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Analysing wholesale market development strategies for decongesting city centre considering retailers' procurement choices

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ABSTRACT

This research is aimed at developing a method for relocating wholesale markets in a city with the objective of decongesting the central area by improving the traffic efficiency and to make it pollution free. This paper proposes a bi-level optimisation framework pursuing the local authority's objective of maximising welfare benefits relative to the spend ensuring good value for money at the upper level. The lower-level framework considers retailers' response to the relocation of wholesale markets allowing them the choice of procurement location. The lower-level problem also models the route choice of commercial vehicle traffic as well as the private vehicle traffic to measure the resulting on-street congestion. The bi-level problem has been solved with integer Particle Swarm Optimisation algorithm for the case of Bandung, Indonesia. The results show that relocating wholesale markets improves the city centre traffic efficiency and pollution level by about 14%. Traffic speeds over the entire city also improve by up to 6.6% and the pollution levels marginally would drop too. Market relocation as a strategy would significantly improve the efficiency and pollution levels but must be carefully planned and evaluated otherwise the emissions outside of city centre could increase.

1. Introduction

Wholesale markets also known as *wet markets* have their origins as old as the cities themselves. In the beginning, wholesale markets were set up to serve the needs of people and thus were typically located in the inner-city areas which are easily accessed by all. It is true that the arrival of modern commerce with efficient supply chain linked to supermarkets/hypermarkets, app-based ordering, e-deliveries alter how the consumers get their groceries and other supplies thus changing the entire industry (TRAN, 2023). Nevertheless, traditional wholesale markets are still relevant to cities of many countries especially for certain commodities like sea food, agriculture/fresh produce (Morganti and Gonzalez-feliu, 2015; Negi and Anand, 2018). This is particularly true in many cities around the world, e.g. Asian cities like Bangkok (Suraraksa and Shin, 2019), Hanoi (Cadilhon et al., 2003), Chennai (Subramanian et al., 2023), Istanbul (Sayin, Ozkan and Ceylan, 2011), South American cities such as Sao Paolo (Guerin and Vieira, 2018) and African cities like Cairo (AlSadaty et al., 2021). Wholesale markets not only act as an important trading hub for wholesalers and retailers but also act as a cultural and culinary icon in the historic city centre areas.

Unprecedented urbanisation and economic growth in cities dramatically increased the production and consumption of goods resulting in changes to the wholesale markets in terms of how/where they operate from relative to the city development (Ofori, 2013). The location of wholesale markets in city centre poses a particular challenge to the local authority concerned. The growth of cities resulted in historic city centres becoming denser ever (Gardrat, 2021). As a result, city centres became very crowded and traffic congestion occurs on a recurrent basis during rush hours causing significant economic loss (Ros-McDonnell et al., 2018). Congestion also raised the level of emissions in central areas decreasing the overall liveability of cities (Shen et al., 2020). Facing with the problems, many local authorities intend to develop new markets away from city centre in a bid to improve the overall quality of living (Aljohani and Thompson, 2018; Dey and Mazumber, 2006; Tennoy, 2020). Despite the aspirations of local authorities there is not much research to support the wholesale market locations making their attempts seemingly ad-hoc.

Literature on urban goods movement is abundant, but, interestingly, very little work was done on wholesale markets. For instance, many works consider the location of warehousing as part of logistics facilities planning and assess whether to move them to outskirts of a city (Dablanc, Ogilvie and Goodchild, 2014; Sakai, Kawamura and Hyodo,

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2015; Strale, 2020). Some refer to this phenomenon as logistics sprawl which is a side-issue to this paper, but it is noted that such relocations are primarily driven by private sector businesses to improve supply chain for competitive advantage (Onstein et al., 2019). However, the case of wholesale market location is completely different as it plays a pivotal role in public policy planning by local governments which is motivated by the objective of improving welfare for all members of the society (Aljohani and Thompson, 2018; Guerin and Vieira, 2018; Krzysztofik et al., 2019). Several others (Shahabi et al., 2013; Jong et al., 2016; Heitz, Launay and Beziat, 2019) focused on urban consolidation centres which indeed reduce the goods traffic flow on city roads but the wholesale markets have an entirely different character with interactions taking place between major stakeholders such as retailers and wholesalers (Nugroho et al 2021).

Wholesale market acts as trade location between wholesalers and retailers. Wholesalers are typically small and medium enterprises with limited capital/resources and deal with customers buying in bulk (Cadilhon et al., 2003). Note that the wholesale market is a location where many wholesalers aggregate to gain a competitive advantage. On the other hand, retailers operate small businesses, often their own, making procurement decisions almost on every day. Retailers prefer wholesale markets for the attractive prices and the ease of moving goods besides being able to inspect the quality of product before buying. Retailers usually purchase goods directly from wholesalers and carry the goods themselves by their own vehicle to keep the costs low (Comi and Nuzzolo, 2014). It is also possible to arrange shipments by the wholesalers which may be chargeable in some cases, yet the shipments may start from the wholesale market since it also acts as a warehouse for wholesalers.

In this context, local authorities need to choose the location of wholesale markets carefully as they can affect the traffic patterns and hence the traffic emissions in the entire city. Also, the local authority should consider how big the market can be depending on the availability of land. Then the local authority should weigh up the benefits against the cost of developing new markets. To aid the local authority's decision making, this paper proposes a model incorporating wholesale market location exploration together with transport interactions within an optimisation framework. The model captures the objective of local authority to maximise the benefit of developing new markets considering their cost of development. Local authority's decisions on where to locate (depending on land availability) and how many units of wholesalers to accommodate are explicitly modelled. This paper advances the earlier work by accounting for retailers' choice of their wholesale market location, which in turn depends on the wholesale market location decisions. Furthermore, retailers' and other road users' route choices are modelled by considering on-street congestion. In this way the interaction between wholesalers and retailers, and the role of wholesale market as a trade hub are properly captured by the model.

The rest of this paper is organised as follows. Section 2 describes the literature that provides the necessary theoretical background to the modeling framework. Section 3 formulates the optimisation problem and Section 4 describes the steps involved in solving it. Section 5 illustrates the principles with a numerical example involving the network of Bandung city in Indonesia. Section 6 concludes the work.

2. Review of wholesale market relocation problems

There were many attempts in the past to manage freight movements in urban areas by relocating logistic facilities away from city centre albeit they are not wholesale markets (See for example, Aljohani and Thompson, 2018). This transforms the supply chain management translating into changes in volumes of the commodity distribution, traffic flow associated with transportation of commodities, frequency of trips, and the time of freight traffic (Lindholm, 2013). Relocating logistics facilities such as warehouses and urban consolidation centres was primarily motivated for pursuing logistics efficiency by private sector businesses. In comparison, wholesale market relocation is a completely different problem as it falls into the realm of public policy involving a wide range of stakeholders such as local authorities, wholesalers, retailers and also other road users pursuing their own objectives. Wholesale markets are primarily planned/developed by local authorities who may regulate the market by issuing licences to wholesale businesses. Wholesalers want to retain their clientele despite the possible relocation while retailers may have a choice to procure from alternative wholesale market locations. Finally, other road users (private vehicles) are affected by on-street congestion and have a choice of route to avoid congestion. This paper examines the case in which public policy intervention of incorporating logistics functions into land use/transportation planning which is carried out by the local authority considering choices of retailers and road users.

Wholesale markets operate a different kind of supply chain relative to modern commerce entities like supermarket or hypermarket. Wholesale market aggregates many wholesalers in one location to sell a range of commodities often involving sea food/fresh produce dealing in bulk particularly to retailers at bargainable prices (Cadilhon et al., 2006; Sayin, Ozkan and Ceylan, 2011). Unlike a supermarket or hypermarket with coordinated supply chain (See Fig. 1a), wholesale market does not have a single supply chain operated within since each individual wholesaler may have a different supplier and thus different supply chain (Kai, 2019). Fig. 1b shows a wholesale market with typical supply chain and its relationship with suppliers, retailers, and end use consumers. Retailers visit wholesale markets regularly to procure in bulk and transport the goods themselves to keep the costs under control. End-use consumers go to retailers to buy household supplies usually in small quantities which does not get affected by the relocation of wholesale markets in the city.

A few studies have attempted to analyse wholesale market relocations around the world. Perspectives such as economic impact of relocation have been investigated. For instance, Dey and Mazumber (2006) and Morckel (2018) indicated that the wholesale market relocation likely to have significant impact on the economic output of wholesalers. A positive economic outcome may be produced by moving the wholesale market from an isolated location to a more accessible location. Another study by Geng et al (2021) investigated the

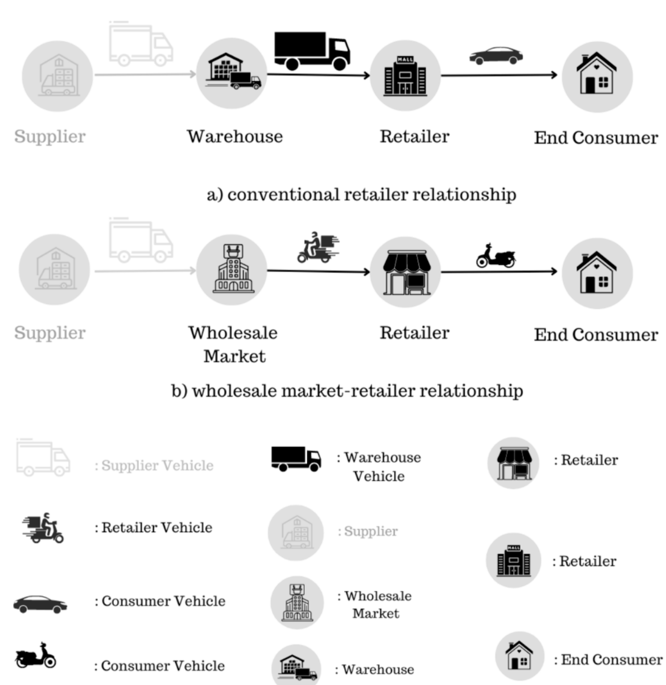

Fig. 1. Schematic relationship between wholesalers and retailers.

willingness of wholesalers to move to a new location and whether a congestion charge would facilitate the move. Aljohani and Thompson, (2018) investigated the impact of wholesale market relocation and found an increase in vehicle-kilometres travelled by both retailers and wholesalers. Some others have investigated the emissions due to relocating wholesale markets which are primarily aimed at freeing up city-centre space for leisure/social use (Tennoy et al 2020).

Critically evaluating the earlier work it is concluded that it had presented a one-sided perspective looking at wholesalers in isolation and did not account for the other side of argument by not considering the choices of retailers. Retailers surely can choose an alternative wholesale market if it suits them better. Neither the impact of local authority's decisions on changing demand patterns nor even the on-street congestion influencing the route choices of retailers/other road users were captured effectively. We believe it is of utmost significance to consider the choices of retailers explicitly as they might choose visiting the town-centre locations for their procurement if the new location is not easily accessible which completely defeats the objective of decongesting city centre. The earlier studies also ignored the perspective of local authority who funds the development of markets and pursue the objective of maximising benefits to all. Thus, in contrast with the earlier studies, our research develops a well-rounded approach by considering retailers' choices embedding the objective of the local authority aiming to optimally locate the new wholesale markets away from city centre. This paper sets out a model from the perspective of a local authority to maximise the benefits for all road users relative to the cost of developing new markets whilst considering the choices of retailers.

This paper applies the method developed for the case of Bandung city in Indonesia. Bandung has many thriving wholesale markets with several retailers spread across, regularly procuring their supplies from wholesale markets. The proposed model is presented in a generalised form and can be adopted to any city where wholesale markets are prominent trade hubs with prevalent independent retailers that make up a significant portion of freight supply chain in the city.

3. Wholesale market relocation problem

Wholesale market relocation decision involves identifying alternative sites as the land availability is a key challenge in many cities around the world. Depending on the size of plot available the number of units per market location can be decided. The location of plot and the number of establishments in a market will influence the cost of development to the concerned local authority. In the light of new markets, retailers will reconsider their choices weighing up the new locations against city centre location which could alter the travel patterns of goods procurement trips. It is known that much of the fresh produce e.g. sea food, agriculture produce sold at wholesale markets comes from outside of the city (Geng et al., 2021), hence the relative position of a market within the city does not affect their pricing. The new travel patterns will thus depend on the relative ease of access to new locations alone. In the light of altered travel destinations, on-street congestion patterns will change too. This will prompt other road users to reconsider their routing (although their O-D pattern does not change) which will affect travel times and overall traffic emissions in the city. All these interactions can be effectively captured in an optimisation framework as specified below.

Bi-level optimisation method perfectly suits the requirements for solving the wholesale market location problem as shown in Fig. 2. The upper level identifies the number of establishments at each existing market location as part of the set up. The inputs then specify new locations and the possible maximum number of wholesaler units at each location. Yet, the actual numbers to locate at each new market are to be determined by the optimisation model subject to available plot sizes. Clearly, *spatial location of market* and *the number of establishments* at *each location* are the upper-level decision variables. The upper-level decisions influence the retailers' *procurement (supplier) location choice* and the *route choices of all road users* including retailers and private motorists which have been considered at the lower level of bi-level problem.

The upper-level problem defines the objective of local authority seeking to maximise the *Benefit Cost Ratio* (BCR) (ψ). The BCR value in the objective function depicts the aspiration of local authority to achieve the best value for money spent. BCR is calculated by dividing the present value of benefits with the present value of costs. The BCR can aid efficient budget allocation decisions especially useful in public policy making situations. BCR value of $\gg 1$, indicates the economic worth of implementing a project. The BCR is a suitable objective function for this problem since it can consider the cost efficiency and can capture the budget constraint accurately compared to other indicators such as the Net Present Value (Bray and Tisato, 2007).

Objective function of the upper-level problem can be written as below:

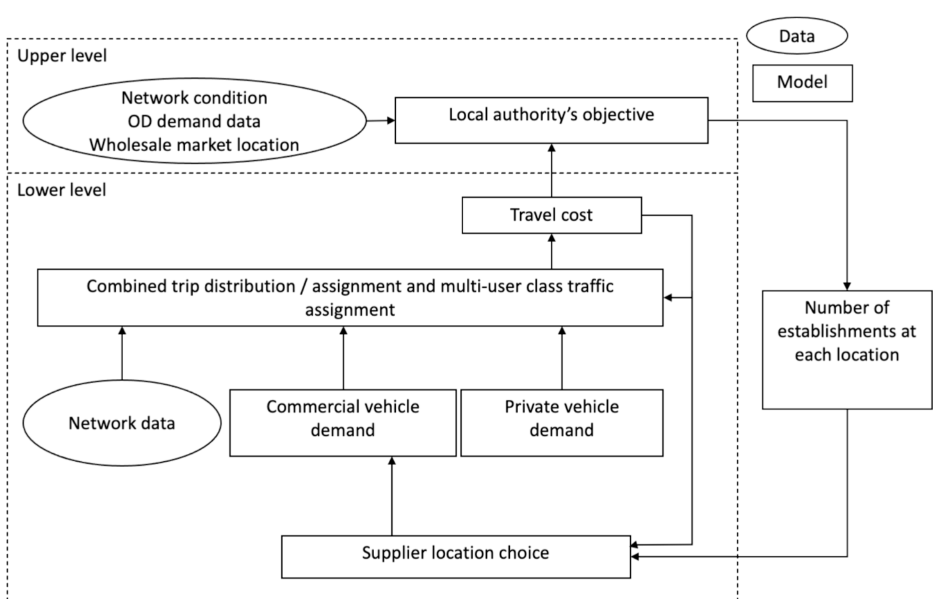

Fig. 2. Bi-level model with interactions between local authority decisions and retailer/ road user responses.

$$\max\psi(n_s) = \frac{\left[\sum_{i\in I}\sum_{a\in A} c_a^{i,0} v_a^{i,0}(n_s^0)\right] - \left[\sum_{i\in I}\sum_{a\in A} c_a^{i,1} v_a^{i,1}(n_s)\right]}{\sum_s Inv_s \times n_s} \tag{1}$$

Sendix shows the full notation and specifies the lower-level problem, but we explain Equation (1) here to progress the exposition. Numerator of the objective function depicts the benefit as the difference in total travel cost between *Business As Usual* (BAU, superscripted '0') and *do-something* (superscripted '1') cases as incurred by both commercial and private vehicles in the entire urban road network. Total travel cost is obtained by multiplying the link cost (c_a^i) with link-based vehicular volume (v_a^i) and summing it over all links of the network. The BAU refers to the case in which the local authority lets the wholesale markets to grow/ operate from where they are, whilst the do-something refers to alternative relocation strategies introduced later in Section 5.2. The difference in total travel cost between BAU and do-something cases is equal to the overall *benefit* gained by all types of road users.

The denominator in Equation (1) represents the total investment cost for all locations which is a function of the number of establishments at each location (n_s) and the cost of development involved which is different for each location s (Inv_s). The investment cost at each location is affected by the land value associated with the location. Given the variable nature of land values even within a ward- zone, we normalise the investment costs as an average of all costs *within* each zone. Note that in the objective function, the investment cost is computed per annum to make it comparable to travel time benefits also computed per annum. The upper-level problem is subject to annual budgetary constraint as below:

$$\sum_s inv_s \times n_s \leq AnnualBudget \tag{2}$$

The lower-level problem (See Appendix) is an extended traffic assignment with multiple user classes comprising *commercial* and *private vehicles* which recognises that the wholesale market location choice would be a function of transport costs which in turn depends on the on-street congestion thus allowing for redistribution of goods trips generated by retailers. Thus, the lower-level problem also includes a model of retailers' destination choice affecting the O-D demand pattern of commercial vehicles. Finally, change in on-street congestion pattern also affects the route choices of other road users i.e. private vehicles, which is tackled by the multiple user class assignment at the lower level. Specification of the lower-level problem is shown in Appendix. To sum up, *commercial vehicles* in our model have a *destination* and *route* choice, whereas *private vehicles* have only the *route* choice as their travel patterns remain unaltered.

The destination choice of retailers as estimated by Nugroho et al., (2021) has been adopted by this paper which is summarised here (See Nugroho et al for full details). The data were collected through a primary interview survey using specially designed questionnaires. The aim of the interview was to get the retailers' characteristics such as sales, total area, number of employees as well as their restocking decisions. The questionnaire employed open questions to get information on retailer's supplier names and locations, transport cost, and frequency of restocking trips. The retailers' supplier location choices were then estimated using multinomial models.

The lower-level model in our paper involves distributing the commercial vehicle trips by predicting the proportion of retailers that would choose a particular supplier location zone given the attribute values of alternative locations. The model estimates trip destinations based on the utility of each location depending on transport cost and the location attractiveness parameters viz., the number of wholesalers and the mere presence of wholesale market. The adopted model from Nugroho et al (2021) is shown in Equation (3) the use of which for this research is justified further in the next paragraph.

$$u_s = -0.295\mu_w + 0.042n_s + 0.547\theta_s \tag{3}$$

where, μ_w is the travel cost for origin–destination pair w,

n_s is the number of establishments at each location, and

θ_s is the dummy variable for wholesale market presence in the destination zone, *1* if there is a wholesale market, and *0* otherwise.

In general, retailer's procurement choices will depend on business profit which is equal to the difference between sales revenue and purchase costs. Sales revenue depends on the sales volume, which does not vary significantly as the retailers have a stable customer base. Retailers may vary sales prices depending on their purchase costs to maintain a certain level of profit. Based on the survey by Nugroho et al (2021), it was found that the wholesale goods prices in city centre and elsewhere in Bandung were not different to each other. Hence, it is reasonable to consider the travel costs as the key determinant of retailers' procurement choices. The fact that retailers operate small businesses, they intend to keep the costs down and often move the goods procured by their own vehicles justifies the use of Equation (3) further.

4. Solution algorithm

In this paper, we use metaheuristic integer Particle Swarm Optimisation (PSO) method to solve the upper-level problem (Motamedi Sedeh, Ostadi and Zagia, 2021) which is a generalised form of the binary series solution used earlier e.g., by Yamada and Febri, (2015). This process is depicted in Fig. 3.

The bi-level problem requires the following input data to find the solutions:

- Initial location of wholesale markets and the number of establishments at each location;
- Initial O-D matrix representing the demand patterns due to retailers' commercial vehicle trips and the private vehicle trips;
- Initial network conditions: road link characteristics such as the number of lanes, free-flow speed, speed at capacity; and
- New market locations together with the possible maximum number of establishments at each location, unit cost of developing a new establishment and the maximum budget available for the development.

The algorithm starts at the upper-level by reading all input data viz., network data, initial O-D demand, and investment costs. The PSO generates *a possible solution* identifying the number of establishments to develop at each new location. The possible solution is then carried to the lower level of the bi-level optimisation.

The lower-level problem will thus update the O-D demand data (D_w^i) as well as the travel times between O-D pairs (μ_w^i) that will be used as input to evaluate the upper-level objective function. The term D_w^i explicitly considers the return trips by assuming them to be equal to the number of outgoing trips i.e., the return trip matrix is the transpose of the outgoing trips which is added to the outward trips to form the new O-D demand. This can be written as:

$$D_w^i = D_{rs}^i + \left(D_{rs}^i\right)^T \tag{4}$$

where, T is the transposition operator. Equation (4) shows that the total number of trips between each O-D pair w is equal to the sum of outbound and inbound trips. The solution procedure iterates between upper and lower levels of the optimisation until it reaches the maximum number of iterations used as the stopping criteria. The steps to solve the bi-level problem can be described as below:

Step 1. Initialization ($j = 1$)

i) Set parameter value, namely, inertia weight ϖ learning factors (γ_1, γ_2), number of particles (M), and number of iterations (J)
ii) Set the maximum velocity of particle ($vel_{\max}$) as the maximum number of establishments to be built at zone-s and the minimum

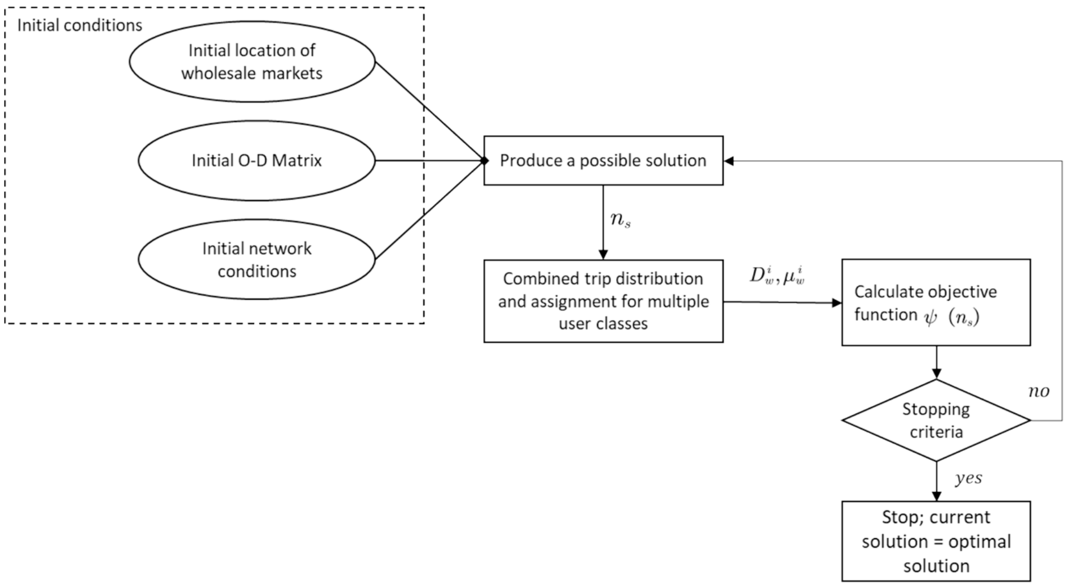

Fig. 3. Solution algorithm for solving the bi-level optimisation problem.

velocity of particles (vel_{min}) as the minimum number of establishments

iii) Set the initial velocity of each particle.

$$z_m^1 = \left[z_{m1}^1, z_{m2}^1, \cdots, z_{mg}^1, \cdots, z_{mG}^1\right] = [0, 0, \cdots, 0, \cdots, 0]$$

iv) Calculate the initial position.

$p_m^1 = \left[p_{m1}^1, p_{m2}^1, \cdots, p_{mg}^1, \cdots, p_{mG}^1\right] = [1, 1, \cdots, 1, \cdots, 1]$, $g \in G$, which is the length of the vector containing candidate solution.

Step 2. Evaluate the fitness of each particle based on the current position i.e., $fit\left(p_m^j\right)$. This step seeks to evaluate the objective function at the current state of relocation decisions which requires the updated travel costs from the traffic assignment at the lower level as set out in Appendix.

Step 3. Update historical best position $pbest_m^j$ and the global best position $gbest^j$ based on their current fitness.

Step 4. Calculate the velocity and the position of each particle using:

$$z_m^{j+1} = \varpi z_m^j + \gamma_1 \Delta_1 \left(pbest_m^j - p_m^j\right) + \gamma_2 \Delta_2 \left(gbest_m - p_m^j\right)$$

$$\Delta_1, \Delta_2 : randomnumberbetween(0, 1)$$

$$z_m^{j+1} = \begin{cases} z_m^{j+1} if vel_{min} < z_m^{j+1} < vel_{max} \\ vel_{max} if z_m^{j+1} > vel_{max} \\ vel_{min} if z_m^{j+1} < vel_{min} \end{cases}$$

$$p_m^{j+1} = p_m^j + z_m^{j+1}$$

$$p_m^{j+1} = \begin{cases} p_m^{j+1} if 0 < p_m^{j+1} < vel_{max} \\ random(0, vel_{\max}) if p_m^{j+1} < 0 or p_m^{j+1} > vel_{max} \end{cases}$$

Step 5. Let $j = j + 1$. If the algorithm has reached the stopping criterion $(j > J)$, then stop the iterations. Otherwise, return to step 2.

At the lower level, the current demand matrix for commercial (retailers') vehicles is updated based on their wholesale market location choice, given the number of establishments at each new location, and assigned to the network based on user equilibrium principle. The combined distribution cum assignment problem is solved by using the Method of Successive Averages (MSA) as proposed by Sheffi (1985). The details of steps involved in solving the lower-level problem are given in the Appendix –see section A2.

5. The case of Bandung wholesale market development

This section illustrates the working of proposed model which seeks optimal locations for the new wholesale markets to develop, and to assess the spatial impact of relocation strategies by road user type, viz., commercial, and private vehicles. We also estimate traffic emissions to assess whether the relocation plan improves the environment.

5.1. Description of the case study

Bandung is the capital province of West Java and a fast-growing metropolitan area in Indonesia. Based on 2020 census, Bandung has 2.5 million citizens with an average density of 14,125 persons / km^2. Bandung also has the highest economic growth in the region which is higher than the national average. Rapid growth in urbanisation can be attributed to the growth in key activities in Bandung area including commercial, trade, industry and education resulting in an immense number of passenger and freight vehicles in the city (Tarigan et al., 2016).

Bandung has thriving wholesale and retail business establishments throughout the city. There are a total of 41 wholesale markets spread across the city housing a total of 22,105 wholesaler units within all such markets put together (Fig. 4). The city centre located to the west has a higher concentration of wholesale markets attracting many retailer trips to the area every day.

Most retailers in Bandung are independent businesses making their own restocking decisions as opposed to centrally managed chain retailers. By selecting a particular wholesale market, retailers generate trips from their home location to the market location or attract trips in the opposite direction from the market to their location. Retailers usually move their goods from wholesale markets on their own by using a modified two-wheeler or a van to keep the costs down. There are 52,356 retailers scattered across the city, with a notable concentration in areas with dense residential population (e.g., western part of the city). Fig. 5 shows the distribution of retailers in Bandung.

In general, the wholesale markets are under pressure to adopt to the changing environment given the wider use of app-based ordering systems. Some of the wholesale establishments may have even

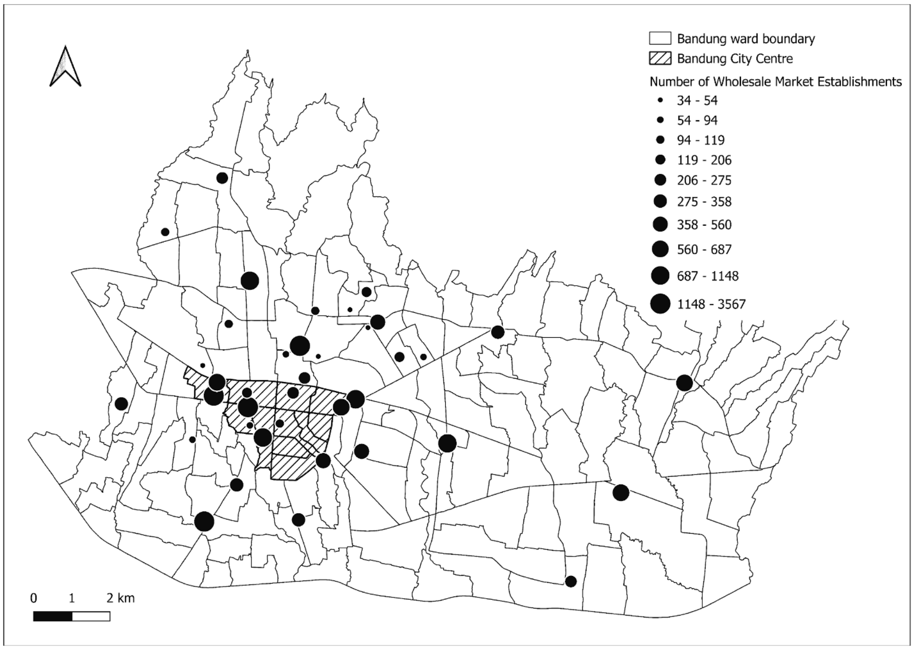

Fig. 4. Location of wholesale markets in Bandung.

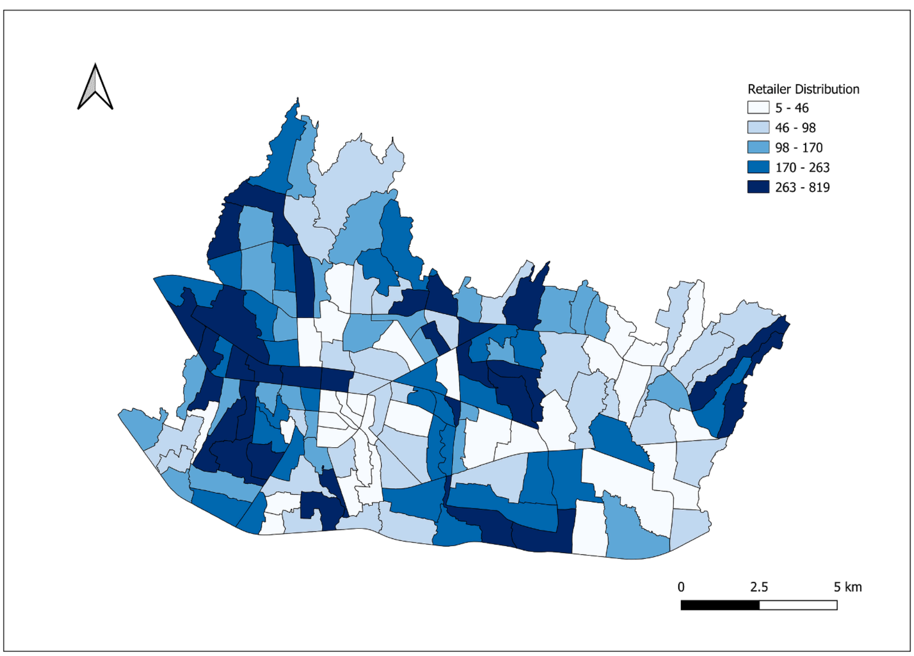

Fig. 5. Spread of retailers in Bandung city.

implemented app-based ordering for their customers. In the case of retailers buying from wholesalers using app-based services, goods still need to be transported from the wholesale market to the retailer's location. Alternatively, if the retailer visits the wholesaler, they move their goods by themselves after the purchase. Either way, in terms of congestion, the impact will be similar although the origin/destination of trips would reverse. Instead, if we consider the wholesaler dropping the goods at several retailers, they could be chargeable in some cases. The app-based ordering in general takes away the flexibility of retailers inspecting the quality of goods before buying, nor gives them the advantage of price bargaining which is inherent to the nature of wholesale markets. There might be some flexibility offered by wholesalers on app-based orders to return the goods if retailers are not satisfied, but this will generate more trips and will significantly affect the retailers' businesses due to the delays involved in receiving the goods again. As stated earlier, the retailers are small businesses, they procure the supplies every day due to lower inventory costs and even have the storage space constraints, thus, retailers will continue to visit the wholesale markets, move the goods by themselves with the aim of keeping the costs low.

To facilitate the modelling work, Bandung area is divided into 152 Traffic Analysis Zones (TAZ), which has 421 road junctions connected by 1,019 road links (See Fig. 6). Retailers located in 152 zones regularly procure their supplies from wholesalers located in 41 zones of the study area. The procurement activity results in 13,354 passenger car unit (PCU) equivalent trips during peak hour by commercial vehicles (CV's).

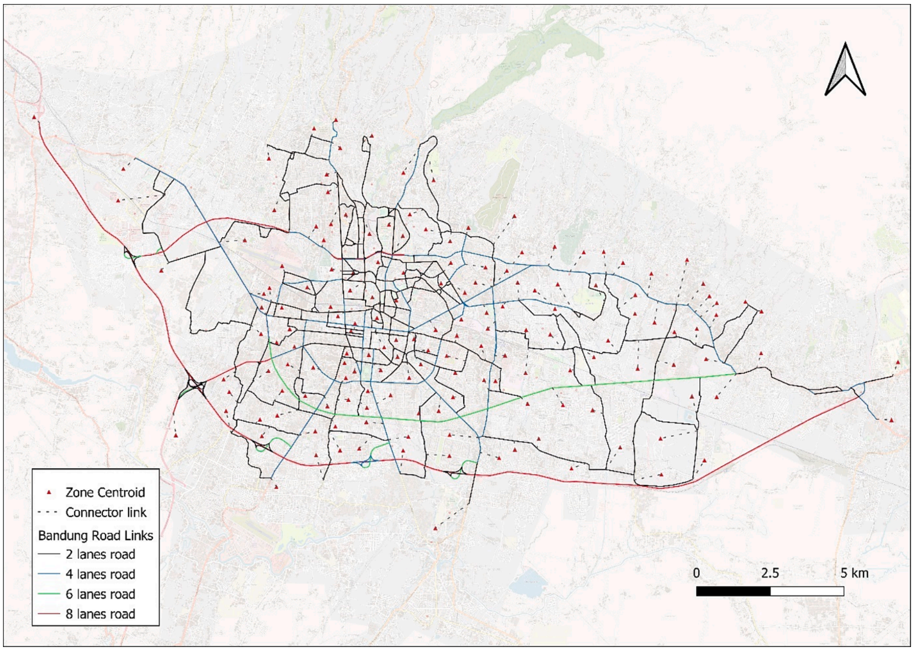

Fig. 6. Bandung road network and zoning system.

In addition, there are 52,121 PCU trips by private vehicles (PV's) making the road network highly congested during rush hour. The CVs and PVs have different values of time (λ_i) which are taken as IDR 16,100 per hour for private vehicles and IDR 20,900 per hour for commercial vehicles (Nugroho, 2015) (1USD ≅ 15,300 IDR).

The main intent of the case study is to explore decentralising the wholesale establishments by moving some of them to five new sites, viz, *Antapani, Arcamanik, Kordon, Dago* and *Saeuran* located to the east of city centre (see Fig. 7). This will encourage independent retailers to restock their shops from nearer wholesale markets helping to alleviate congestion not only in the city centre but also in areas outside. It will also increase economic activities in less-developed parts bringing in the much-needed homogeneity of development throughout the urban area. However, there is a limitation on the available budget to undertake the development of new markets and any solution should strictly be within the available budgetary limit. In addition, each possible new location has a limited land area available for development thus limiting the maximum number of establishments that can be built at each location. Relocation strategies also have a minimum number of establishments to be developed to ensure the construction can be efficiently planned.

Table 1 outlines the wholesale market development plan. It shows the minimum and maximum number of establishments that can be built at each location. The table also shows the area constraints and the initial investments required for developing the markets at each location. Assuming that each establishment will have 18 m^2 area, we calculated the maximum possible number of establishments that can be developed

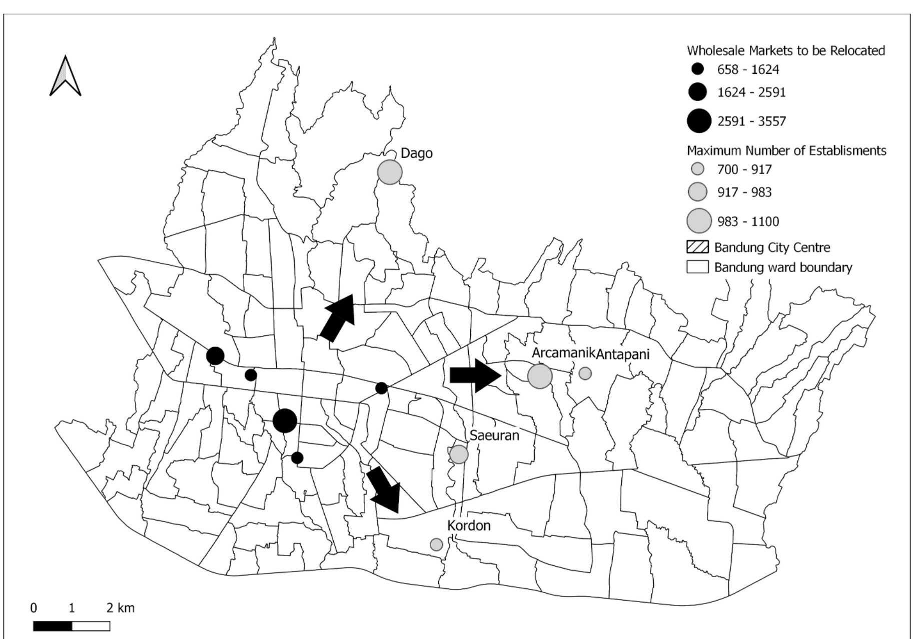

Fig. 7. Potential sites for developing new wholesale markets.

Table 1
Outlay of wholesale market development plan.

Location	Available area(m^2)	Minimum number of establishments	Maximum number of establishments	Number of possible solutions	Land acquisition cost (Million IDR/m^2)#	Construction cost (Million IDR/m^2)	Investment cost (Million IDR / establishment)
Antapani	16,200	750	900	16	1.96	1.6	64
Arcamanik	18,000	800	1000	21	1.96	1.6	64
Dago	12,600	500	700	21	2.84	1.6	80
Kordon	19,800	700	1100	41	0.62	1.6	40
Saeuran	17,100	800	950	16	0.62	1.6	40

[#]Source: Bandung Local News Papers.

at each location. Total investment cost was calculated based on the cost for each establishment. The total cost comprises of land acquisition cost and construction cost. The construction cost of 1.6 million IDR/m^2 was assumed at all locations but the land acquisition cost varies from 0.62 to 2.84 million IDR/m^2, depending on the location. It was assumed that the development of new markets will take place over a five-year period. The local authority, however, cannot develop as many as 4,650 establishments, since the plan will require an investment of IDR 259.6 billion in five years (i.e., IDR 51.9 billion/year) which is beyond the available budget of IDR 49.5 billion/year. Thus, we seek to optimise the BCR by varying the number of establishments at each new location to fit within the budget available.

Given the problem as above, let us work out the possible number of solutions. Let us consider the number of establishments to develop in multiplies of ten so that the problem remains practically feasible to solve. For instance, the number of establishments at Antapani can be stepped through from 750 to 760, to 770 and so on to 900. Thus, the possible number of discrete solutions for Antapani will be equal to 16 combinations of the establishment numbers. Similarly, the number of possible solutions at other locations can be worked out too. Multiplying all possible solutions across five locations gives us a total number of 4,628,736 which is a challenging problem, yet practically possible to find a solution. The optimal solution from all possible combinations will be generated by using PSO in the optimisation scheme. Furthermore, we have calibrated the integer PSO's parameters to ensure that the solution obtained from optimisation process is valid. The calibrated parameters are shown in Appendix.

5.2. Description of the relocation strategies

The modelled strategies are described as below (See Fig. 8):

Base Case: Base Case represents the initial condition with all wholesalers located where they are in the prevailing situation.

BAU: *Business As Usual strategy allows for the wholesale establishments to grow naturally due to the ongoing economic trends @3.2 % per annum over a period of five years. Similarly, PVs also grow @4.7 % pa.*

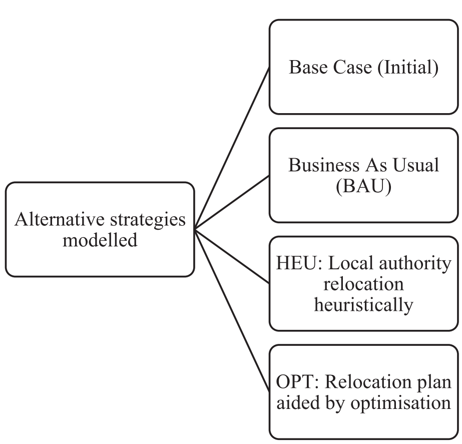

Fig. 8. Wholesale market relocation strategies modelled.

Two relocation strategies are defined further as below:

HEU: This strategy envisages closing down Pasar Baru, the largest *wholesale market in the city centre of Bandung and relocate all establishments to new market locations. This strategy represents the heuristic decision of local authorities and uniformly distributes the establishments among the new locations; and*

OPT: This strategy seeks to optimise *the relocation by considering all wholesale markets located in the city centre to move to the new locations subject to space and budgetary constraints.*

Fig. 8 summarises the strategies modelled and the distribution of wholesale markets in the new locations is shown in Table 2. It is noted that HEU in Table 2 is the result of the heuristic decision by the authorities whereas OPT column indicates the outcome of the optimisation process.

5.3. Comparing the results of alternative relocation strategies modelled

5.3.1. Traffic efficiency and value for money

Given the objectives of local authority of improving traffic efficiency whilst also ensuring value for money, we will firstly assess the overall impact on travel times and the BCR value. Fig. 9 shows the estimated annual travel times (primary y-axis) by the relocation strategies HEU and OPT alongside of the Base Case and BAU. Firstly, it is noted that the travel time significantly increases due to the growth in traffic and congestion will worsen as indicated by the BAU travel time relative to the Base Case, thus, doing nothing is not an option. The modelled strategies predict that the efficiency will improve with relocation as the overall travel times would reduce by up to 2.7 % with HEU and by 5.3 % with OPT strategy. It means that developing new wholesale markets will indeed deliver efficiency. The results also clearly indicate that the OPT-based relocation is nearly twice as good as HEU in terms of relieving the congestion in Bandung.

In terms of value for money (BCR shown on the secondary y-axis in Fig. 9), the OPT plan produces much better BCR value of 4.33 relative to 2.43 by HEU relocation plan. This clearly shows the benefit of using the OPT plan over the ad-hoc HEU plan. This is because despite the larger number of establishment units to develop by OPT, there is clearly a much larger proportionate welfare benefit to obtain, thus the OPT outperforms the HEU's limited plan in terms of value for money.

5.3.2. Impact of market relocation on travel patterns

We will consider the changes to travel patterns due to the relocation of markets assessing whether the revised land use structure is effective in attracting more trips to the east of the city centre. Fig. 10 shows the

Table 2
Distribution of wholesale market establishments at new market locations.

No	Location	HEU	OPT
1	Antapani	736	760
2	Arcamanik	736	890
3	Dago	736	650
4	Kordon	736	1010
5	Saeuran	736	920

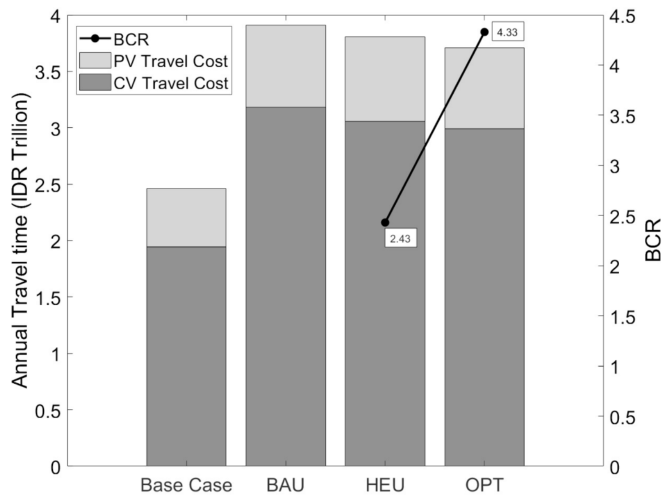

Fig. 9. Total travel time and BCR by alternative strategies.

retailer trip destination patterns based on the BAU strategy. Retailer trip destinations to the city centre markets by BAU will increase significantly over the Base Case due to a strong upward trend in the number of wholesale market establishments in the city. This indicates that without doing something, the city centre will experience worse-ever traffic congestion soon.

Figs. 11 and 12 show the retailers' spatial distribution of trips with HEU and OPT relocation strategies. Both plans will successfully alter the travel patterns by moving the retailer trip destinations away from city centre to the less developed eastern parts of the city. Pasar Baru, the zone with the largest number of trip destinations of 3678 during peak hour in the city centre (shown large black circle in Fig. 10) now reduces to zero trips (Fig. 11) due to the closure of the market by HEU strategy. The OPT strategy generates a balanced distribution of trips and Pasar Baru reduces to 1748 trips (in Fig. 12) as it attracts much lesser number of trips than BAU. On the other hand, zones in eastern part of city attract sizeably large number of trips which were hitherto zero in Fig. 10 to light yellow or even orange in Figs. 11 and 12. From this analysis it can be concluded that relocating the markets away from city centre significantly alters the travel patterns and that OPT generates a much more realisable outcome than the HEU which dramatically cuts down the trips erstwhile destined to city centre zones.

5.3.3. Analysing traffic network performance

We look at the traffic performance in detail in this section and how the two strategies viz., HEU and OPT compare. Table 3 shows the results of traffic performance by various strategies separated spatially viz., city centre, outside of city centre and overall network of the entire city. As the local authority objective involves improving traffic efficiency, we will largely comment on traffic speeds in the ensuing. However, the table includes greater amount of detail such as total distance travelled, total hours spent by private and commercial vehicles, all results separated by location, some of which were used in estimating the emission levels as described later.

Firstly, it is noted that the city centre speeds will drop by 19 % from the Base Case to as low as 12.9 kph by BAU. However, the OPT plan can revive the city centre speeds by up to 14 %, even better than the HEU plan. This is due to the larger number of establishments to move to the new locations by OPT than the HEU strategy.

Outside of city centre area will also benefit from the relocation schemes which would experience increased speeds by up to 5.4 % by the OPT plan, once again better than that of the HEU plan. It is noted that the relocation as a strategy increases the total vehicle-km travelled by about 1.8 % in outside of city centre area which could have an implication for the increased pollution levels. However, as the average speed increases, both private and commercial vehicles put together would spend lesser time on the network thus it is important to estimate the pollution levels at the expected speeds as described in Section 5.4 later.

Finally, we now look at the overall network speeds in the city. Comparing the OPT outcomes with the BAU, the relocation as a strategy effectively increases the speeds by about 6.6 %. HEU is also effective in

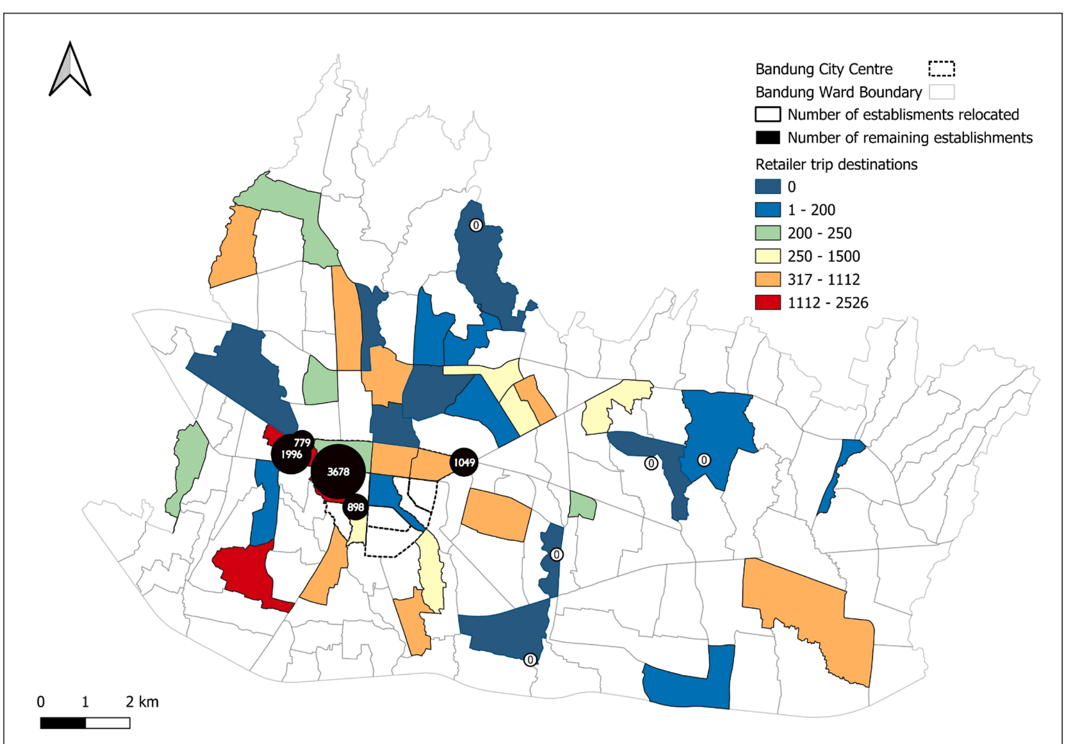

Fig. 10. Retailer trip destinations by BAU strategy.

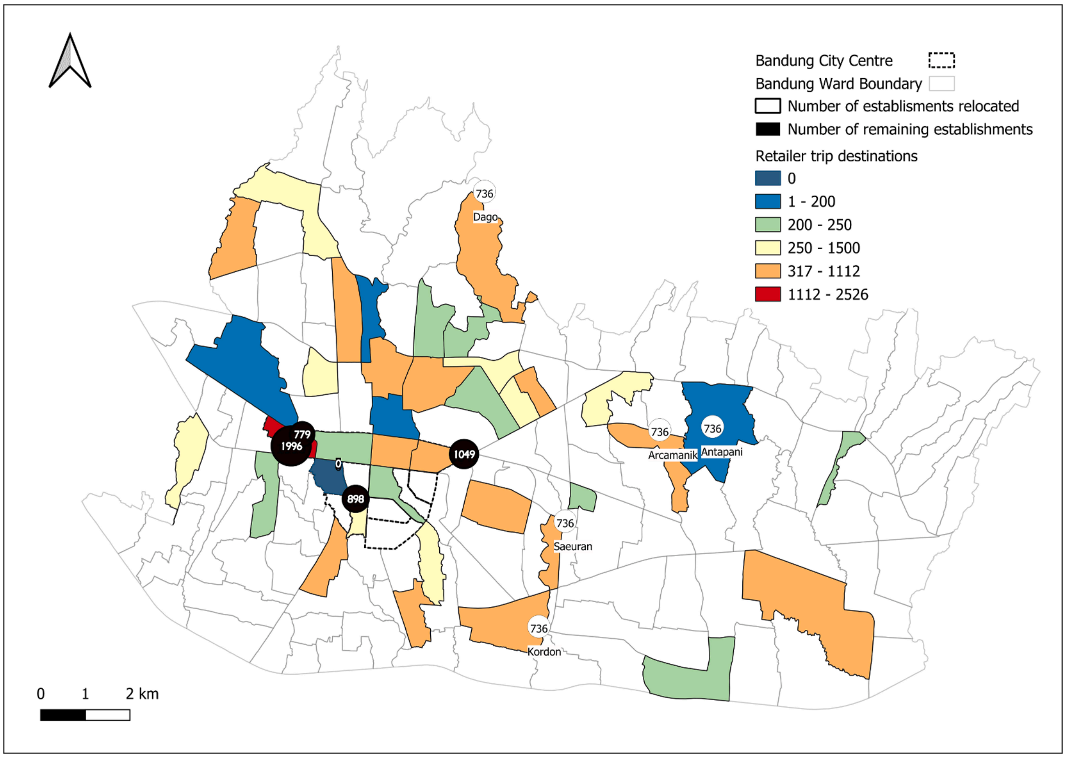

Fig. 11. Retailer trip destinations by HEU strategy.

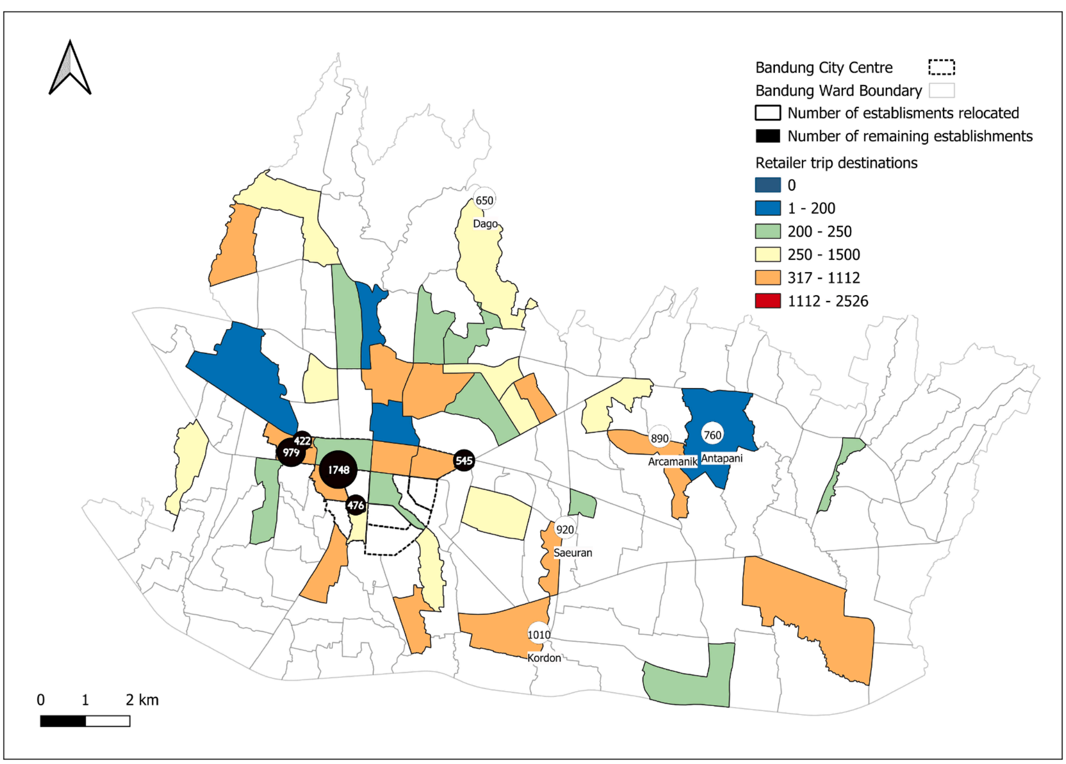

Fig. 12. Retailer trip destinations by OPT strategy.

increasing speeds but to a lesser extent by 5.3 %. This clearly indicates that the OPT plan outperforms the HEU on all counts and indeed improves the efficiency over BAU plan.

5.3.4. Estimating emissions due to wholesale market relocations

Besides the traffic performance we also estimate the GHG emissions to assess the impact of relocation. Emission factors were adopted from COPERT 5 (Ntziachristos and Samaras, 2000) based on a typical vehicle for each user class, PV and CV. Passenger cars and light commercial

Table 3
Traffic performance summary by location (per annum).

Location	Summary statistic	User type	Base Case	BAU	HEU	OPT
City centre	VKT (,000 vehicle-km)	PV	72,222	94,395	99,749	98,531
	VHT (,000 vehicle-h)		4,395	7,093	6,698	6,508
	Network Speed (km/h)		16.4	13.3	14.9	15.1
	VKT (,000 vehicle-km)	CV	16,567	19,396	14,909	14,900
	VHT (,000 vehicle-h)		1,236	1,682	1,342	1,188
	Network Speed (km/h)		13.4	11.5	11.1	12.5
	VKT (,000 vehicle-km)	All	88,789	113,791	114,657	113,431
	VHT (,000 vehicle-h)		5,631	8,775	8,040	7,696
	Network Speed (km/h)		15.8	12.9	14.3	14.7
Outside of city centre	VKT (,000 vehicle-km)	PV	467,681	606,016	609,527	607,777
	VHT (,000 vehicle-h)		14,294	23,483	22,693	22,250
	Network Speed (km/h)		32.7	25.8	26.9	27.3
	VKT (,000 vehicle-km)	CV	100,620	117,797	130,333	128,988
	VHT (,000 vehicle-h)		3,282	4,704	5,222	5,075
	Network Speed (km/h)		30.7	25.1	24.9	25.4
	VKT (,000 vehicle-km)	All	568,300	723,813	739,860	736,765
	VHT (,000 vehicle-h)		17,576	28,188	27,915	27,324
	Network Speed (km/h)		32.3	25.6	26.5	27.0
All network	VKT (,000 vehicle-km)	PV	539,903	700,410	709,276	706,308
		CV	117,187	137,193	145,242	143,888
		All	657,089	837,604	854,518	850,196
	VHT (,000 vehicle-h)	PV	18,689	30,576	29,391	28,758
		CV	4,518	6,387	6,564	6,263
		All	23,207	36,963	35,955	35,020
	Network Speed (km/h)	PV	28.9	22.9	24.1	24.6
		CV	25.9	21.5	22.1	23.0
		All	28.3	22.6	23.8	24.1

vehicles both petrol fuelled with EURO 2 technology were used as the typical vehicles as they are the most sold types in Indonesia. Fig. 13 shows the relationship between speed and emission factors for both vehicle types according to COPERT 5 model. Simply multiplying the earlier estimated vehicle-kilometres of travel by vehicle type with the corresponding emission factor at an appropriate speed and summing them over all modes/road links of the network gives the estimated emissions (Table 4).

Table 4 shows the estimated GHG emissions for each strategy. Firstly, the results clearly show that the OPT-based relocation will improve the city centre environment as the emissions will drop by about 14 % compared to the BAU strategy. Closing the largest wholesale market in city centre also improves the environment but to a slightly lesser extent by 13 %.

Outside of city centre the environment will however marginally worsen as the emissions will increase by 5 % with HEU. However, OPT-based relocation is better than HEU although the emissions are expected to increase slightly less by up to 3 %. This is because the VKT by CVs outside the city centre significantly increase producing higher traffic emissions.

Table 4
GHG Emissions for each strategy (kg/h).

Location	User Type	Base Case	BAU	HEU	OPT
City Centre	PV	88,211	134,204	134,555	132,734
	CV	113,963	142,011	105,417	104,584
	All	202,174	276,215	239,973	237,318
Outside of city centre	PV	388,951	577,645	577,829	571,973
	CV	375,094	520,356	577,222	560,770
	All	764,045	1,098,002	1,155,052	1,132,743
All Network	PV	477,162	711,849	712,385	704,707
	CV	489,057	662,367	682,640	665,355
	All	966,219	1,374,216	1,395,024	1,370,062

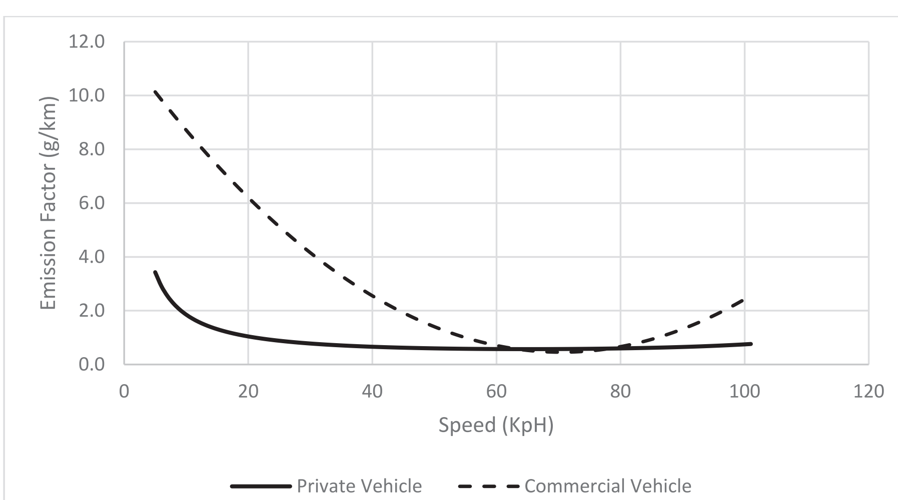

Fig. 13. Emission factors for private and commercial vehicles based on vehicle speeds.

Overall, the city environment improves with relocation of wholesale markets away from the city centre. Overall city emissions are expected to reduce by the OPT-based relocation though only marginally, but the heuristic HEU solution worsens the environment with 1.5 % higher emissions than BAU. This result clearly illustrates the advantage of adopting OPT method over the heuristic approach.

6. Discussion on the results

City centre congestion and pollution became a concern to many local authorities, and they started relocating the wholesale markets as a solution to the problem. However, due to an apparent lack of insights on the arising impacts, they tend to adopt heuristic approaches while relocating the markets. This research aimed at supporting the effort by local authorities, develops a framework and assesses the impacts by alternative approaches. The results clearly indicate that relocating wholesale markets indeed would help in reducing the congestion but could lead to increased pollution levels if not properly planned. As seen from the OPT results, pollution levels in the city centre would drop significantly (−14 %) but elsewhere in the city could be marginally worse off (+3%) due to higher vehicle-km travelled by commercial vehicles. Overall, pollution levels in the entire city would marginally drop. This outcome seen together with a strong increase in traffic efficiency over the entire network (+6.6 %), clearly indicates the benefit of relocating the markets. Heuristic procedures should be avoided as they are likely to generate worse outcomes especially in terms of increased pollution levels.

7. Concluding remarks

Historically, wholesale markets were developed in central areas of towns and cities, but with rapid urbanisation driven by population and economic growth, their centralised location became debatable. City centres typically have narrow roads where most of the economic activity takes place, thus, they became extremely congested over time. Many local authorities consider developing new wholesale markets elsewhere with a view to decongesting city-centre areas as well as facilitating social space-making. In a bid to support the effort of local authorities, this paper presents a new, yet robust approach for evaluating the benefits of potential relocation strategies involved.

This paper proposes an optimisation methodology to capture the interaction between local authority's decisions and retailers'/other road users' responses in a bi-level framework. The problem involved is a combinatorial optimisation with finitely large number of solutions. This paper employs an integer Particle Swarm Optimisation (PSO) used to solve large-sized real-life problems.

The proposed model is applied to the case of Bandung city, Indonesia. Specific to Bandung, the following conclusions were drawn:

- Bandung city centre suffers from a high level of congestion as the economy continues to grow, thus doing nothing is not a sensible option. Modelling results clearly indicate that the plan of developing new markets away from city centre indeed helps by significantly reducing traffic congestion not only in city centre but also in the entire city. Moreover, emission levels in the city centre would also drop with relocations making the city centre cleaner and efficient, thus, more liveable meeting the local authority's objective.
- Outside of city centre area also benefits from the relocation by improved traffic speeds. However, the outside city centre environment worsens though marginally due to the significantly higher commercial vehicle-km travelled. The reduction in city centre emissions could off-set these marginal increases elsewhere though. The OPT-based relocation plan reduces the overall emissions by counterbalancing the increases against strong reductions in city centre. On the other hand, if the relocation follows ad-hoc methods, they could worsen the situation as indicated by higher HEU emissions overall.

The approach presented in this paper could be found useful by other cities considering the development of new markets. The methods described in the paper can be employed to generate potentially beneficial solutions for a detailed economic evaluation in later stages. Public consultation events can be informed by the impact of alternative relocation plans helping them to hold meaningful discussions and in reaching decisions in an objective manner. Relationship between retailers and end-use customers which has not been modelled in this paper could be potentially interesting for further work given the advancements taking place in e-commerce space. Future studies may also include a framework that can evaluate the impact of enabling mechanisms such as tax incentives, parking management to promote the wholesale market development/ relocation by local governments.

CRediT authorship contribution statement

Taufiq Nugroho: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Chandra Balijepalli:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Febri Zukhruf:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. -Lower-level optimisation problem

This Appendix describes the notation and specifies the lower level problem. Solution procedure to solving multiple user class assignment with the destination choice for commercial vehicles is shown. Finally, this appendix also outlines the calibration of PSO parameters required for the optimisation.

A1. Notation and specification of lower-level optimisation problem

The notation used for describing the problem is as follows:

A	Set of links in the network
a	Index of links in the network, $a \in A$
r, R	Origin Zones, $r \in R$
s, S	Destination zone, $s \in S$
W	Set of all O-D Pairs, $w \in W$
w	Index of O-D pairs. Each O-D pair formed by a combination of r and s, where r denotes origin zone and s denotes destination zone. $r \in R, s \in S$ and $rs \in W$
i	User class index, 1 for commercial (retailers') vehicles, and 2 for private vehicles
l_a	Length of the link a in km
D_w^i	Trip demand for O-D pair w by user class i
D_r^i	Total trip demand for user class i from origin zone r
P_w^i	Set of all paths connecting O-D pair w for user class i, $w \in W$
$t_a(v_a)$	Link travel time function for link a
k_a	Capacity of link $a \in A$
g_a	Speed on link $a \in A$
v_a^i	Link flow on link a by user class i
f_p^i	Path flow by user class using path $p, p \in P_w, w \in W$
c_a^i	Generalized travel cost for user class i on link a
C_p^i	Path generalized travel cost for user class i using path $p, p \in P_w, w \in W$
λ_i	Value of time for user class i
δ_p^a	$\delta_p^a = 1$ if path p uses link a otherwise zero $p \in P_w, w \in W$
$d^i(w)$	Demand function for user class i
μ_w^i	Minimal travel cost for O-D pair w for user class i, $w \in W$
β	Logit parameter related to travel time attributes
ξ	Area for each establishment in m^2
$Tinv_s$	Total investment cost in zone s
inv_s	Investment cost for adding an establishment in zone s
φ_s	Available area for wholesale market at zone s in m^2
u_s	Utility for market zones s

Provided the notation as above, the following relations will hold throughout the paper:

$$v_a = \sum_{i \in I} v_a^i \tag{A1}$$

$$v_a^i = \sum_{w} \sum_{p \in P_w} \delta_p^a f_p^i \tag{A2}$$

Equation (A1) shows that the total flow on each link is obtained by summing the flow of each user class on the link. The relationship between link flow and path flow is defined by equation (A2) implying the flow of a user class on a link is equal to the path flow summed over all O-D paths that use the given link.

Link travel time follows the standard BPR function, which assumes that the travel time on the link is associated with the total flow on the link. The α in BPR function (equation (3) depends on the characteristics of a road.

$$t_a = t_0 \times \left(1 + 0.15\left(\frac{v_a}{k_a}\right)^{\alpha}\right) \tag{A3}$$

The lower-level problem in this paper is a traffic assignment problem with destination choice. Note that the traffic equilibrium with destination choice is a special case of the 'variable demand' problem in which the total number of trips originating from each origin node is assumed to be fixed but the numbers choosing each destination is a variable. In this case, the total trips for each O-D pair depends on a distribution function. Formally, this condition can be written as:

$$D_r^i = \sum_{s \in S} D_{rs}^i \tag{A4}$$

$$D_w^i = d^i\left(\mu_w^i\right) \tag{A5}$$

Equation (A4) defines the total number of trips from a particular origin zone r to all possible destination zones which is equal to the trip demand for a given user class (say, $i = 1$ for commercial vehicles) generated from the zone. Equation (A5) shows the distribution function that determines the number of trips that should be assigned to each destination from each origin. Note that the destination choice is affected by the minimum travel time obtained from the assignment process.

In this paper we incorporate logit function for the destination choice process. Traffic user equilibrium assignment problem including distribution with logit function as given by Fisk and Boyce (1983) is used in this paper. The convex optimisation problem for multiple user class cases can be written as below:

$$\min_{v,d} \sum_{a \in A} \int_o^{v_a} t_a(w)dw + \sum_{w \in W} \sum_{i \in I} \frac{1}{\beta} D_w^i \ln D_w^i - D_w^i \tag{A6}$$

$$\text{s.t.} \sum_{p_w^i \in P_w^i} f_w^i = D_w^i \ \forall w \in W \qquad \text{A7)}$$

$$f_p^i \geq 0 \forall p_w^i \in P_w^i, w \in W \tag{A8}$$

$$D_r^i = \sum_s D_{rs}^i \tag{A9}$$

Equation (A6) respresents the objective function of minimising the travel time for all user classes. Equation (A7) conserves the travel demand for user class i for O-D pair w by setting it equal to the sum of flows by all paths for the user class. Equation (8) ensures non-negativity of flows. Equation (A9) becomes a constraint that makes sure the flow at equilibrium condition follows the attraction constraint set by the logit formula. The logit model can be written as below:

$$D_w^i = d^i\left(\mu_w^i\right) = D_r^i \frac{e^{-\beta u_s(\mu_w, n_s)}}{\sum_{s \in S} e^{-\beta u_s(\mu_w, n_s)}} \quad \text{A10)}$$

We have commercial and private vehicles, the value of time (VOT) parameter differs significantly between the two modes. In the presence of distinct VOT's for each user class the travel disutility can be measured in money terms by equation (A11) as below:

$$c_a^i = \lambda_i t_a(v_a) \tag{A11}$$

A2. Solution algorithm for solving the lower-level assignment cum distribution problem

The procedure for solving the combined user equilibrium traffic assignment for each user class is as below:

Step 0*: Initialization*. Find a set of feasible flows $D_w^{i,j}$ and $v_a^{i,j}$ set $j = 1$

Step 1: *Update*. Calculate $c_a^{i,j} = \lambda_i t_a\left(v_a^{i,j}\right)$ and the demand at current iteration

$D_w^{i,j} = D_r^{i,j}\frac{e^{-\beta u_s(\mu_w, n_s)}}{\sum_{s \in S} e^{-\beta u_s(\mu_w, n_s)}}$ then calculate the performance of dummy links $c_w = \frac{1}{\beta}\ln(D_w^{i,j})$

Step 2: *Direction finding*. Find auxiliary demandv path flow $h_{w,p}^{i,j}$ by calculating the demand and performing All-or-Nothing assignment between pairs. Then get auxiliary path flow $x_a^{i,j}$ and auxiliary demand flow $Q_w^{i,j}$ by using equation:

$$x_a^{i,j} = \sum_w \sum_p h_{w,p}^{i,j} \delta_p^a$$

$$Q_w^{i,j} = \sum_p h_{w,p}^{i,j}$$

Step 3: *move-size determination*. Find the move size variable using MSA, α_j, such that $\alpha_j = \frac{1}{j}$

Step 4: *Flow update:*

Set : $v_a^{i,j+1} = v_a^{i,j} + \alpha_j\left(x_a^{i,j} - v_a^{i,j}\right)$

$$D_w^{i,j+1} = D_w^{i,j} + \left(Q_w^{i,j} - D_w^{i,j}\right)$$

Step 5: *Convergence check*: if

$$\frac{\sqrt{\sum_{a \in A}\left(v_a^{i,j+1} - v_a^{i,j}\right)^2}}{\sum_{a \in A} v_a^{i,j}} + \frac{\sqrt{\sum_{w \in W}\left(D_w^{i,j+1} - D_w^{i,j}\right)^2}}{\sum_{w \in W} D_w^{i,j}} \leq \varepsilon$$

Then terminate, otherwise let $j = j + 1$. ε is set to be 0.001.

A3. PSO parameter calibration

Finally, PSO parameter calibration has been done to ensure the quality of optimisation solutions. The optimisation method firstly was tested for initial condition to investigate the best value of PSO parameters for solving the upper-level problem. The best value of inertia weight $\overline{\omega}$, learning factors (γ_1, γ_2), number of particles (M), and number of iterations (J) are determined. The maximum $M \times J$ are set to 4500 and therefore the range of $M \times J$ to be tested are set to 30 x 150, 45 x100, 50 x 90. The range of other parameters was set at 0.7 to 1.2 for inertia weight, and from 1 to 2 for learning factors. Each combination of these parameters was evaluated for a total of ten runs based on the best, average, and worst solutions.

The best PSO parameter value for this problem was found to be 45 x 10 for $M \times J$ parameter, 0.7 for inertia weight and 1 for both learning factors. This set of parameter values gave us the best objective function (the maximum value of objective function i.e., 4.330). Furthermore, the set gives the minimum value for average objective function (i.e., 4.275) indicating that these parameters can produce a consistent result.

Table A1 below shows the overall results of the tests conducted.

Table A1
Results from PSO parameter value tests.

Parameter	Value								
M	30	45	45	45	45	45	45	45	50
J	150	100	100	100	100	100	100	100	90
γ_1	1	1	1	1	1	2	2	2	1
γ_2	1	1	1	1	1	2	2	2	1
$\overline{\omega}$	1	1	1	0.7	1.2	1	0.7	1.2	1
Random runs	10	10	10	10	10	10	10	10	10
max obj fun	4.317	4.295	4.330	4.330	4.330	4.327	4.327	4.327	4.286
min obj fun	4.256	4.277	4.234	4.234	4.234	4.243	4.243	4.243	4.288
average obj fun	4.280	4.287	4.290	4.275	4.286	4.299	4.297	4.299	4.299

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