

Highlights

Evaluating Heterogeneous Ambulance Fleet Allocations in Jakarta

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- Mathematical modelling for maximising survival with heterogeneous patients and fleets
- Population based neighbourhood search algorithm for finding better fleet allocations
- Fixed point numerical solution to equation used to approximate utilisation of vehicles
- A sequential simulation for ambulance demand and capacity planning
- Application to Jakarta for policy recommendations and testing future demand scenarios

Evaluating Heterogeneous Ambulance Fleet Allocations in Jakarta

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Abstract

Ambulance services have a duty of care to the clinical outcomes of the population they serve, and therefore aim to maximise the chances of survival and improve patient outcomes following a medical emergency. Despite this, although the ambulance location-allocation problem has been widely studied, it has predominantly focused on minimising response times or maximising coverage alone, and not explicitly for considering patient outcomes. In this paper we propose a modelling approach to consider where to optimally locate different types of emergency response vehicles in order to maximise patient outcomes within a heterogeneous population. To achieve this, we develop a heuristic algorithm for finding better fleet allocations which is used in conjunction with a discrete-event simulation model of ambulance services with heterogeneous vehicles. A major contribution of this heuristic is the numerical solution of a system of equations to be able to approximate the utilisation of vehicles. Traditionally this utilisation is problematic as it is both an input and an output of the allocation of vehicles. Our approach is informed by, and tested on, real-world data from Jakarta, Indonesia. Using our developed models, decision makers are better able to understand ambulance fleet capacity needs and locations, and their impact on patient outcomes.

Keywords: Ambulance Planning, Emergency Medical Services, Simulation, Health Care, Optimisation, Mathematical Modelling

1. Introduction and Background

Time-critical conditions (TCCs) are a substantial cause of mortality worldwide, responsible for an estimated 54% of all deaths [12]. Emergency medical services (EMS) play a pivotal role in responding to TCCs and saving patients from life-threatening medical conditions. Most EMS research, especially planning to meet increasing ambulance demands, tends to be focussed on high-income countries including, for example, Australia [22], Germany [34], and USA [5]. In contrast, most low and middle-income countries (LMICs) lack an organised EMS system, with most ambulances used purely for patient transport and not as an emergency care vehicle [28]. However, the burden of deaths due to TCCs is much greater in LMICs than in high-income countries, the difference being around threefold [9]. For traffic accidents, strokes and heart attacks, rapid access to appropriate treatment is especially vital.

The application of our research is focused on Indonesia, as supported by an award for Global Challenges Research Funds (GCRF). In Indonesia, an LMIC, there has been very little prior work on developing an EMS strategy, driven largely by inadequate resources including a lack of financial investment and human capital [28, 29, 37]. Related research by the authors [8] has highlighted particular challenges in Indonesia as a lack of a single coordinated EMS, the ability or willingness to pay for an ambulance, a large geographical area, and areas of severe traffic congestion especially in Jakarta, the capital.

When our research programme commenced in October 2019, ambulance services in Jakarta were provided by many disparate, mostly private providers that charge patients for their use, such as private hospitals. We initially partnered with Ambulans 118, a non-government charitable ambulance service established in 2005 by the Indonesian Surgeons' Association, that currently operates in five cities across Indonesia: Jakarta, Palembang, Yogyakarta, Surabaya and Makassar. Unlike private providers, Ambulans 118 suggests that a donation is made for use of its EMS vehicles, but otherwise provides free emergency medical care and is also leading on paramedic training across the country.

The overarching goal of our research was to work with the Indonesian Government, the different ambulance providers, and hospitals, to help them forecast emergency demand and make critical decisions on the optimal types, capacities and geographical locations of emergency vehicles within a potentially co-ordinated EMS system, starting with Jakarta. To facilitate this, in collaboration with Ambulans 118 we organised workshops in Jakarta in February 2020, thankfully just before the COVID-19 pandemic and lockdowns, which were attended by over 170 people including doctors, nurses, paramedics, academics, and officials from the Indonesian Ministry of Health. This paper presents some aspects of the overall research programme, specifically focusing on the development of a simulation model and location-allocation heuristics for maximising patient survival.

Fundamental to the project and the research described in this paper was an initial study that we carried out in order to better understand patient needs and the barriers to use of ambulances in Indonesia. Throughout the month of December 2020, we undertook comprehensive surveys in Emergency Departments (EDs) across Jakarta and published the first known study in to EMS demand within the country [8]. Our study showed that the utilisation of ambulances by patients attending EDs is considerably low and of concern. The low utilisation is contributed to patients'

lack of awareness of available ambulance services given a lack of coordination, patients’ disinclination to use ambulances due to high costs, and long response times. All of these barriers impact on patient outcomes, especially for those with life-threatening conditions. For example, remarkably more trauma patients took a car-share ride (20%) or motorcycle (20%) to reach the ED than an ambulance (just 10%), while only 14% of critical cardiovascular patients used an ambulance compared to 67% travelling to hospital by private car or a car-share ride.

The first contribution of this paper is an extension the work of [18] to consider both heterogeneous patients and heterogeneous fleets. Here a maximal survival objective is formulated, from vehicle allocations and utilisations, which are themselves found by numerically solving a relationship on the vehicles’ share of the demand. This is then used in a heuristic to find allocations that maximise patient survival. Secondly, we develop a comprehensive sequential discrete event EMS simulation that models and evaluates heterogeneous fleet allocations of emergency vehicles by utilising a novel approach in which transit jobs, rather than patients, are framed as the queueing ‘customers’. Our methodology utilises two discrete event simulations of the same system that are run sequentially and together combine to form the logic of a single simulation of a heterogeneous fleet; and key performance indicators (KPIs) are calculated by making use of survival functions. Thirdly, we demonstrate the use and impact of our modelling framework applied to current and proposed ambulance allocations in the city of Jakarta, thus supporting Government-level decision making with an overall goal to improve the lives of those living in LMICs. This leads to decision support and managerial insights in Indonesia, although the developed modelling framework could be readily applied to other locations.

The paper is structured as follows: Section 2 gives an overview of the literature on modelling ambulance allocations. Section 3 describes an optimisation model, including the survival objective, utilisation considerations, and a heuristic algorithm to find better fleet allocations. Section 4 outlines the logic of the sequential discrete event simulation models for heterogeneous fleets. Section 5 gives a case study, describing the current emergency service situation in Jakarta and applying the optimisation and simulation results. Section 6 discusses the findings and contributions of the paper.

2. Literature Review

There is a rich literature on Operational Research applied to EMS location and related allocation problems. Literature reviews that include these topics are Aringhieri et al. [2], Bélanger et al. [4], Farahani et al. [11], Li et al. [20], Liu et al. [21], Reuter-Oppermann et al. [30] and Wang et al. [36].

Emergency medical services can be evaluated using different performance measures with coverage and response time being the predominant metrics [24]. However, missing a response time target by just one second, for example, would be considered as a ‘failure’ in many models with no appreciation at all of the impact on patient survival or outcome [24]. This seems somewhat restrictive and short-sighted, which is why we focus on survival as a metric and thus, in the following, compare and contrast papers using that metric with our approach.

Table 1 provides an overview of recent research that focus on the survival metric. We break down related papers into discrete event simulation (DES), queueing theory and optimisation meth-

ods, and we provide a summary of each paper from the table as well as compare and contrast them with our modelling and solution approach.

Reference	Year	DES	Queueing Theory	Optimisation
Amorim et al. [1]	2019			✓
Boutilier and Chan [6]	2022		✓	
Erkut et al. [10]	2008			✓
Knight et al. [18]	2012		✓	✓
McCormack and Coates [23]	2015	✓		✓

Table 1: Break down of related research that focuses on survival.

Amorim et al. [1] propose an integrated strategic and tactical planning approach which features an optimization model and a local search heuristic based on Gaussian Processes. Their methodology is applied to the city of Porto while reporting on performance metrics such as survival. Our approach is different because we use a discrete-event simulation framework and a cross-entropy optimisation approach to determine the number of ambulances required in each station.

Boutilier and Chan [6] develop an integrated location-queueing model that incorporates existing EMS response times in a drone network. They use a p-median approach and an Erlang loss model. Although survival is not their main optimization criterion, they report how many patients would survive using their approach.

Erkut et al. [10] can be considered the first modelling approach that considers decaying survival probabilities during response time. The rationale is, because survival can be thought of as a more robust and generic objective for EMS performance measurement than coverage or average response time. In an application of a recently developed Maximal Survival Location Problem model (MSLP), the authors use data from Edmonton, Canada and show that maximising survival is superior to other objectives in clinical outcome for cardiac arrest patients.

McCormack and Coates (2015) [23] focus on the optimization of EMS vehicle fleet allocation and base station location through the use of a genetic algorithm (GA) with an integrated EMS simulation model. Their objective is maximization of the overall expected survival probability across patient classes. Applications of the model were undertaken using real call data from the London Ambulance Service. The difference between their modelling approach and our is that we have a different survival function, focus on a different heuristic optimization and evaluate our approach with data from a development country and have higher traffic volume and congestion in our data.

Knight, Harper and Smith [18] provide a supporting extension of the MSLP that allows it to be applied more generally to real-world EMS systems, acknowledging that different patients have varying levels of expected survival probabilities. The Maximum Expected Survival Location Model for Heterogeneous Patients, MESLMHP, allows multiple classes of patient groups to be defined, where previously only cardiac arrest patients formed part of the objectives for primary response. In reality, by definition any emergency patient has a necessity for swift attendance, and

a timely response to any incident type may impact on clinical outcome in some way. It is for this reason MESLMHP is designed to be generic enough to accommodate any number of patient groups, with each class weighted dependent upon the relative urgency of the incident. More than just a contribution to the model's demand input, these patients are included in the optimisation when maximising total population survival probability.

3. Optimising Allocations for Maximal Survival

Here we outline a method of finding vehicle allocations that that maximise the expected survival of patients. We assume that there are two types of vehicle: primary vehicles, typically ambulances, that must be dispatched to all patients; and secondary vehicles, typically rapid response motorcycles, that can travel faster than primary vehicles, and are dispatched to some patients to respond to an emergency faster than the primary vehicle. Secondary vehicles cannot transport patients, but are used in conjunction with primary vehicles to reduce response times. The problem then, is for a given set of vehicle locations (that is ambulance stations), a given total number of primary vehicles, and a given total number of secondary vehicles, how many vehicles of each type should be stationed at each location to maximise expected survival across all patients.

3.1. Survival Functions

A key concept here is the survival curve of a patient. In reality, some emergency incidents do not result in a substantive deterioration of a patient's status over time; however, in all situations, there is a reasonable cut-off beyond which a patient should not expect to have to wait for care, and mixture of theoretical survival functions and step functions can be utilised. Survival probabilities for critical incidents, calculated from a theoretical monotonically decaying survival function reported in the literature [33] are used to demonstrate an attainable level of success from a response. One particular survival curve $s(t)$ of Equation 1, represents survival until hospital discharge following cardiac arrest; its origins are explained in detail by [18]. Figure 1 shows the difference between using this survival curve and a hard cut-off of 8 minutes. However, hard cut-off curves like Equation 2, with a cutoff of L can still be used to represent meeting artificially selected targets.

$$s(t) = \left(1 + e^{0.26+0.139t}\right)^{-1} \quad (1)$$

$$s_L(t) = \begin{cases} 1 & \text{if } 0 \leq t \leq L \\ 0 & \text{if } t > L \end{cases} \quad (2)$$

3.2. Maximal Expected Survival Location Model with Heterogeneous Patients and Heterogeneous Fleet

Here we propose a Maximal Expected Survival Location Model with Heterogeneous Patients and Heterogeneous Fleet (MESLMHPHF). It is an extension of the MESLMHP model given in [18], which did not consider heterogeneous fleets. This is a model of survival that can be used as an objective function for optimisation algorithms. It is a weighted expected survival function

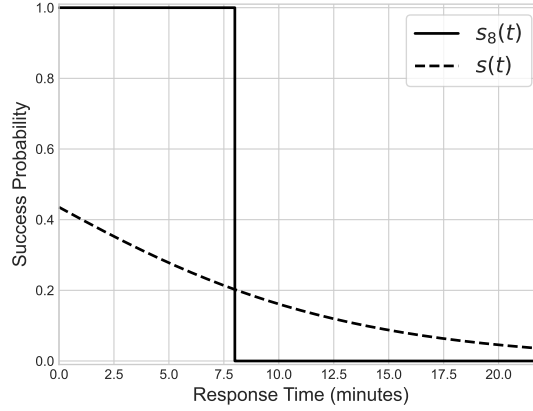


Figure 1: Survival function $s(t)$, estimated by [33] compared with a current EMS target, $s_L(t)$ with $L = 8$, represented as a step function (binary coverage).

as the objective function which considers heterogeneous patients (different specialties) and heterogeneous fleets (both primary vehicles, EAs, and secondary vehicles, RRVs), and is constructed by appropriately summing these survival curves, described in Section 3.1, across the population, multiplying by ambulance availability where appropriate.

We first present some notation. Let \mathcal{P} be the set of pick-up locations, indexed by p ; \mathcal{A} be the set of ambulance locations, indexed by a ; and \mathcal{K} be the set of medical specialties, indexed by k . An allocation is given by Z_a and \tilde{Z}_a , where Z_a is the number of primary vehicles allocated to ambulance location a ; and \tilde{Z}_a is the number of secondary vehicles allocated to ambulance location a . Also let:

- \tilde{t}_{pa} be the expected travel time from vehicle location a to pick-up location p for primary vehicles;
- $\tilde{\tilde{t}}_{pa}$ be the expected travel time from vehicle location a to pick-up location p for secondary vehicles;
- λ_{pk} be the rate at which patients of specialty k make calls from pick-up location p ;
- $s_k(t)$ be the survival function function associated with patients of specialty k ;
- π_a be the average utilisation of primary vehicles stationed at location a ;
- $\tilde{\pi}_a$ be the average utilisation of secondary vehicles stationed at location a .

To incorporate heterogeneous fleets the set of specialties \mathcal{K} is partitioned into two sets, \mathcal{K}_A , those patients that can be seen by secondary vehicles, and \mathcal{K}_B , those patients who are seen by primary vehicles only. Then the MESLMHPHF is given by Equation 3,

$$g(Z_a, \tilde{Z}_a) = \sum_{p \in \mathcal{P}} \sum_{a \in \mathcal{A}} \left(\sum_{k \in \mathcal{K}_A} w_k \lambda_{pk} \hat{\Psi}_{kpa} + \sum_{k \in \mathcal{K}_B} w_k \lambda_{pk} \Psi_{kpa} \right) \quad (3)$$

where w_k is a weight associated with patient speciality type k (for this study we assume $w_k = 1$ for all k). Now Ψ_{kpa} can be interpreted as the probability of a patient $k \in \mathcal{K}_B$ at pick-up location p being seen by a primary vehicle from location a and surviving; while $\hat{\Psi}_{kpa}$ would be the probability of patients of speciality $k \in \mathcal{K}_A$ at pick-up location p being seen by any vehicle from location a and surviving. Equation 3 is the weighted sum over the expected survival probabilities of all patient specialities, all patient pick-up locations, and all ambulance stations. These survival probabilities are given by Equations 4 and 5 respectively,

$$\Psi_{kpa} = s_k(t_{pa}) (1 - \pi_a^{Z_a}) \prod_{\alpha \in \mathcal{A}} \pi_\alpha^{(Z_\alpha \beta_{p\alpha a})} \quad (4)$$

$$\begin{aligned} \hat{\Psi}_{kpa} &= s_k(\hat{t}_{pa}) (1 - \tilde{\pi}_a^{\tilde{Z}_a}) \prod_{\alpha \in \mathcal{A}} \tilde{\pi}_\alpha^{(\tilde{Z}_\alpha \beta_{p\alpha a})} \pi_\alpha^{(Z_\alpha R_{p\alpha a})} \\ &+ s_k(t_{pa}) (1 - \pi_a^{Z_a}) \prod_{\alpha \in \mathcal{A}} \pi_\alpha^{(Z_\alpha \beta_{p\alpha a})} \tilde{\pi}_\alpha^{(\tilde{Z}_\alpha (1 - R_{p\alpha a}))} \end{aligned} \quad (5)$$

Here $R_{pa_1a_2}$ and $\beta_{pa_1a_2}$ are binary variables indicating the preference of sending a vehicle from one station to another: $\beta_{pa_1a_2}$ indicates if a vehicle of the same type can reach p quicker from a_1 than a_2 , defined in equation 6, while $R_{pa_1a_2}$ indicates if a primary vehicle at a_1 can reach p quicker than a secondary vehicle at a_2 , defined in equation 7.

$$\beta_{pa_1a_2} = \begin{cases} 0 & \text{if } a_1 = a_2 \\ 1 & \text{if } t_{pa_1} \leq t_{pa_2} \\ 0 & \text{otherwise.} \end{cases} \quad (6)$$

$$R_{pa_1a_2} = \begin{cases} 1 & \text{if } t_{pa_1} \leq \hat{t}_{pa_2} \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

Equation 4 is the probability of a patient surviving (their survival function), multiplied by the availability of primary vehicles at that ambulance station, multiplied by the unavailability of vehicles at closer stations. Equation 5 extends this to two vehicles types, the first part of the sum repeating the logic for the faster secondary vehicles, and the second part of the sum adapting that logic for primary vehicles, who will only be contribute the patient's survival if all faster secondary vehicles are also busy. These interpretations are given as annotations to the equations in [Appendix A](#).

A key consideration is the vehicle utilisations π_a and $\tilde{\pi}_a$; discussed in the next subsection.

3.3. Utilisation Considerations

The models above assume that the utilisations of each vehicle type at each vehicle location is known, which is a potentially restrictive assumption. These utilisations π_a and $\tilde{\pi}_a$ depend on the demand to station a , which itself depends on the vehicle allocations. One method of overcoming this, used in [18], is to consider utilisation as the ratio of demand and service rates, shown in Equations 8 and 9. Here we let $\frac{1}{\mu}$ and $\frac{1}{\tilde{\mu}}$ be the average job times of primary and secondary vehicles, then λ_a and $\tilde{\lambda}_a$ represent the share of the demand seen by primary and secondary vehicles from vehicle location a , respectively.

$$\pi_a = \frac{\lambda_a}{\mu} \quad (8)$$

$$\tilde{\pi}_a = \frac{\tilde{\lambda}_a}{\tilde{\mu}} \quad (9)$$

The average job times for each vehicle type, μ and $\tilde{\mu}$, may indeed vary with vehicle location due to travel times. However, a larger part of the job times might be taken up by delays at the pick-up locations, delays at the hospital, and refuelling, which are not generally location dependant. Therefore we feel it is reasonable to fix these. On the other hand, the demand experienced by vehicles at each location $a \in \mathcal{A}$ would be location specific, and would depend on the number and utilisation of the vehicles at every other location.

3.4. Numerical approximation of utilisation

For primary vehicles, which operate independently of secondary vehicles, the relationship between demand experienced at each location, λ_a , and the allocations and utilisations of all other locations, is given by Equation 10. For secondary vehicles, the relationship between demand experienced at each location, $\tilde{\lambda}_a$, and the allocations and utilisations of all other locations, is given by Equation 11. Note that this also depends on the utilisations of the primary vehicles, π_a .

$$\lambda_a = \sum_{p \in \mathcal{P}} \sum_{k \in \mathcal{K}} \lambda_{pk} \left(1 - \left(\frac{\lambda_a}{\mu} \right)^{Z_a} \right) \prod_{\alpha \in \mathcal{A}} \left(\frac{\lambda_\alpha}{\mu} \right)^{(Z_\alpha \beta_{p\alpha a})} \quad (10)$$

$$\tilde{\lambda}_a = \sum_{p \in \mathcal{P}} \sum_{k \in \mathcal{K}_A} \lambda_{pk} \left(1 - \left(\frac{\tilde{\lambda}_a}{\tilde{\mu}} \right)^{\tilde{Z}_a} \right) \prod_{\alpha \in \mathcal{A}} \pi_\alpha^{(Z_\alpha R_{p\alpha a})} \left(\frac{\tilde{\lambda}_\alpha}{\tilde{\mu}} \right)^{(\tilde{Z}_\alpha \beta_{p\alpha a})} \quad (11)$$

We propose finding the true vehicle utilisations by first solving Equation 10 for the λ_a ; determining the primary vehicle utilisations with Equation 8; then using these to solve Equation 11 for the $\tilde{\lambda}_a$; and determining the secondary vehicle utilisations with Equation 9. These can be solved numerically. In our implementation this is solved using the MINPACK hybrd and hybrj algorithms by using Scipy's `fsolve` function [35].

3.5. Heuristic Optimisation

In order to maximise the MESLMHPHF objective function presented in Section 3.2, we use a population-based neighbourhood search evolutionary heuristic algorithm. A population of possible solutions is created and ranked according to the objective, then for each generation of the heuristic a proportion of the best performing solutions is kept, and are mutated to complete the population for the next generation. To encourage exploration, the number of times each solution is mutated begins high and gradually decreases throughout the run of the simulation. The heuristic takes five hyper-parameters: N the population size, κ the number of solutions to retain to the next generation, m_0 the initial mutation rate; c the cooling rate; and H the number of generations. The heuristic is described in Algorithm 1.

Algorithm 1: Population-based Neighbourhood Search Evolutionary Algorithm

```

1 Create a population of  $N$  random allocations ( $Z_a, \tilde{Z}_a$ );
2 for  $i \leftarrow 0$  to  $H$  do
3   Rank the population according to Equation 3;
4   Keep the top  $\kappa$  solutions;
5    $m \leftarrow \lceil m_0 - \max(m_0, ic) \rceil$ ;
6   for  $j \leftarrow 0$  to  $N - \kappa$  do
7     Randomly choose and copy a solution from the population;
8     Mutate that copy of the solution  $m$  times;
9     Place mutated copy in a separate population;
10  end
11  Combine populations;
12 end
13 Rank the population according to Equation 3; Output the top ranking solution.
```

Mutations one of four possible changes: randomly change the location of one primary vehicle; randomly change the location of one secondary vehicle; randomly remove one primary vehicle and add secondary vehicles to 3 randomly chosen locations; and randomly remove 3 secondary vehicles and add a primary vehicle to a randomly chosen location. If it is required that exact vehicle numbers need to be retained, then only for first two mutations need be chosen.

The source code for the optimisation heuristic, including the evaluation of the MESLMHPHF objective function and the solution method for the utilisation considerations is available at [], and development history can be seen at <https://github.com/drvinceknight/upgraded-octo-barnacle>. Numerical results are discussed in Section 5.

4. Simulating Allocations

Discrete event simulation (DES) is a common methodology that allows us to investigate given scenarios under uncertainty. Here it will be used to quantify the effectiveness of given ambulance allocations by measuring a range of key performance indicators (KPIs), such as the average response time, the percentage of abandoned calls, vehicle utilisations, and expected survival based

on response times. The simulation is built using the Ciw library [26], and the model logic is described below. Its central ideas include modelling transit jobs as customers, rather than the patients themselves, and simulating primary and secondary vehicles as two simulations sequentially, with the output of the former being the input of the latter.

First, in addition to that introduced in Section 3.2, let us introduce the following notation, let:

- \mathcal{Y} be the set of hospitals, indexed by y ;
- \tilde{B}_{pa} be the traffic-free travel time from ambulance location a to pick-up location p ; and let B_{pa} be a random variable representing the time it takes for an ambulance to drive this distance;
- \tilde{C}_{py} be the traffic-free travel time from pick-up location p to hospital y ; and let C_{py} be a random variable representing the time it takes for an ambulance to drive this distance;
- \tilde{D}_{ya} be the traffic-free travel time from hospital y to ambulance location a ; and let D_{ya} be a random variable representing the time it takes for an ambulance to drive this distance;
- \tilde{F}_{pa} be the traffic-free travel time from pick-up location p to ambulance location a ; and let F_{pa} be a random variable representing the time it takes for an ambulance to drive this distance;
- G_k be a random variable representing the time the ambulance spends with patients of speciality k at the pick up location;
- J_k be a random variable representing the time the ambulance spends with patients of speciality k at the hospital;
- Θ be a random variable representing the time the ambulance spends re-fuelling, re-stocking, and resting between transit jobs;
- q_{pky} be the probability that a patient of speciality k from pick-up location p is taken to hospital y . Note that $\sum_y q_{pky} < 1$ is possible, that is a patient may not go to any hospital, in which case the ambulance returns to their ambulance location.

4.1. Simulating Primary Vehicles

For primary vehicles the logic to simulate is as follows: Patients make a call from one of a number of pick-up locations and await an ambulance to pick them up and take them to an appropriate hospital. Ambulances are stationed at a number of ambulance locations; when a patient makes a call, all free ambulances from any location calculate their expected time to reach that patient, and the ambulance with the smallest expected time to the patient is called out. The ambulance drives from its current ambulance location to the patient's pick-up location, then if a hospital is required, from the patient's pick-up location to the hospital, and then from the nearest hospital back to their original ambulance location. If a hospital is not required, the ambulance returns to their original ambulance location.

Rather than considering patients as customers in a queue, here the situation is re-framed to model transit jobs as customers, with the ambulances as servers.

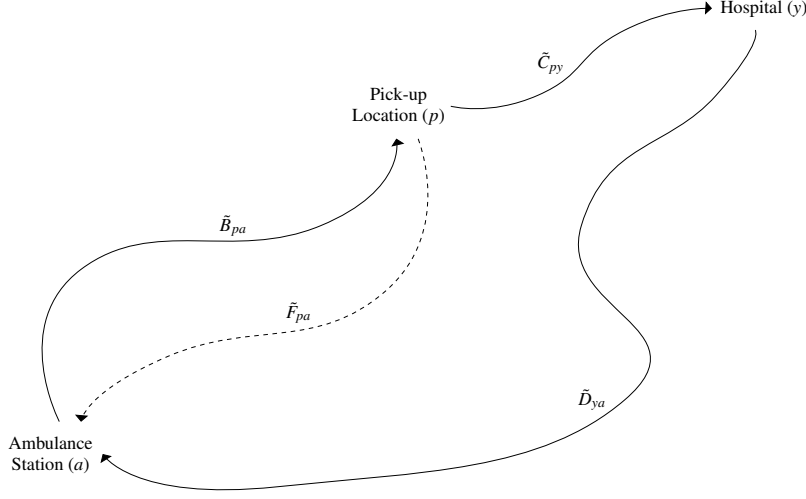


Figure 2: Ambulance routes for a given transit job.

Transit jobs can be categorised into classes corresponding to the pick-up locations \mathcal{P} and speciality \mathcal{K} . Jobs of class $(p, k) \in \mathcal{P} \times \mathcal{K}$ arrive with rate λ_{pk} . Servers can be categorised into classes corresponding to the ambulance locations \mathcal{A} . Service times are server-dependent, that is the service time of a transit job of type (p, k) , being served by a server of class a , will have service time T_{paky} given by Equation 12 if a hospital is required, and service time T_{pak} given by Equation 13 if no hospital is required.

$$T_{paky} = B_{pa} + G_k + C_{py} + J_{yk} + D_{ya} + \Theta \quad (12)$$

$$T_{pak} = B_{pa} + G_k + F_{pa} + \Theta \quad (13)$$

That is T_{paky} and T_{pak} is the overall time the ambulance spends dealing with that transit job and is unavailable to receive any more transit jobs. Figure 2 shows the route a particular ambulance will take when servicing a transit job, where there is a probability $1 - \sum_y q_{pky}$ that the ambulance will return, possibly on a different route, assuming distances are not symmetrical, to the ambulance location after a pick-up (dashed line), when patients do not need to go to the hospital.

From a patient's point of view their service only lasts $G_k + C_{py} + J_{yk}$, (or G_k if no hospital is required), and their waiting time is B_{pa} plus the time waiting for an ambulance to be dispatched. However in our case, if there are no free ambulances at the time of call, it is assumed that patients find their own care or transport, and so the call is abandoned. Therefore, the time waiting for dispatch is always zero.

Furthermore, all service times are time dependent, and calculated from travel distances and approximate hourly traffic levels, described in Section 4.2.

4.2. Travel Time Calculations

Each day is split into a set of periods, \mathcal{H} indexed by h . Within each period traffic levels are considered constant but differ from period to period. Traffic levels influence the speed of the

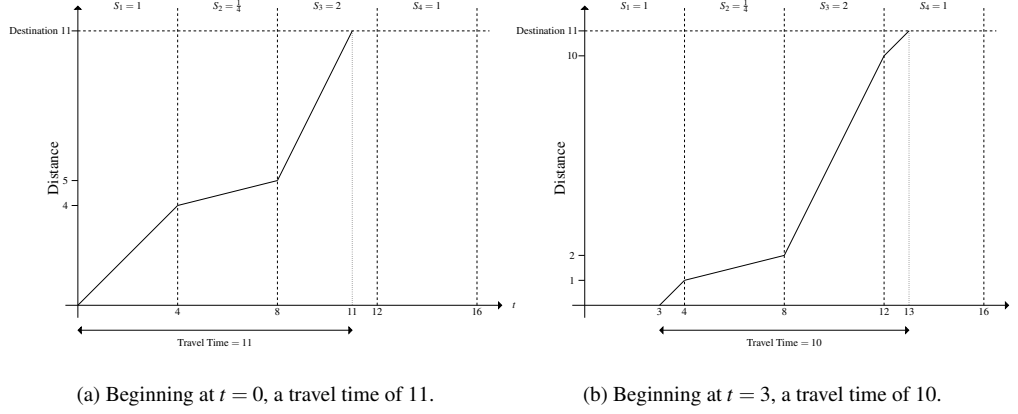


Figure 3: Example of calculating travel times for two different starting times.

ambulance through a delay factor d_h associated with each period. Therefore, the expected speed S_h at which an ambulance travels during period h is given by Equation 14,

$$S_h = s d_h \quad (14)$$

where s is the average speed that ambulances drive given no traffic. The relationship between time travelled and distance covered is piece-wise linear with slope S_h in period h . Therefore, travel times are calculated using this relationship.

As an example, consider the scenario where for the first period $t \in (0, 4)$ we have $S_1 = 1$; for $t \in (4, 8)$ we have $S_2 = \frac{1}{4}$, for $t \in (8, 12)$ we have $S_3 = 2$, and for $t \in (12, 16)$ we have $S_4 = 1$. Consider that the vehicle must travel 11 units. If the vehicle begins its journey at $t = 0$, then the expected travel time would be 11 time units, shown in Figure 3a. However if the vehicle begins its journey at time $t = 3$ then the expected travel time is 10 time units, shown in Figure 3b.

This is the method used to calculate the expected values of B_{pa} , C_{py} , D_{ya} and F_{pa} for the transit job service times, from the traffic-free travel times \tilde{B}_{pa} , \tilde{C}_{py} , \tilde{D}_{ya} and \tilde{F}_{pa} respectively. Furthermore it is assumed that travel times for each segment of the route (from vehicle location to patient, from patient to hospital, and from hospital back the the vehicle's location) follow a Triangular distribution around the calculated expected travel time, between 75% and 125% of the value.

4.3. Time-dependent Demand

Additionally, it is assumed that calls arrive according to a Poisson distribution, with rates λ_{pk} , and that these rates are time dependent. Each day is split into four 6-hour periods, the morning, afternoon, evening and night, and each speciality k and pick up location p will have a different call arrival rate for each of these periods.

For some locations and specialties the number of observed calls might be very low, and so the λ_{pk} rate would be very low. This can cause synchronicity issues when sampling arrivals [27], where artificially long inter-arrival times can be introduced at the beginning of one time period due to the low arrival rate in the previous time period. In order to overcome this here, rather than

sample inter-arrival times iteratively from an Exponential distribution, an entire schedule of arrival dates are sampled at the beginning of the simulation run, first by sampling the number of arrivals required in each time period from a Poisson distribution, and then by sampling specific dates within that time period using a Uniform distribution.

This mechanism, and alternative to thinning [19], was implemented in the Ciw software in version v2.3.3 [32], and described in the documentation here: https://ciw.readthedocs.io/en/latest/Guides/time_dependent.html.

4.4. Simulating Secondary Vehicles

Secondary non-transit vehicles, can in general travel faster than primary transport vehicles, and so can be dispatched at the same time as a primary vehicle but reach the patient earlier, reducing the response time for that patient and thus their survival probability. They are only dispatched for patients of speciality $k \in \mathcal{K}_A$, and if the closest secondary vehicle can reach them before the closest primary vehicle. Here secondary vehicles are simulated in a second discrete event simulation, run sequentially, but simulating the exact same time period and events as the first simulation. This is similar to sequential hybrid simulation methodology [7, 25], however in this case the two combined components are both DES, and are combined to simplify the logic of each component.

This is possible as there are no synchronicity issues between the two components. Primary vehicles operate independently of secondary vehicles, that is the way primary vehicles respond to a patient is unaffected by the presence or lack of a secondary vehicle. Therefore, primary vehicle logic is not compromised by simulating primary vehicles in isolation. Secondary vehicles are impacted by the behaviour of primary vehicles, they must remain with the patient until the primary vehicle arrives, and so must be simulated after the simulation of primary vehicles, taking as inputs the exact list of events that occurred. That is the logic of the secondary vehicles is determined by observing the actions of primary vehicles and reacting to them. Simulation results are combined for each individual patient, to determine their response time caused by either primary or secondary vehicles.

Secondary vehicles are chosen in the same way as primary vehicles, by choosing out of the currently free vehicles the one with the smallest expected time to patient. Their service times are reactionary to what occurred with the primary vehicle. Let B_{pa_2} be the time it takes for the secondary vehicle to travel from its location a_2 to the patient pick-up location p ; \hat{B}_{pa_1} is the time it took for the primary vehicle to get from its location a_1 to the patient pick-up location p ; \hat{G}_k is the time the primary vehicle spent with the patient; and \hat{F}_{pa_2} is the time it takes to return to the secondary vehicle's location a_2 from the patient pick-up location p . Note that \hat{B}_{pa_1} and \hat{G}_k are exact values obtained from the initial simulation of the primary vehicles, while B_{pa_2} and F_{pa_2} are random variables to sample in the subsequent simulation. Travel times are calculated as described in Section 4.2, replacing the primary vehicle delay factor, d_h , with a delay factor for secondary vehicles, \tilde{d}_h . This accounts for secondary vehicles travelling faster and reacting to traffic differently to primary vehicles.

Exact synchronicity considerations are shown in Figure 4:

- whenever the secondary vehicle reaches the patient before the primary vehicle, they remain with the patient until the primary vehicle leaves;

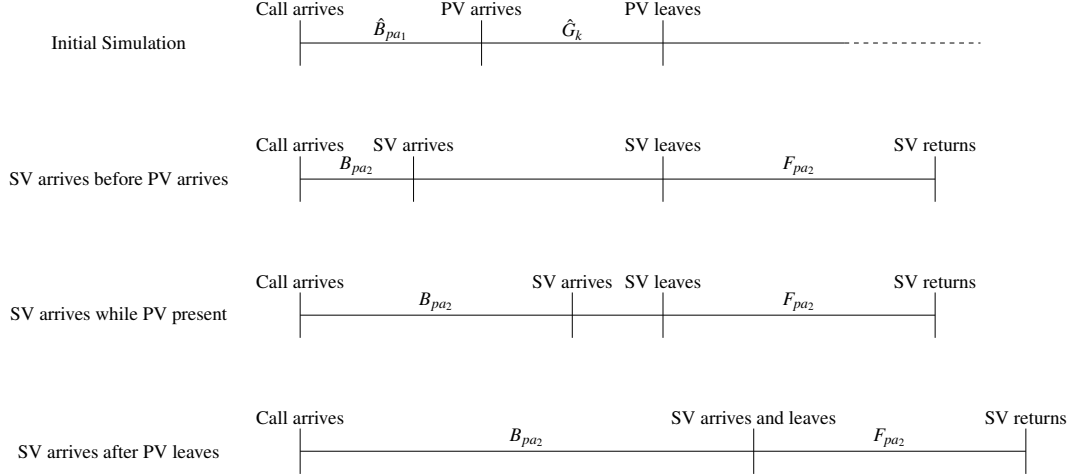


Figure 4: Visualising secondary vehicle (SV) logic reacting to the primary vehicle's (PV) actions.

- if secondary vehicle arrives after the primary vehicle they will immediately return to their stations as they are not needed at the scene;
- if the expected time for the secondary vehicle to reach the patient exceeds the expected time for the primary vehicle to reach the patient then the secondary vehicle is not deployed, and so that transit job would be abandoned in the secondary simulation (although still seen by a primary vehicle in the initial simulation).

Therefore job service times for secondary vehicles, \tilde{T}_{pak} , are given by:

$$\tilde{T}_{pak} = \max(B_{pa2}, \hat{B}_{pa1} + \hat{G}_k) + F_{pa2} \quad (15)$$

4.5. Combined Model

Combining the logic presented in Sections 4.1 and 4.4 gives the overall simulation logic for simulating both primary and secondary vehicle types. It is used to quantify the effectiveness of a given allocation (Z_a, \tilde{Z}_a) for all $a \in \mathcal{A}$, by recording several useful KPIs. In this work, the KPIs of interest are: the average primary vehicle utilisation, the average secondary vehicle utilisation, the mean response time, the percentage of abandoned calls (that is a measure of the primary vehicle unavailability), and the expected overall survival. Survival is modelled using a combination of survival function curves and hard cut-offs, and is described in Section 3.1.

5. The Case of Jakarta

Jakarta, the capital of Indonesia, has a population of 10.5 million [17] residing within 664 km². The city is divided into five municipalities and one district, each of which is divided into sub districts and, in turn, neighbourhoods. There is a total of 42 sub districts and 261 neighbourhoods within mainland Jakarta (excluding the Thousand Islands regency in the north) [16], a map is given in Figure 5.



Figure 5: Map of Jakarta’s Municipalities.

As described in Section 1, there are many challenges to calling for an ambulance in Jakarta, as captured in [8]. This work showed an initially fragmented ambulance service with poor data collection meaning that estimating the true demand for ambulances in Jakarta was itself particularly challenging. Based on this work the regional government of Jakarta invested in a new fleet of coordinated ambulances accessible via the single emergency number 119. This work, in collaboration with Ambulans 118 and the 119 Emergency Ambulance Service, finds potential fleet allocations using the optimisations methods given in Section 3, and evaluates these allocations’ effectiveness using the simulation described in Section 4.

The models are parameterised using demand data that covers all 261 neighbourhoods from 1 January to 31 December 2019, before the COVID-19 pandemic. Data from 2020-2021 was naturally heavily skewed by the pandemic, with significantly lower demand, and so was not considered as representative of a typical period for forecasting future needs, hence the decision to use the available 2019 demand. Working with our ambulance partners, after careful consideration the following patient ‘specialities’ ($kin\mathcal{K}$) were agreed based on clinical need (although other categories could readily be adopted and included as necessary):

- **A1 - High priority emergency patients:** critical patients who require immediate life-saving assistance with a target ambulance response time of 8 minutes. In our data set there were 168 identified calls that met this criterion.
- **A2 - Other emergency patients:** urgent patients that require assistance with a target response time of 15 minutes. In our data set there were 23,784 calls of this type.
- **B - Non-emergency patients:** patients that still benefit from an ambulance response but non-critical with a target response time of 60 minutes. There were 31,725 calls of this type in the data set.

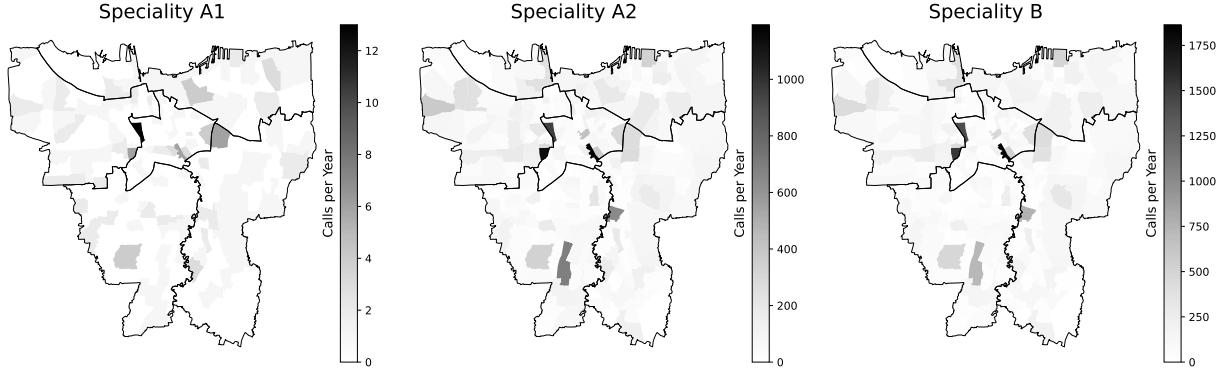


Figure 6: Number of calls received by speciality and neighbourhood.

Here secondary vehicles can be called to patients of speciality A1 and A2, therefore $\mathcal{K}_A = \{A1, A2\}$ and $\mathcal{K}_B = \{B\}$. The number of calls from each of these specialities varies by neighbourhood, as shown in Figure 6. It can be seen that many calls are highly concentrated in a handful of neighbourhoods rather than spread throughout the city.

Firstly, in Sections 5.1 and 5.2 we use the discrete event simulation to find KPIs that to measure the performance of the currently used allocations, and two proposed grid allocations for the city. Appendix B provides further details on the parameterisation of the model.

5.1. Current Allocation

As of October 2022, the 119 service in Jakarta ran a fleet of 81 primary Emergency Ambulances (EAs) and 13 secondary motorbike Rapid Response Vehicles (RRVs), distributed across 67 ambulance stations throughout the city. Figure 7 summarise the allocations vehicle locations.

5.2. Proposed ‘Grid’ Allocation

Discussions with senior staff at 119 identified that they were seriously considering to re-configure their ambulance allocations into a grid structure, placing an ambulance station at regular intervals throughout the city and uniformly distributing the vehicles that they felt would ensure coverage. Two possible grid allocations were being considered: one placing an EA every 3km across the city (giving a total of 70 vehicles), and another placing three EAs every 5km across the city (giving a total of 72 vehicles). Figure 8 show these proposed allocations.

We run the simulation for both the current and the two proposed grid allocations, and results are shown and compared in Table 2. We observe that the two proposed grid allocations perform much worse than the current allocation as measured by mean response time, survival, and percentage of calls abandoned.

5.3. Planning for Future Demand

Similarly to many other cities worldwide, ambulance services in Jakarta anticipate that demand for services will grow in future years, not least that there is now a coordinated service accessible via a single common number ‘119’ to call. This should help raise awareness and visibility of an

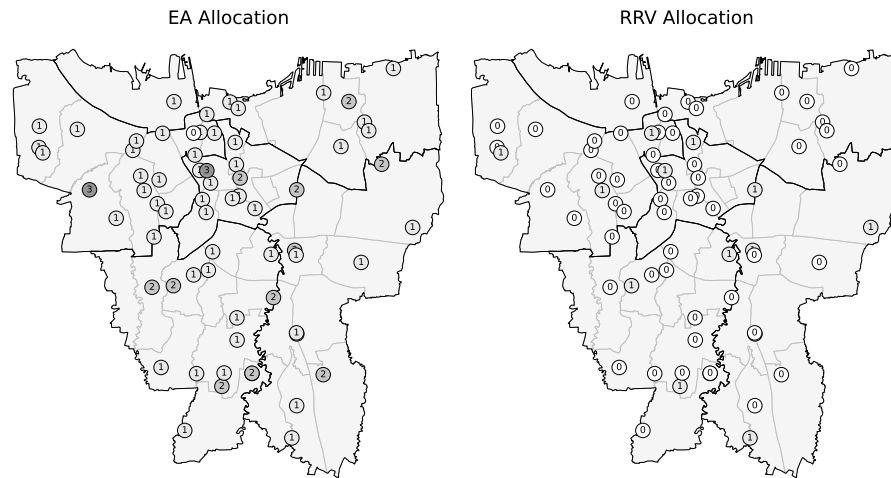


Figure 7: Map of current Emergency Ambulance (EA) and Rapid Response Vehicle (RRV) locations and allocations to ambulance bases across Jakarta.

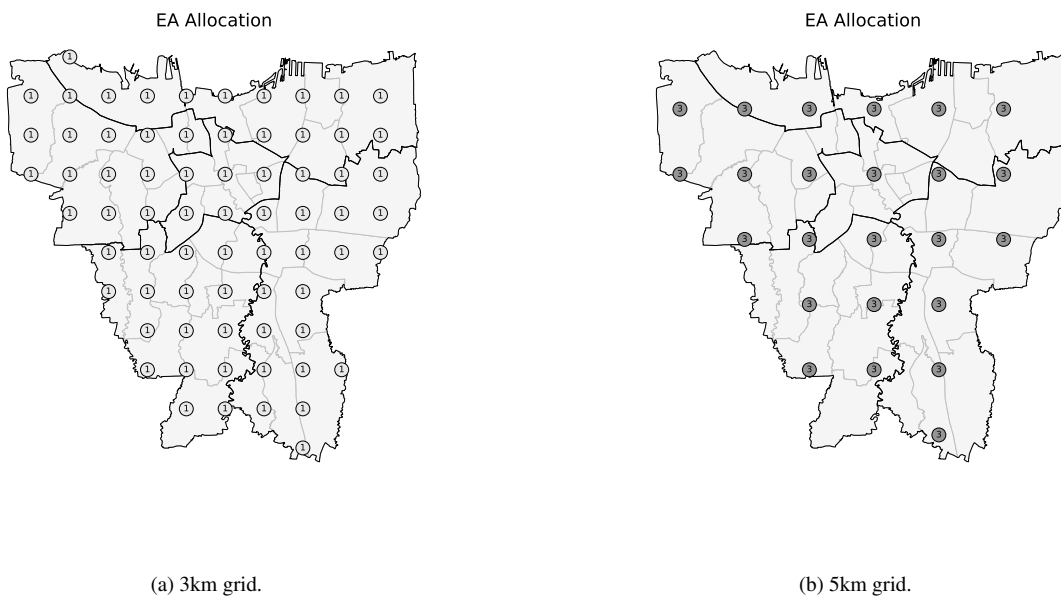


Figure 8: Proposed grid allocations.

Allocation	Baseline	Grid 3km	Grid 5km
Number of EAs	81	70	71
Number of RRVs	13	0	0
Ambulance Utilisation	31.7%	37.4%	36.6%
RRV Utilisation	40.9%	-	-
Mean Response Time (mins)	16.80	22.39	24.14
Overall Survival	75.5%	63.7%	61.0%
Percent Abandoned	0.034%	0.430%	1.028%

Table 2: Calculated KPIs for the current and proposed grid allocations.

Reason	% of emergency respondents
Used Ambulance	13.0
Too expensive	5.2
Not available	13.1
Would take too long	16.5
Not necessary	15.7
Not aware of service	33.1
Other	3.5

Table 3: Barriers to use of an ambulance service in Jakarta, from [8].

ambulance service. In the case of Jakarta, certainly increased use of 119 and therefore increased demand would be a desired outcome resulting from proactive actions by the Indonesian Government.

We consider four different demand scenarios, developed by considering the result of our cross-sectional study of patients attending EDs in Jakarta [8]. As part of the survey, randomly selected patients arriving at each emergency department were asked whether they had used an ambulance to attend, and reasons for not using an ambulance. For those patients who were categorised by the medical staff as emergency and for whom therefore an ambulance might have seemed a sensible option, the responses are given in Table 3.

The survey confirmed three major barriers to use, namely: the service’s visibility (33.1% of respondents were unaware of the service), the service’s reliability (13.1% of respondents reported that there was no ambulance available and 16.5% of respondents believed it would take too long), and the service’s cost (5.2% of respondents cited cost as a deterrent). Therefore, four demand scenarios were considered, corresponding to addressing each of these barriers in turn:

- **demand_13**: representing the current situation where approximately 13% of emergency patients (specialities A1 and A2) do use an ambulance.
- **demand_19**: representing the situation where visibility is addressed. Here, we distribute the 33.1% of the respondents who were unaware of the service proportionally between using

Demand Scenario	demand_13	demand_19	demand_34	demand_45
Ambulance Utilisation	31.7%	38.9%	54.9%	62.5%
RRV Utilisation	40.9%	47.7%	62.3%	68.5%
Mean Response Time (mins)	16.80	17.98	22.18	23.97
Overall Survival	75.5%	67.7%	52.6%	46.0%
Percent Abandoned	0.034%	0.315%	3.910%	10.004%

Table 4: Calculated KPIs for the current allocation under the four possible demand scenarios.

the ambulance and amongst the remaining issues. Using this methodology we would expect 19.4% of emergency patients to now use an ambulance.

- **demand_34**: representing the situation where reliability and visibility are addressed. Using the same methodology we would expect 34.8% of emergency patients to now use an ambulance.
- **demand_45**: representing the situation where cost, reliability and visibility are all addressed. Using the same methodology we would expect 45.4% of emergency patients to now use an ambulance.

Guided by our findings in [8], recent changes mean that the 119 services is now free to use for Jakarta residents, so certainly the highest demand (demand_45) scenario is plausible in the near future. After discussions with our partners, it was agreed that for each of the scenarios we should assume that non-emergency demand (speciality B) remains unchanged.

Table 4 gives the derived KPIs for the current allocation for each of these demand scenarios in the simulation. In all measured KPIs, the performance worsens as emergency demand increases, thus motivating the need to find better allocations and investigate the effect of varying resource levels and explicit consideration of patient outcomes, detailed in Section 5.4.

5.4. Improving the Current Allocation

Applying the optimisation heuristic from Section 3 to the current allocation re-allocates the 81 EAs and 13 RRVs. The hyper-parameters used for this optimisation algorithm throughout this study are given in Table 5, which include approximations for the average service times of primary and secondary vehicles derived from the initial simulation model. Appendix C shows some initial explorations on the hyperparameter choices, giving confidence that the chosen parameters, with a large enough number of iterations N , are sufficient to find allocations that perform well.

Figure 9 shows the new allocation (in comparison to Figure 7. Table 6 compares the simulation derived KPIs between the current and the optimised allocations; it can be seen that a number of them increase.

5.5. Finding Optimal Allocations for Any Resource Level

The heuristic algorithm described in Section 3.5 finds allocation of ambulances across the 67 current ambulance stations for a given number of primary and secondary vehicles. Information

Parameter	Value Used	Explanation
μ	$\frac{1}{4.5 \times 60}$	Average primary vehicle service rate.
$\tilde{\mu}$	$\frac{1}{3.5 \times 60}$	Average secondary vehicle service rate.
N	240	Population size.
κ	40	Number of solutions to keep per generation.
m_0	6	Initial number of mutations.
c	0.25	Cooling rate, rate at which number of mutations decreases.
H	500	Number of generations.

Table 5: Hyper-parameters used in the optimisation for all experiments.

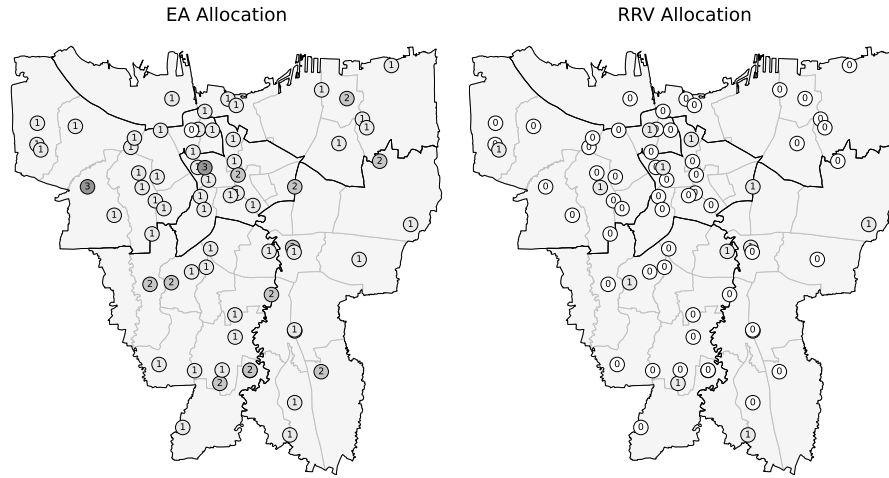


Figure 9: Improved allocation of 81 EAs and 13 RRVs.

	Allocation	Baseline	Improved
Ambulance Utilisation		31.7%	31.7%
RRV Utilisation		40.9%	40.9%
Mean Response Time (mins)		16.80	16.80
Overall Survival		75.5%	75.5%
Percent Abandoned		0.034%	0.034%

Table 6: Comparing KPIs for the current and improved allocations.

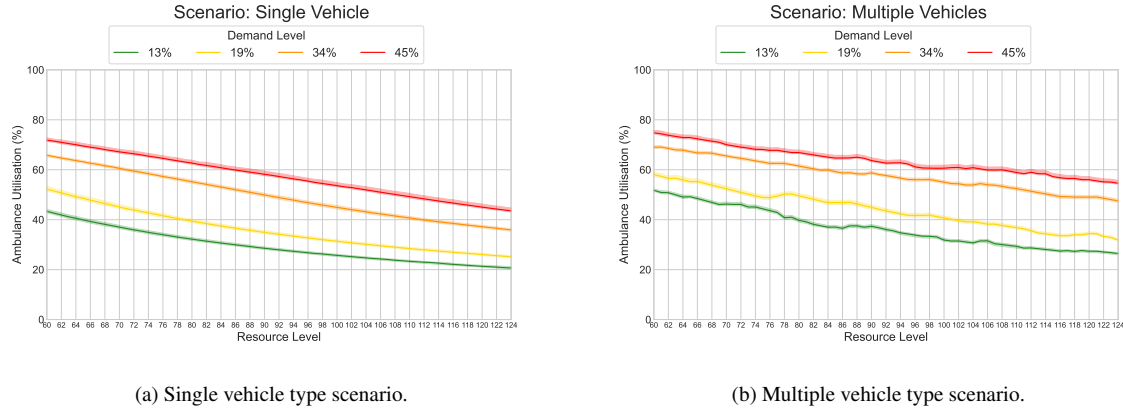


Figure 10: Ambulance utilisation results.

supplied by one of the ambulance operators suggested that in terms of total running costs one EA (primary vehicle) was approximately equivalent to three RRVs (secondary vehicles), and so we consider three RRVs to be one resource; that is, a resource level of 60 could represent 60 primary and 0 secondary vehicles, or 59 primary and 3 secondary vehicles, or 58 primary and 6 secondary vehicles, and so on. For a given resource level we run the optimisation algorithm for all possible combinations of numbers of primary and secondary vehicles, though as every patient must be seen by a primary vehicle, we do not consider the case when the number of secondary vehicles exceeds the number of primary vehicles. Allocations were found for each resource level between 60 and 125 EA equivalents, and we report KPIs for the best performing, in terms of maximal survival, combinations, as well as for the case when the number of secondary vehicles is fixed at zero. We call these the multiple vehicle type and single vehicle type scenarios.

Figures 10-14 display the obtained KPIs for each of these allocations. It can immediately be seen that increasing the resource level has a positive effect on all KPIs, with vehicle utilisations, mean response times, and percentage abandoned decreasing, and overall survival increasing. Similarly, as expected increasing the demand of emergency calls has a negative impact on all KPIs.

It is particularly interesting to compare the scenario in which single vehicle types (only emergency ambulances) were allocated against the scenario where multiple vehicle types (both emergency ambulances and rapid response vehicles) were allocated. For equivalent resource levels, introducing secondary vehicles increases ambulance utilisation, and so decreases availability, resulting in an increase in abandoned calls. However, introducing secondary vehicles also results in a large decrease in the mean response times, and so a large increase in the percentage of patients seen within target.

It is also noticeable that the increases or decreases in the simulation derived KPIs are not necessarily monotonic with increases in resource level. This is due to the derived allocations being based on the MESLMHPHF score only, which is a measure of survival, while the simulation derived KPIs are indirect measures of performance. This may indicate that these indirect measures of performance, such as mean response times or percentage within target, are not good indicators of survival.

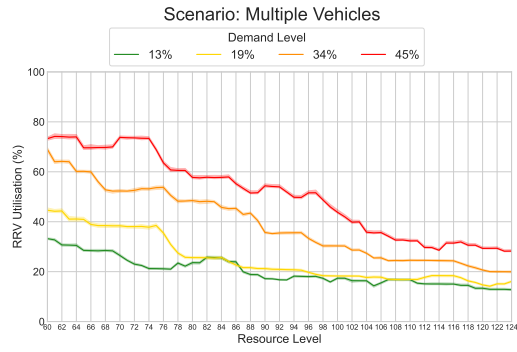
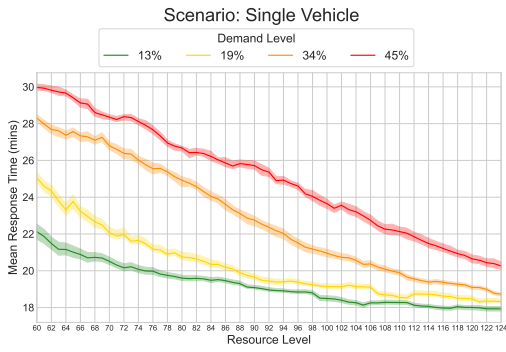
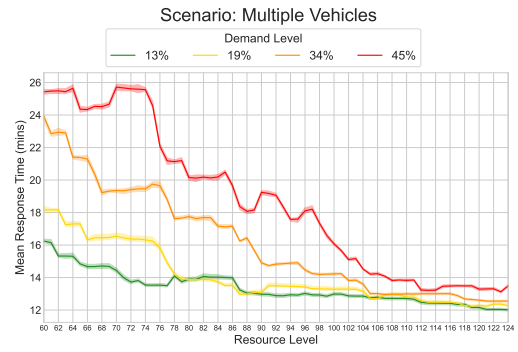


Figure 11: RRV utilisation results.

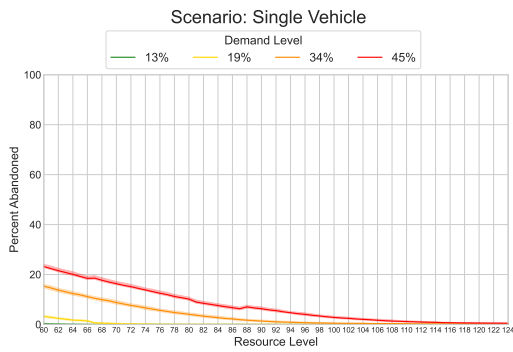


(a) Single vehicle type scenario.

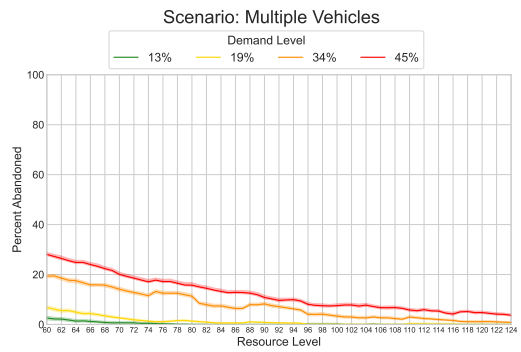


(b) Multiple vehicle type scenario.

Figure 12: Mean response time results.



(a) Single vehicle type scenario.



(b) Multiple vehicle type scenario.

Figure 13: Percent of abandoned calls results.

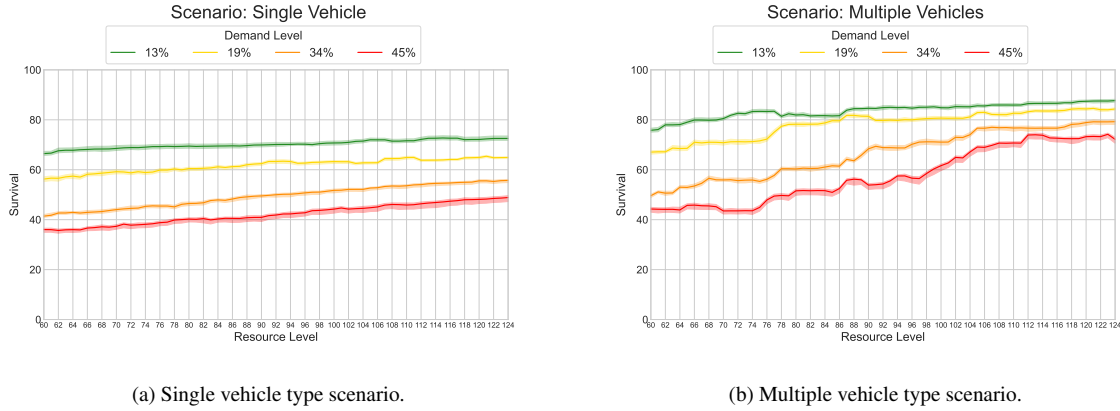


Figure 14: Overall survival results.

Demand Scenario	Mean Response Time	Overall Survival	Percent Abandoned
demand_13	60, (50, 30)	60, (50, 30)	80, (66, 42)
demand_19	70, (60, 30)	78, (63, 45)	101, (79, 66)
demand_34	88, (75, 39)	106, (83, 69)	> 124
demand_45	99, (85, 42)	> 124	> 124
Current Level	16.8 minutes	75.48%	0.0339%

Table 7: Resources required to maintain current KPI levels when optimising locations under the four demand scenarios.

Crucially, the plots show that the allocations produced by the optimisation algorithm perform better than the current allocation for the same demand and resource levels. The current levels include 81 EAs and 13 RRVs, so a resource level of 85.33, with multiple vehicles. Comparing the derived allocations for this level in Figures 10-14 to the results given in Table 2, the derived allocations give lower ambulance and RRV utilisations, lower mean response times, and a higher percentage of patients seen within target.

As experiments were run across all demand scenarios, we can see how much more resources would be required, if optimally located, to achieve a similar level of service as is currently offered, when demand increases. Table 7 shows, for each demand scenario, the minimum resource level and vehicle type breakdown required to meet the current level in each of the following KPIs: mean response time, overall survival, and percentage of calls abandoned. For example, in order to maintain the current 75.48% overall survival, under the demand_19 scenario the city would require 63 EAs and 45 RRVs. It is noticeable that fewer resources are required to maintain the current mean response time than to maintain the current overall survival.

6. Discussion & Conclusions

This paper has described the development of EMS demand and capacity models and their application to the city of Jakarta, Indonesia. To our knowledge, this is the first such study of analysing emergency ambulance services in Jakarta, and the work has directly assisted and guided providers and the government to make investment decisions for a coordinated and free to use EMS.

Firstly, we have considered patient survival and outcomes within a developed MESLMHPHF model. By considering geospatial travel times and accounting for the varying needs of different patient types through categorising patients by speciality and through using different survival function profiles, an expected overall survival was given. This could be used within an optimisation process, in this case by using a population-based neighbourhood search evolutionary heuristic, to find vehicle fleet allocations that maximise expected survival. This expected survival function extends previous work in [18] to include more than one vehicle type. A particular novelty here was numerically solving utilisation relationships, Equations 10 and 11, to calculate the expected survival.

Secondly, a discrete event simulation model has been used to evaluate existing and potential heterogeneous vehicle ambulance fleet allocations in terms of key performance measures, such as response times, survival, and vehicle utilisation rates. This takes into consideration geospatial demand and travel, and temporal variation in demand and traffic levels. A novel feature of our approach is that the model comprises of sequential simulations, feeding data directly from one into the other in order to simulate primary and secondary vehicles separately while maintaining synchronicity, with the overall aim of reducing the complexity of the simulation logic.

Both models investigate ambulance service activity in the case of heterogeneous patients and heterogeneous fleets. Heterogeneous patient groups consider those with distinct demand profiles, priorities, and survival functions. Heterogeneous fleets concern different types of vehicles, in our case emergency ambulances (EAs) which respond to every patient, and Rapid Response Vehicles (RRVs) which can be utilised to reach patients faster, despite being unable to transport patients themselves.

Using a combination of models has permitted an approach that can capture performance measures or take into account factors that each model in isolation can not. For example, the maximum expected survival model is a lot more appropriate for use within an optimisation process as the runtimes are a far more reasonable than the simulation. On the other hand, the simulation allows for greater complexity such as temporal demand, and is able to capture a greater range of KPIs.

A key feature of both models, and their novelty, is the consideration of heterogeneous fleets. In a highly populated area such as Jakarta (around 16,000 population per km²), the inclusion of RRVs such as paramedics on motorbikes is very important, given RRVs can access areas that cannot easily or quickly be accessed by ambulances. Results from both the optimisation and simulation research showed that the RRVs can help increase the overall survival and reduce the response times, especially crucial when responding to life threatening events such as cardiac arrests [13].

The results of our research also suggest that allocation strategies may not be intuitive to ambulance service managers, further emphasising the value of a modelling approach. For example, senior managers suggested the use of a grid allocation to maximise geographic coverage, with ambulances equally spread across the city. This was shown to be sub-optimal because neighbour-

hoods have different population densities and characteristics. For example, the number of daily commuters in Jakarta is considerably high during day time due to work and education [15]. Municipalities where trading, educational institutions, and offices are concentrated may become more populated during day time. The model has quantified the deterioration in response times and patient outcomes should a fixed grid system be implemented, leading to 119 to drop this consideration.

The ambulance posts in Jakarta depend on the service provider. Those ambulances provided by the government are in various locations including government buildings as well as community clinics and sub-district hospitals. In our case, we used current ambulance posts as the locations for allocating the resources. As demands for ambulances may change from time to time, future work could evaluate different, and perhaps dynamic, ambulance posts that depend on changing demand volumes in neighbourhoods by time of the day.

The data used for ambulance demand covered one year from 1 January to 31 December 2019, prior the COVID-19 pandemic. Recent studies related to ambulance demand indicate that the pandemic has severely impacted on the utilisation of EMS, for examples in call volumes [31] and in specific medical conditions such as trauma [3], and possibly still continue to affect demand. Ambulance providers, such as 118 and 119, may use our modelling tools to incorporate future demand data and re-evaluate resource needs. To aid this, we are currently working on interfacing the simulation and optimisation into a single easy to use decision support tool with a dashboard (data visualiser).

Studies have shown that the quality in pre-hospital data collection varies considerably in Indonesia [14]. We encountered similar challenges and have suggested to 119 and the Indonesian Government that they should continue to strive to improve the coverage and quality of data collection. Future work could explore in more depth unmet demand that is not recorded in the ED or in the ambulance data.

Indonesia is a vast country with an uneven population density and varying quality of available healthcare resources. The models have been parameterised with data from a high population, high density urban area which is also relatively well resourced with healthcare facilities compared to other regions in the country. Ambulance services in rural areas of Indonesia may not have the same quality in management and organisation compared to the capital, Jakarta. We intend to conduct future studies to apply the developed models to analyse ambulance demand and allocations in different areas of Indonesia, including in rural regions.

In conclusion, the developed models have demonstrated a novel approach in modelling ambulance allocations that incorporate multiple vehicle types and health conditions, whilst also capturing patient survival. Our work has already informed major decisions on the design of a free to use and coordinated EMS system for Jakarta. Ongoing collaboration will continue to assist ambulance providers and the Indonesian Government in providing evidence-based decision making for the benefit of patients and the population they serve, including the exploration of the roll-out of 119 beyond Jakarta to other regions of Indonesia.

Acknowledgements

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Appendix A. Annotated Objective Function

$$g(Z_a, \tilde{Z}_a) = \sum_{p \in \mathcal{P}} \sum_{a \in \mathcal{A}} \left(\sum_{k \in \mathcal{K}_A} w_k \lambda_{pk} \hat{\Psi}_{kpa} + \sum_{k \in \mathcal{K}_B} w_k \lambda_{pk} \Psi_{kpa} \right)$$

Expected number of patients surviving, given allocations Z_a and \tilde{Z}_a

Number of patients of a speciality in \mathcal{K}_A surviving

Number of patients of a speciality in \mathcal{K}_B surviving

Weights

$$\Psi_{kpa} = s_k(t_{pa}) (1 - \pi_a^{Z_a}) \prod_{\alpha \in \mathcal{A}} \pi_{\alpha}^{(Z_{\alpha} \beta_{p\alpha a})}$$

Probability of patient speciality k at location p being seen by a *primary* vehicle from station a and surviving

Probability of surviving

Probability of that a *primary* vehicle is not busy

Probability all closer *primary* vehicles are busy

$$\begin{aligned} \hat{\Psi}_{kpa} &= s_k(\hat{t}_{pa}) (1 - \tilde{\pi}_a^{\tilde{Z}_a}) \prod_{\alpha \in \mathcal{A}} \tilde{\pi}_{\alpha}^{(\tilde{Z}_{\alpha} \beta_{p\alpha a})} \pi_{\alpha}^{(Z_{\alpha} R_{p\alpha a})} \\ &+ s_k(t_{pa}) (1 - \pi_a^{Z_a}) \prod_{\alpha \in \mathcal{A}} \pi_{\alpha}^{(Z_{\alpha} \beta_{p\alpha a})} \tilde{\pi}_{\alpha}^{(\tilde{Z}_{\alpha} (1 - R_{p\alpha a}))} \end{aligned}$$

Probability of patient speciality k at location p being seen by a vehicle from station a and surviving

Probability of surviving

Probability of that a *secondary* vehicle is not busy

Probability all closer *secondary* vehicles are busy

Probability all closer *primary* vehicles are busy

Probability of that a *primary* vehicle is not busy

Probability of surviving

Appendix B. Model Parameters

Call arrival rates λ_{pk} are derived from 2019 demand data slit by municipality and speciality, and time of day. Probabilities q_{pky} are similarly derived from the 2019 data of transit journeys. All traffic-free travel times are found using Google Maps API, while time-dependent traffic delays are found from the TomTom website. The other models are parameterised in the following way:

- From a sample of calls the time at site G_k was found to follow a lognormal distribution with parameters $\mu = -0.6219$ and $\sigma = 0.8048$. For the case of Jakarta this was modelled identically for all specialities k . Comparison between the lognormal fit and the sampled times are given in Figure B.15.
- From discussions with staff at the ambulance service in Jakarta, the time at hospital J_k was modelled as a Uniform distribution between 40 and 60 minutes for the emergency specialities A1 and A2, and between 20 and 30 minutes for non-emergency speciality B.
- From discussions with staff at the ambulance service in Jakarta, the refill time Θ is taken to be 60 minutes for an emergency ambulance, and 15 minutes for an RRV.

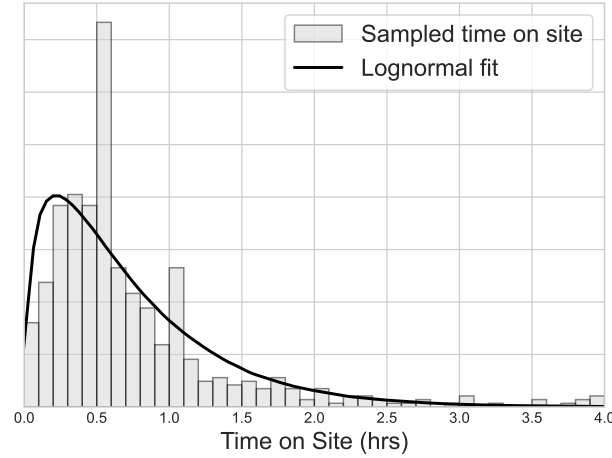


Figure B.15: Comparison between the sampled time on site and the lognormal fit.

Appendix C. Exploration of Optimisation Hyperparameters

Figure C.16 shows the performance of the population-based neighbourhood search evolutionary heuristic algorithm under different values of the hyperparameters N , κ , m_0 , and c .

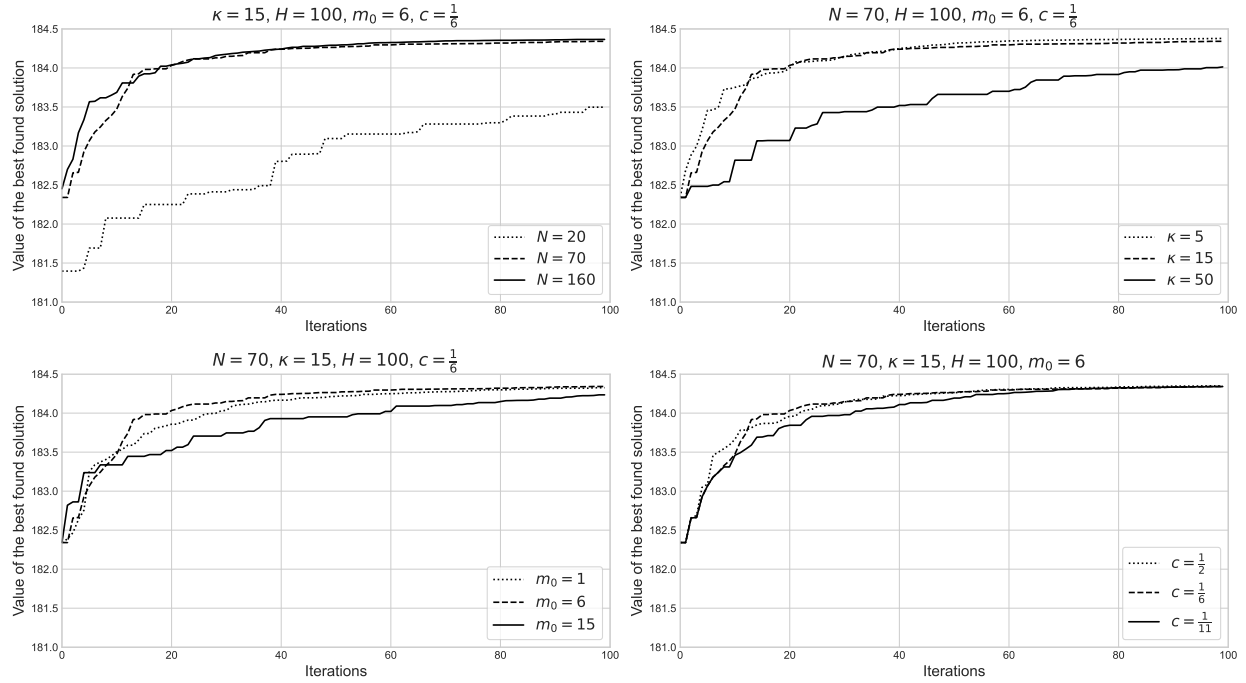


Figure C.16: Comparison between optimisation performance for low, medium, and high values of N , κ , m_0 , and c . Optimisation is run on demand scenario 19, for 70 primary and 30 secondary vehicles.

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