumulated) risk values of male and female drivers are shown. In the last row of the table, the normalized risk scores are calculated based on the average risk values. A score of 1 represents the average risk experienced by the entire workforce. By using the proposed model, the reduction in the average workload and risk values can be observed for both genders, particularly for female drivers.

6. Conclusion and Discussion

VRP approach with reduced gender-differentiated impacts is proposed for the first time in this study. This study incorporates the gender-differentiated limits into route planning optimization, providing a more preferable working condition for female drivers. The main contribution of this study is that it proposes a novel sustainable vehicle routing model that promotes gender equality in logistics. The studying analysis gives an insight into the possible cost tradeoffs for providing female drivers with more preferable working conditions with the ultimate goals of improving their well-being and increasing gender diversity within the workforce.

Table 3. The impacts of regular and proposed VRPs.

	Regular VRP		Proposed VRP	
Gender	Female	Male	Female	Male
Average workload (Kcal)	681.83	586.13	538.15	706.90
Avg risk	13.00	14.00	9.33	11.25
Normalized risk score	0.96	1.03	0.89	1.08

In this study, the gender-differentiated impacts are translated into the penalty costs, being minimized by the single objective function. The penalty cost coefficients can be adjusted to better reflect the actual direct and indirect cost components incurred by the company from the excessive workload and risk burden experienced by the drivers. Various multi-objective techniques are also available to be used when it is desirable to set up the impacts as separated main optimization objectives.

While the burden on female drivers can be reduced, attention must be given to male drivers as well, as their average normalized risk score can be higher, as shown in the results. Regarding the driver wage, male drivers gain more income on average in our example case, due to the higher energy expenditure limit and more loading/unloading tasks that they can perform. It is important to address the need for female drivers to do certain tasks to make up for the lower income under the less-impact plan generated by the proposed model. This will result in efficient workforce utilization and improved job retention for female drivers. Other areas of improvement to be addressed in our future study include

- the accounting of carbon emissions or other environmental impacts
- the use of a larger problem or a real case study
- more decision-making factors and uncertainty
- further exploration and integration of gender inequality issues that may exist in logistics operations.

- how to achieve gender equality together with other sustainable development goals that are relevant to the geographical location of interest
- the consideration of synergies and trade-offs among some of the SDGs [28] in the context of vehicle routing and related supply chain problems.
- a wider integration of all three decision levels: strategic, tactical, and operational
- the strengthening of the linkages between the sustainability impacts and urban characteristics

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