Design, modelling, evaluation, and optimisation of intensive care unit network in Hong Kong: abridged secondary publication

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KEY MESSAGES

1. We built a framework involving the design, evaluation, and optimisation of intensive care unit (ICU) networks in Hong Kong, particularly during pandemics and mass casualty events.
2. The model for the Hong Kong ICU network enables central management and sharing of ICU beds to improve quality of service metrics without incurring additional expenditure on new resources.
3. We analysed real data from hospitals in the New Territories Northeast cluster and identified appropriate arrival process and length of service distributions for different types of patients (internal emergency, external emergency, and elective).
4. We applied the International Ethics Standards for Sustainability Assurance framework to evaluate the rejection or deferral rate for each type of patients, with reasonable accuracy.
5. We proposed a heuristic algorithm based on particle swarm optimisation to determine the optimal set of relevant network parameters, and then combined it with the International Ethics Standards for Sustainability Assurance method for evaluating each setting. The combination can effectively reduce computation time by up to two orders of magnitude while obtaining the same optimal solution.

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Introduction

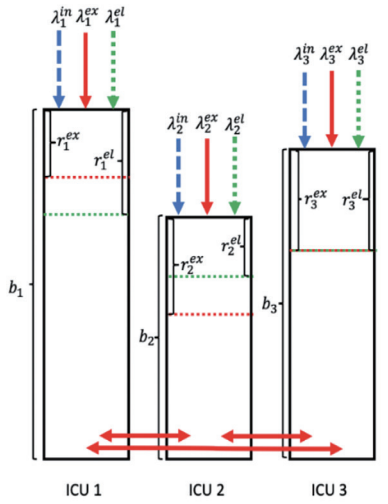
Intensive care units (ICUs) can cost up to six times more per day than general wards.[1] Their demand exceeds supply;[2] thus, efficient use of ICUs, especially during epidemics and mass casualty events, is crucial. This requires the systematic development of policies for ICU admission. One solution is to group multiple ICUs into a network, allowing some patients to be treated at any ICU within the network.[3]

We developed analytical models to study hypothetical scenarios, such as short-term increases in admissions caused by epidemics or mass casualty events, and to develop special policies for handling such scenarios. Our models can perform 'what if' analyses on historical events to determine policy effectiveness. This study aimed to demonstrate that (1) an ICU resource-sharing policy increases the proportion of successful admissions, compared with a non-sharing scenario; (2) a framework for evaluating and optimising the control parameters associated with our proposed policies facilitates better management and planning of ICU resources; and (3) newly proposed tools for performance evaluation and optimisation provide significantly enhanced computational efficiency and accuracy comparable to state-of-the-art approaches.

Methods

We constructed a network model comprising multiple ICU hospitals and three classes of patients: internal emergency, external emergency, and elective (Fig 1). Although internal emergency and elective patients must be treated at their original hospital, external emergency patients are flexible and may overflow to any hospital in the network. A reservation threshold was introduced for each class of patients, such that a certain class could not be admitted if the number of available ICU beds at the hospital was below the threshold.

Over 3400 records spanning January 2016 to January 2017 were collected from three ICU hospitals in the New Territories East Cluster (Prince of Wales Hospital, Alice Ho Miu Ling Nethersole Hospital, and North District Hospital). The peakedness (variance-to-mean ratio) of selected patient presentations was high, requiring more general processes than the classical Poisson process used in queuing models. We used two-moment match methodology[4] to construct an interrupted Poisson process to fit the mean, variance, and peakedness of actual traces of patients by type and hospital. The length of service (LoS) distributions of all types of patients were used because individual



ICU j has a total of b_j beds.

Internal emergency patients have access to all beds in the primary hospital.

Elective patients for ICU j have access to the first $b_j - r_j^{el}$ beds in the same ICU.

External emergency patients for ICU j will attempt to access the first $b_j - r_j^{ex}$ beds in the same ICU, and will have access (overflow) to other ICUs with sufficient available capacity (after accounting for reservation policies in respective ICUs)

FIG 1. The proposed intensive care unit (ICU) network model, patient arrivals by class, overflow of external emergency patients, and bed reservation policy.

data were unavailable. Exponential and lognormal distributions were utilised to investigate the sensitivity of quality-of-service metrics to the LoS distributions and corresponding parameters.

Although discrete event simulations can accurately evaluate key performance metrics in ICU networks, they are not scalable for optimisation in large-scale systems, in which repeated measurements are needed to verify feasibility and optimality. We used the International Ethics Standards for Sustainability Assurance (IESA) framework,[5] which has demonstrated effectiveness in evaluating blocking probabilities in ICU networks. We applied particle swarm optimisation, a representative heuristic algorithm designed to improve efficiency over exhaustive search in obtaining optimal solutions to large-scale problems. Specifically, we adopted a variant designed for optimisation problems involving integer decision variables.

Results

We demonstrated the effect of pooling ICU beds across four hospitals (ie, multiplexing). The overall patient rejection rate was reduced by approximately 78%, compared with the baseline approach, which restricted patients' access to beds outside their original hospital (Fig 2). Although a similar reduction in patient rejection rate could be achieved by increasing the number of beds by 30% to 40%, our multiplexing approach offered a more cost-effective solution without additional expenditure.

Low relative differences in the first three moments were achieved by fitting the interrupted Poisson process to real traces of patient arrival data so that it represented the arrival process for all patient traces in the later stage of the project.

The patient rejection rate, a key quality-of-service metric, was not particularly sensitive to changes in LOS distribution. Given that the IESA framework has shown accuracy across a wide range of scenarios in which assumptions of Poisson arrivals and exponentially distributed LoS values are satisfied, the framework was deemed a valid tool for approximating patient rejection rates in the Hong Kong ICU network.

A weighted sum of rejection rates across patient types was minimised by adjusting bed reservation thresholds for each patient class, while maintaining the rejection rate for each patient class below a predetermined threshold. In ICU networks comprising three to 17 hospitals, results and computation times of three approaches

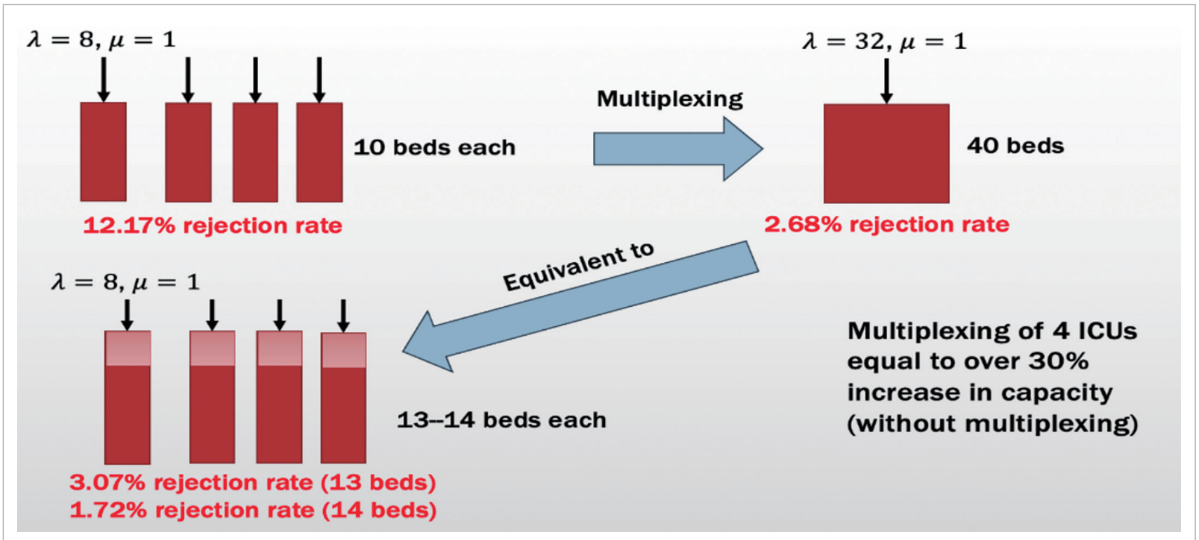


FIG 2. Improvement in rejection rate through multiplexing available resources within the intensive care unit (ICU) network.

were compared: (1) discrete event simulation for evaluation and exhaustive search for identifying the optimal solution (baseline approach); (2) IESA for evaluation and exhaustive search for identifying the optimal solution; and (3) IESA for evaluation and particle swarm optimisation for identifying the optimal solution. All three approaches produced the same reservation threshold solution, indicating that IESA accuracy was sufficient for optimisation purposes. In a comparison of computation times, the heuristic particle swarm optimisation + IESA approach reduced the computation time by up to two orders of magnitude, compared with the baseline approach (Fig 3).

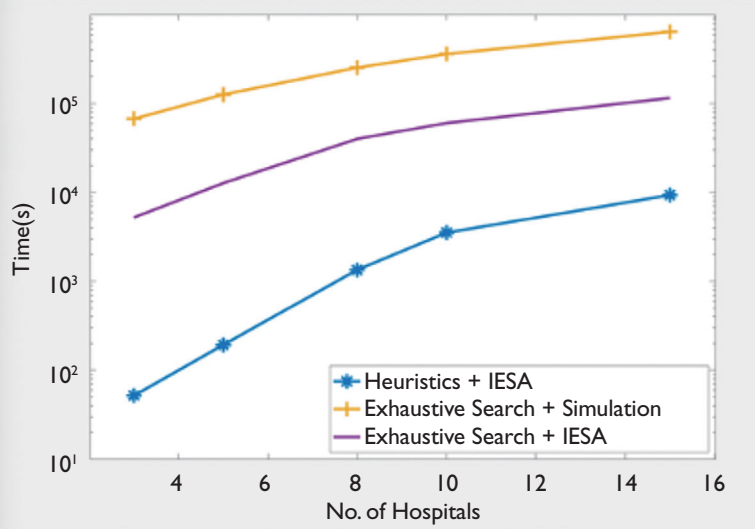


FIG 3. Comparison of computational efficiency across optimisation approaches as the number of intensive care unit (ICU) hospitals in the network increases.
Abbreviation: IESA=International Ethics Standards for Sustainability Assurance

Discussion

During pandemics or mass casualty events, it is likely that many infectious cases or casualties will occur at a single location, leading to a surge of patient arrivals requiring ICU care. Our proposed policies for coordinating the response of multiple hospitals through the pooling of available resources can help improve efficiency in handling such incidents.

Hong Kong has a rapidly ageing population; >30% of residents are projected to be aged ≥65 years by 2036. This will increase the burden on the healthcare system, including ICUs. Our proposed models can simulate hypothetical scenarios of increased patient arrivals caused by epidemics, mass casualty events, or population ageing, addressing both short-term and long-term increases in ICU demand.

The substantial enhancement provided by our design, modelling, evaluation, and optimisation tools may prove useful in other applications, particularly those involving multiple ICUs interconnected via patient referrals.[3] Future simulations may incorporate additional parameters, such as the number of ICU beds allocated to each hospital and factors related to patient referral policies. Our proposed models may help address questions regarding the balance between efficiency and fairness within a network of ICUs.

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Disclosure

The results of this research have been previously published in:

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