



## Original article

# The application of optimisation modelling and geospatial analysis to propose a coronary care network model for patients with ST-elevation myocardial infarction

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## ARTICLE INFO

## Keywords:

Emergency care system  
Myocardial infarction  
Prehospital cardiac care

## ABSTRACT

**Background:** The incidence of myocardial infarction is increasing in South Africa. Prompt treatment is indicated to reduce mortality. One way of expediting treatment is to set up regional referral recommendations that can guide prehospital providers on the best reperfusion strategy for a particular patient. A coronary care network model for patients who present with ST-elevation myocardial infarction is proposed, using the North West province, of South Africa as a case study.

**Methods:** Geospatial analysis with network optimisation modelling was applied, to determine which strategy (prehospital thrombolysis, in-hospital thrombolysis or percutaneous coronary intervention) was most appropriate for patients presenting within each of the municipal wards of the North West province.

**Results:** An efficient and swift recommendation for the optimal reperfusion strategy is obtained using the current model, even in the instance of a large amount of ward data with additional constraints. For most municipal wards (204, 53%) percutaneous coronary intervention is the preferred reperfusion strategy based on proximity.

For the remainder of the wards prehospital (138, 36%) or in-hospital (44, 11%) thrombolysis is recommended.

**Conclusion:** A scalable and efficient method of determining the optimal reperfusion strategy for a patient presenting with ST-elevation myocardial infarction in the North West province, is presented. This approach can serve as a model which can be applied to other settings and can form the basis of regional coronary care network development priorities and resource allocations.

## African relevance

- Cardiovascular disease and myocardial infarction are on the increase in Sub-Saharan Africa
- There are limited resources to manage patients presenting acutely
- Without a systems overview, it is difficult to distribute resources, and plan for the development of coronary care systems
- This study shows a quick and efficient way to obtain this overview and assist in guiding development

## Introduction

Cardiovascular diseases are currently on the rise in South Africa and other low- to middle-income countries (LMICs) [1]. ST-segment

elevation myocardial infarction (STEMI) is the emergent presentation of cardiovascular disease and requires early intervention and reperfusion to decrease mortality and improve outcome [2]. LMICs, such as South Africa have a shortage of PCI-capable facilities and thrombolysis could be a more realistic reperfusion strategy [3]. Despite having greater PCI resources in Europe, thrombolysis is still administered to STEMI patients who present far away from PCI-capable facilities [4,5] in countries such as Finland, Norway, Cyprus, Italy, and Serbia [6]. Hence, thrombolysis still plays a role even in high income countries when time to PCI is long.

Patients have a better outcome when they are treated with PCI. However, this benefit only exists if PCI can be achieved within 120 min [2]. Failing this timeframe, thrombolysis is recommended [2]. In order to optimise compliance with these recommendations and to improve

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<https://doi.org/10.1016/j.afjem.2020.04.008>

Received 1 May 2019; Received in revised form 12 March 2020; Accepted 13 April 2020

Available online 26 May 2020

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efficiency of referrals, the European Resuscitation Council recommends that regional coronary care networks taking these timeframes into account, be developed [2]. To this end, regionalised strategies should be proposed for patients presenting with STEMI.

By using mathematical modelling (optimisation and geospatial analysis), the aim of this study was to propose the optimal reperfusion strategy in a coronary care network model for patients who present with STEMI.

## Methods

### Study design

This study applied geospatial analysis [7] with network optimisation modelling [8], to determine which strategy (thrombolysis or PCI) is most appropriate for patients presenting within each of the municipal wards of the North West province. These recommendations are based on the proximity of the patient to the closest hospital, with priority given to PCI-capable facilities. The geospatial analyses aggregate and analyse the data and send it to the optimisation software that selects the best treatment option swiftly.

### Setting

South Africa has a tremendous shortage in PCI-capable facilities [3], have significant delays to reperfusion [9,10] and is characterised by poor access to PCI based on geography and socio-economic status [3]. The North West province of South Africa has only one PCI-capable facility, serving a population of 3.7 million people, and covers a landmass of 104,882 km<sup>2</sup> [3]. The median (range) drive time to a PCI-capable facility in the North West province is 115 min (3–454 min) [11]. This province borders the Gauteng province, where 46% of the country's PCI-capable facilities can be found [3]. For these reasons, it was felt that the North West province would be the best to exemplify the optimisation model.

### Data sources

PCI-location data was obtained from a previous study [3]. The locations of regional non-PCI hospitals were obtained through local directories and correspondence with the relevant Departments of Health and private hospital groups. Points within the North West province were plotted using ArcGIS 10 and ArcGIS Online (Esri, California, United States). Further, by using the current South African ward demarcation lines, the mathematical mid-point of each ward (ward centroid) was determined.

### Reperfusion timelines

Reperfusion can be done by two means: thrombolysis or percutaneous coronary intervention (PCI). PCI shows a mortality benefit should it occur within 120 min of first medical contact [2]. First medical contact (FMC) is defined as the moment that the patient presents with signs and symptoms to the initial healthcare provider. In the context of this study, first medical contact is therefore defined as the moment that the ambulance arrives first on scene [2]. Thrombolysis should be initiated within 10 min of STEMI diagnosis, preferably in the prehospital setting should PCI not be reachable within 120 min [2]. Unfortunately, the cost for ambulances to carry these medications might preclude widespread availability in LMICs, such as South Africa; notwithstanding the waste of expensive medications should they expire at an ambulance base. For this reason, the model suggests a preference for in-hospital thrombolysis should it be reachable within 30 min. This is in accordance with previous recommendations [2,12]. Failing this, it suggests prehospital thrombolysis (PHT). Fig. 1 outlines the reperfusion strategies and timelines used in this model.

### Analysis of proximity

Proximity analysis [7] was used to determine the projected driving time from each ward centroid to the closest PCI-capable and PCI non-capable facility. ArcGIS Online (Esri, California, United States) calculates drive times using predicted typical traffic trends. Typical traffic trends for each road are determined within ArcGIS by averaging a week's historic real-time travel speeds, in five minute intervals. These travel times were then imported into an optimisation model.

### Optimisation model

The model selects the optimal reperfusion strategy in a hierarchical fashion, based on the time constraints in Fig. 1. First, primary PCI is selected if possible, hereafter in-hospital thrombolysis and finally pre-hospital thrombolysis. This decision problem was solved with linear optimisation, and integer programming using Lingo Version 13 (Lindo systems Inc., Dayton Chicago, United States). Linear optimisation is a mathematical method used to determine the best (optimised) possible outcome from a given set of requirements (reperfusion strategies based on travel time) and limits (time constraints, based on guideline recommendations) [13]. This approach has been applied to transport problems in emergency medical services previously [14]. The data input, definitions and the detailed model are contained within the Technical Appendix.

### Geographic representation

After solving the optimisation model, reperfusion decision results were extracted to Microsoft Excel (Microsoft Corporation, Washington, United States). Using the coded number of each ward as unique identifier, a geospatial join was created between the optimisation results and the ward centroid files in ArcGIS (Esri, California, United States). Hereafter, each ward centroid was colour coded based on proximity and the recommended reperfusion strategy.

Ethical approval was obtained from the Human Research Ethics Committee of the University of Stellenbosch (HREC Ref Nr: M14/07/027).

## Results

The number of wards and population for each reperfusion strategy is presented in Table 1. For 60% of patients, primary PCI is the preferred reperfusion strategy based on their proximity (assuming availability and no other delays).

By colour coding each ward according to Fig. 1, Fig. 2 presents the recommended reperfusion strategies for each ward in the North West province.

## Discussion

By using mathematical modelling (optimisation and geospatial analysis), an optimal reperfusion strategy in a coronary care network model for patients who present with STEMI in the North West province of South Africa, is proposed. Based on proximity and assuming no delays, most patients in the North West province should be referred for primary PCI; while one third of the population in the province should receive prehospital thrombolysis (PHT). For patients living around areas with regional non-PCI hospitals, expeditious transport and in-hospital thrombolysis should be considered.

The use of network optimisation modelling has been used for decades within the field of operations research and industrial engineering, but has only recently been applied within healthcare. By using this novel application, this study suggests optimal reperfusion strategy recommendations for patients with STEMI. Decomposing and solving the optimisation problem for every ward centroid is more efficient than

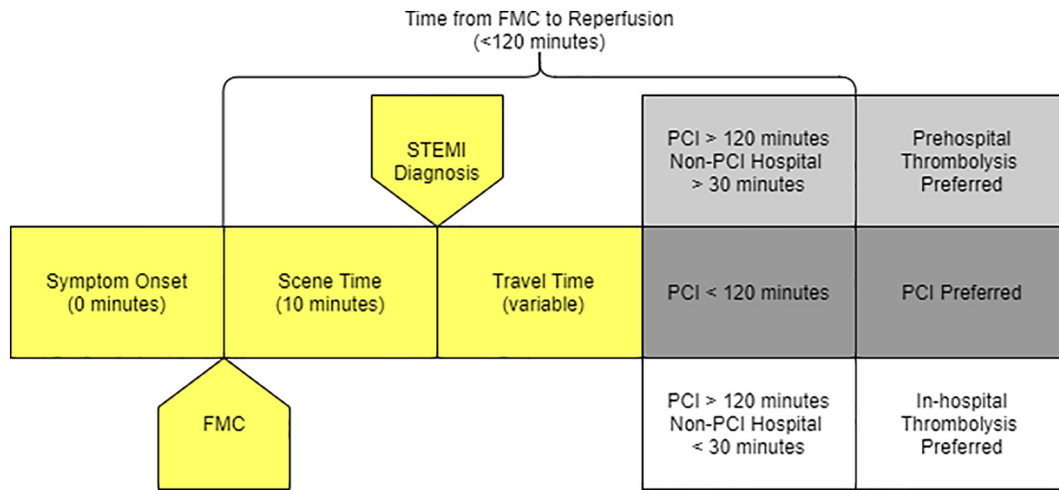


Fig. 1. Reperfusion decisions.

Table 1  
Wards and reperfusion strategy.

	Wards, n (%)	Population, n (%)
PCI preferred <sup>a</sup>	204 (53%)	938,380 (60%)
In-hospital thrombolysis preferred	44 (11%)	185,994 (12%)
Prehospital thrombolysis preferred	138 (36%)	452,525 (28%)

PCI: percutaneous coronary interventions.

<sup>a</sup> Assuming 24-hour PCI access and no other delays.

using an overall model approach. The reason is that the optimization is in the class of integer programming and is therefore, usually hard to solve for larger instances. Hence, with the current modelling approach optimal solutions are swiftly received, even in the case of a large amount of ward centroids and additional constraints. This approach could be utilised in real time to provide treatment decisions at the bedside based on actual, live traffic and proximity conditions. This approach is also scalable, and can be implemented to provide similar recommendations for an entire country.

In this manner, two models are therefore implementable, a static

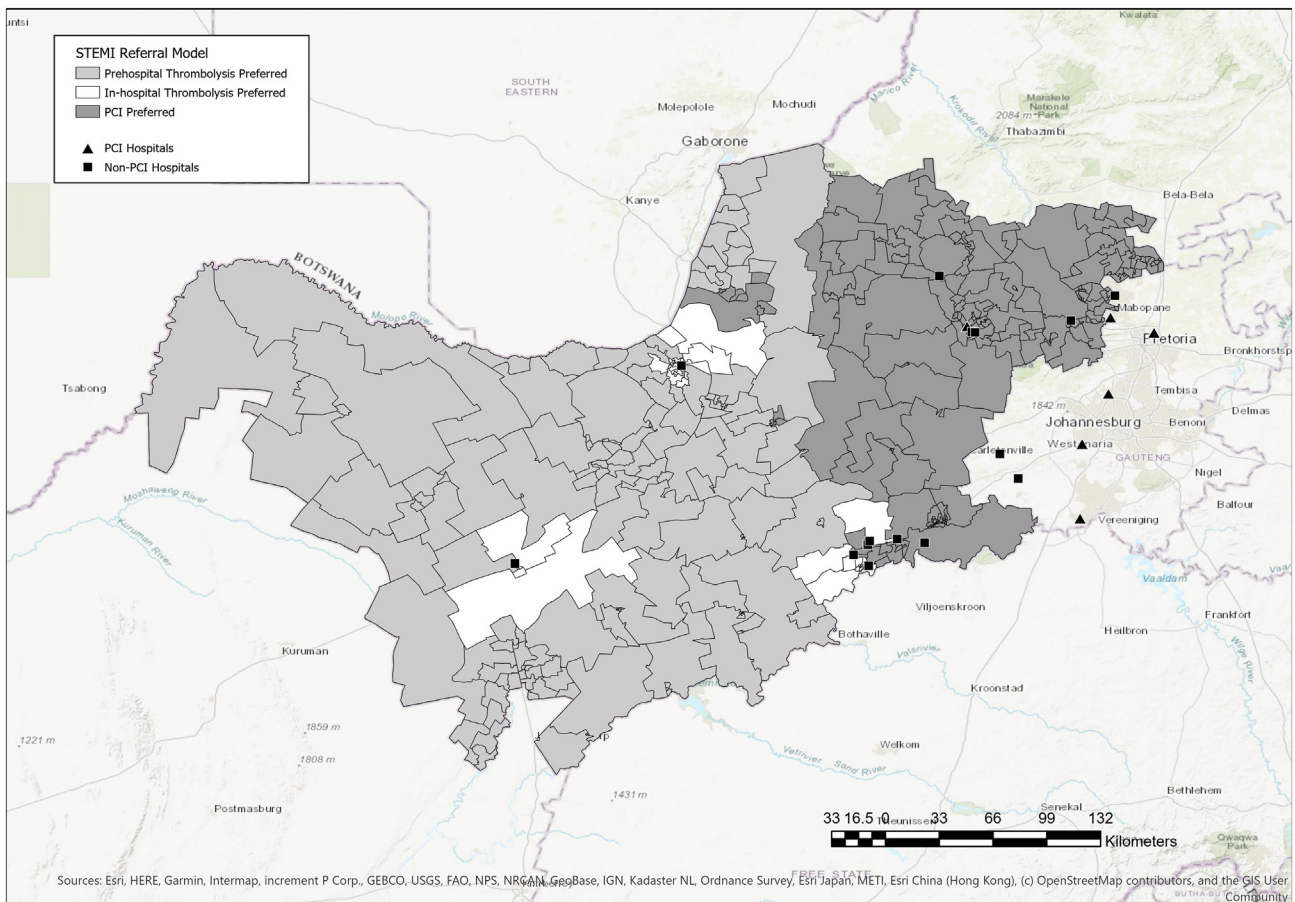


Fig. 2. The North West province with reperfusion strategy recommendations.

and dynamic (real-time) model. By employing a case-by-case basis, one could not allow for adequate coronary network planning and resource allocation in the low- to middle-income setting. A static model informs the specific priorities in the development and implementation of regionalised coronary care networks. It can therefore allow for tailored resource allocation and targeted education programmes based on proximity to existing resources and proposed reperfusion strategies, as identified by the model. The model can guide where practitioners that are licensed to provide prehospital thrombolysis should be recruited and deployed, where thrombolytic agents should be stocked and where twelve lead ECG equipment (with or without telemetry) should be placed. Efficient resource-allocation can be guided. The real-time model may then be used to make a decision at the bedside to individualise the specific treatment strategy based on current road conditions and traffic situations.

The optimisation model assumes prompt contact with ambulance services, as recommendations are based on drive times from FMC with emergency medical services, rather than patients who self-present to other healthcare providers. In the South African context, few people utilise ambulance transport and thus end up presenting to primary care physicians or closer non-PCI capable facilities [10,12]. This contributes to significant delays in PCI [12]. Low rates of ambulance utilisation in myocardial infarction have also been described in China [15], Ireland [16], and the United States [17]. For this reason, public education campaigns should highlight the importance of ambulance transport. Secondly, ambulance personnel should be educated and mandated to preferentially transport patients to PCI-capable facilities if within the referral areas. Redundancies should be considered as ambulances will be out of commission for a longer period, and might place strain within an already resource-limited ambulance context [18]. The use of helicopter emergency medical services (HEMS) could increase the proportion of patients with timely PCI access [19]. HEMS activation and flight times could be included in the model, to provide for this transport option.

To account for resource constraints, in-hospital thrombolysis was included as a recommendation in a smaller proportion of STEMI patients in the North West province, based on proximity. Previous South African and international studies have found that there are many in-hospital delays to thrombolysis [10,12,20]. In order to ensure timely in-hospital thrombolysis, a concerted effort should be made to identify and mitigate causative factors. To avoid in-hospital delays it has been suggested to extend thrombolysis to the prehospital environment [2].

A recent Cochrane Review found that PHT significantly decreases the time to treatment in patients with STEMI, without increasing the risk of adverse effects [21]. A PHT programme might be of particular value in low- and middle income countries with limited access to PCI [21,22], or in the rural areas of higher resourced countries [22]. Internationally, only certain prehospital providers are trained and licensed to administer PHT [23]. In South Africa, only prehospital providers with a four year degree in emergency medical care (Emergency Care Practitioners, ECPs) are authorised to perform PHT. There is a critical shortage of ECPs in South Africa [24]. In addition, the cost of thrombolytic agents and the risk of expiry (and waste), may prevent the widespread distribution of thrombolytics to all ambulances.

Regardless of the setting, it is suggested that accurate dispatch prediction algorithms be developed to identify patients most at risk of STEMI, so that prehospital providers with 12 lead ECGs and trained in PHT preferentially be dispatched to the right cohort of patients. It is further suggested that these vehicles be based in areas where PHT is the recommended reperfusion strategy (the dark zones in this model). These approaches might allow for the effective direction of limited resources to the patients with the greatest need for PHT with minimised delays.

To safely implement a PHT programme for STEMI, a contextual system should be developed that is tailored to each specific milieu. Regardless of setting however, literature suggests that the essential

components to a prehospital thrombolysis programme should include: prehospital personnel trained in 12 lead ECG acquisition and diagnosis (or ECG telemetry) [2,25], eligibility criteria for thrombolysis [2,25], direct access to expert cardiology consult [25], and immediate referral to a PCI-capable facility after prehospital thrombolysis [2]. Within the context of a new system, a robust clinical governance system should also be developed.

The current study has some limitations. The analysis of proximity is based on typical (average) drive times and traffic conditions and therefore exceptions are not accounted for. Other timelines such as delays in patient help-seeking, emergency services dispatch centres, response times and locations of ambulances, and scene times were not taken into consideration. It is possible that drive time could dramatically change over time as road infrastructure is developed. However, these variations can easily be implemented into the model for more specific recommendations, even in real time, and could be tested in future studies. In-hospital delays to PCI or thrombolysis have also not been accounted for. These timelines can be included as input constraints as they become available through descriptive studies.

Further research should be done into some of the essential components for prehospital thrombolysis programmes and minimising in-hospital reperfusion delays, especially in LMICs. Epidemiological studies should identify areas with a high incidence of STEMI.

As this optimisation model is easily scalable, it should be applied in other provinces in South Africa to provide national coronary care network recommendations for patients with STEMI. The model may also serve as a template for other settings, and for other conditions that are dependent on the development of networks, such as trauma and stroke care.

## Conclusion

By utilising optimisation modelling and geospatial analysis, a coronary care network model for patients presenting with STEMI in the North West province of South Africa, is proposed. This model can be applied in other settings, where it can form the foundation for the development of coronary care networks and prehospital thrombolysis programmes, tailored to each unique context. The next step is to include other constraints not currently in the model and develop the model for real time application. Furthermore, and especially in the context of LMICs, a programmatic cost analysis should be performed to determine whether these recommendations are cost effective.

## Dissemination of results

The results of this study was published in a thesis. The results were also shared with the South African Heart Association to assist them in their development of coronary care networks in South Africa.

## Authors' contribution

Authors contributed as follows to the conception or design of the work; the acquisition, analysis, or interpretation of data for the work; and drafting the work or revising it critically for important intellectual content: WS contributed 60%; LO 25%; and LK contributed 15%. All authors approved the version to be published and agreed to be accountable for all aspects of the work.

## Declaration of competing interest

Dr Willem Stassen is an editor of the African Journal of Emergency Medicine. Dr Stassen was not involved in the editorial workflow for this manuscript. The African Journal of Emergency Medicine applies a double blinded process for all manuscript peer reviews. The authors declared no conflicts of interest.



## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.afjem.2020.04.008>.

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