ISSN 2090-3359 (Print)
ISSN 2090-3367 (Online)

Advances in Decision Sciences

Volume 28
Issue 4
December 2024

Published by Asia University, Taiwan and Scientific and Business World

Assessing the Efficiency of Hong Kong Public Hospital Sector During the COVID-19 Pandemic: An Input-oriented Structural Efficiency Approach

TSANG, Chun Kei
Department of Economics and Finance, Hong Kong Shue Yan University
Business, Economic and Public Policy Research Centre, Hong Kong Shue Yan University
* ***Corresponding Author*** E-mail: cktsang@hksyu.edu

LI, Sung Ko
Department of Economics and Finance, Hong Kong Shue Yan University
Business, Economic and Public Policy Research Centre, Hong Kong Shue Yan University
Centre for Sustainable Development Studies, Hong Kong Baptist University
E-mail: skli@hksyu.edu

LEE, Shu Kam
Department of Economics and Finance, Hong Kong Shue Yan University
Business, Economic and Public Policy Research Centre, Hong Kong Shue Yan University
E-mail: sklee@hksyu.edu

Received: May 16, 2024; First Revision: August 22, 2024;

Last Revision: October 11, 2024; Accepted: November 30, 2024;

Published: December 31, 2024

Abstract

Purpose: The available literature on the impact of COVID-19 on the healthcare system is relatively limited. This paper aims to evaluate the efficiency of the public hospital sector in Hong Kong during the COVID-19 pandemic.

Design/methodology/approach: One characteristic of the Hong Kong public hospital sector is the cluster-based management model. This paper developed an input-oriented structural efficiency measure with subgroups not yet documented in the literature. This measure is then applied to the data from 38 public hospitals in 7 hospital clusters managed by the Hong Kong Hospital Authority (HA) from fiscal year 2017-18 to 2022-2023. The study contributes to the field of Decision Sciences by applying and extending Data Envelopment Analysis (DEA), a core operations research technique, to provide actionable insights for strategic planning and resource allocation in public health systems.

Findings: The results show that the excess resource usage of the whole hospital sector increased from around 24% before the pandemic to around 40% during the late pandemic period. The results further reveal that it mainly originated from the inefficiency within individual hospitals. Resource allocation among hospital clusters is very efficient, whether before or during the COVID-19 pandemic. However, resource allocation within hospital clusters worsened in three clusters but improved in another three clusters.

Originality/value: This paper makes an original contribution by developing and applying a novel input-oriented structural efficiency measure that accommodates subgroups, a methodology not previously documented in the literature for this context. By applying the new measure developed, this paper evaluates the efficiency of the Hong Kong public hospital sector during the COVID-19 pandemic and decomposes such inefficiency into individual hospital clusters and levels of the public hospital sector.

Keywords: COVID-19; Hong Kong Hospital Sector; Cluster-based Model; Input-oriented Structural Efficiency; Data Envelopment Analysis (DEA)

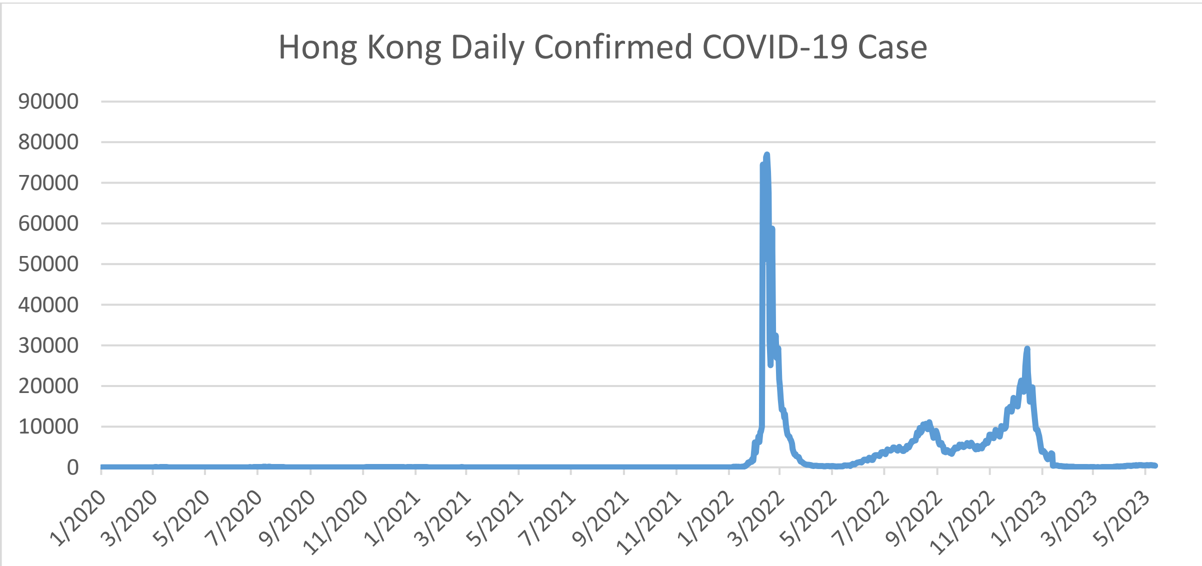
JEL Classification: C11, I18, L31

1 Introduction

In December 2019, a new coronavirus known as SARS-CoV-2 emerged, causing COVID-19. The first cases were recorded in Wuhan, China, and the virus rapidly spread globally. On 23 January 2020, Hong Kong reported its first confirmed case of COVID-19. In response to the outbreak, the Hospital Authority (HA) announced the activation of the Emergency Response Level, the highest warning tier for public hospitals.[1] Visiting arrangements in all public hospitals had been suspended, with only compassionate visits allowed based on clinical considerations. Everyone entering public hospitals and clinics was required to wear surgical masks. Volunteer services and clinical attachments in public hospitals were also suspended. All hospital clusters reviewed their non-emergency services to adjust operations and focus on the resources needed to manage the novel coronavirus.

With strict measures such as temporarily closing entertainment venues and mandatory mask-wearing in all public places, Hong Kong successfully limited daily confirmed COVID-19 cases to below 150 in 2020 and 2021. However, a severe outbreak occurred in late February 2022, with daily confirmed COVID-19 cases peaking at over 75,000, over 1% of her population (see Figure 1). As COVID-19 patients overwhelmed public hospitals, the Hong Kong SAR government and the Hospital Authority focused on adopting more radical measures, including designating the Queen Elizabeth Hospital as a primary facility for COVID-19 patients.[2] Non-COVID-19 patients were transferred to other hospitals or deferred their treatment plans. Although the situation then came under control in late April 2022, a few more outbreaks occurred in late 2022 and early 2023. To sum up, 2020 to 2023 are the COVID-19 period in Hong Kong, and the city's public hospital sector was greatly challenged in 2022 and 2023.

Figure 1: Hong Kong Daily Confirmed COVID-19 Cases



Data Source: School of Public Health, The University of Hong Kong. https://covid19.sph.hku.hk/dashboard. Accessed on 13 July 2023.

[1], on 25 January 2020. https://www.info.gov.hk/gia/general/202001/25/P2020012500689.htm. Accessed on 11 July 2023.

[2] news.gov.hk, Hong Kong. QEH to Receive COVID-19 Patients. 9 March 2022. https://www.news.gov.hk/eng/2022/03/20220309/20220309_122210_867.html. Accessed on 11 July 2023.

There are several possible impacts of COVID-19 and its related restrictive measures on the Hong Kong public hospital sector. The HA is responsible for overall planning, and hospital cooperation is encouraged. Since all public hospitals are under the control of HA, it can be regarded as a central planning management system. The coping measures with COVID-19 diminish the contact among people and the flow of resources. They weaken hospitals' cooperation and harm the aggregate provision of hospital services. Both planning and cooperation are adversely affected. Furthermore, measures for fighting COVID-19 in hospitals are introduced, e.g., the extra effort of sterilization and the requirement of social distancing. The daily management and operations inside hospitals become less efficient because the HA staff are required to spend extra effort to prevent the spread of the disease.

As Hong Kong announced the end of all restrictions related to COVID-19 in mid-2023[3], it is important to assess the impact of COVID-19 and the associated restrictive measures on the public hospital sector in Hong Kong during the pandemic. This paper seeks to assess the efficiency of the public hospital sector in Hong Kong during the COVID-19 pandemic. To analyse the impact of the COVID-19 pandemic and its associated restrictive measures, the method presented by Tsang and Li (2020) was developed into an input-oriented structural efficiency measure that accommodates the presence of subgroups. To the best of our knowledge, this methodology with subgroups has not yet been documented in the literature.

This paper examines data from 38 public hospitals across seven hospital clusters managed by the Hong Kong Hospital Authority (HA) for the fiscal years 2017-18 to 2022-2023, encompassing both pre-COVID-19 and COVID-19 periods. The new approach allows researchers to assess and compare the efficiency of the Hong Kong public hospital sector across different years. The findings will provide a comprehensive understanding of how the COVID-19 pandemic and its associated restrictions have impacted the delivery of hospital services. This offers a significant policy implication for government officials when designing measures for future pandemic outbreaks.

Specifically, the research questions of the paper are:

RQ1: Has the efficiency of the Hong Kong hospital sector been negatively impacted during the pandemic?
RQ2: Has the efficiency of individual hospitals been negatively affected during the pandemic?
RQ3: Has the efficiency of resource allocation been negatively impacted during the pandemic?
Since the Hong Kong public hospital sector adopted a clustering system, two additional studies have emerged:
RQ4: Did the changes observed in RQ3 result from resource allocation among different clusters or within the same clusters?
RQ5: Have the efficiency patterns in the Hong Kong hospital sector varied across different clusters?

By employing an advanced Data Envelopment Analysis (DEA) framework, this study provides a robust tool for evidence-based decision-making in healthcare management, a key area of interest in

[3] news.gov.hk, Hong Kong. LeaveHomeSafe code scanning lifted. 13 December 2022. https://www.news.gov.hk/eng/2022/12/20221213/20221213_161346_083.html. Accessed on 11 July 2023.

Decision Sciences. The remainder of the paper is organized as follows. Section 2 reviews the literature and theoretical background. Section 3 introduces a modified model of input-oriented structural efficiency that includes subgroups. Empirical estimations, data, and results are presented in Section 4. Finally, Section 5 provides the conclusions of this study.

2 Literature Review and Theoretical Background

In December 2019, a coronavirus called SARS-CoV-2, which caused the new disease COVID-19, was first reported in Wuhan, China. Since then, COVID-19 has quickly spread across the globe. The primary focus has been on prevention and containment, alongside an ongoing effort to understand the disease's characteristics for early detection, effective management, and triage information (Allen & McAleer, 2020; Tuan, et al., 2022). This pandemic significantly impacted the healthcare system, drawing the attention of numerous scholars to the effects on healthcare service delivery. Some studies indicate a decline in the efficiency of the healthcare system during the COVID-19 pandemic. (See, for example, Mishra, et al., 2023; Henriques & Gouveia, 2022; Androutsou, et al., 2022) However, previous studies have mainly concentrated on assessing the efficiency of individual healthcare units rather than looking at the efficiency of the healthcare system as a whole, especially resource allocation. As Li and Cheng (2007) highlighted, the methods used to measure individual and group efficiency are different, which can lead to varying policy implications.

The Hong Kong Hospital Authority (HA), a statutory body established under the Hospital Authority Ordinance of Hong Kong Special Administrative Region in 1990, has been managing the public hospital sector in Hong Kong, including 43 public hospitals (and institutions) and 122 outpatient clinics with over 89,000 staff members and 20,000 beds for the 7.5 million population as of March 2022 (Hong Kong Hospital Authority, 2022). One characteristic of the Hong Kong public hospital sector is the cluster-based management model.[4] While the chief executive (CE) of HA handles the top-level management of the whole sector at the head office, seven hospital clusters are established to confine the roles and clinical linkages of hospitals in clusters to avoid duplication, with the continuity of healthcare services. A cluster chief executive (CCE) is appointed as the head of each cluster and is responsible for the overall operation of the hospitals and services in the cluster to facilitate the rationalization of services and amalgamation of hospital functions. Refer to Ng and Li (2022) for an in-depth discussion on the cluster-based management model of the Hong Kong public hospital sector.

In this model, the Chief Executive (CE) of the Hospital Authority (HA) oversees the overall management of the sector from the head office. Seven hospital clusters have been established to streamline operations and ensure continuity of healthcare services. Each cluster has a Cluster Chief Executive (CCE), who is responsible for the overall operation of the hospitals and services within the cluster. This structure is designed to facilitate the rationalization of services and the consolidation of hospital functions, ultimately preventing duplication of efforts. The CCE oversees the budget and ensures that resources are used effectively to maximize health benefits for the population served. The CCE reports directly to the CE of the HA. Within each public hospital, the Hospital Chief Executive

---

[4] See Ng and Li (2022) for a detailed discussion on the cluster-based management model of the Hong Kong public hospital sector.

(HCE) serves as the hospital manager and reports to the CCE of the cluster to which the hospital belongs. A study evaluating the resource efficiency of the HA from 2000 to 2013 revealed persistent issues, such as inequitable resource allocation and poor management, despite the HA's ongoing efforts to improve healthcare services (Guo, et al., 2017). Hospital clusters improve healthcare delivery by bringing together multiple facilities, which enhances coordination, efficiency, and quality of care. This model is particularly advantageous in areas with dispersed populations, limited resources, or differing healthcare infrastructure. Clustering management enhances resource allocation, service access, and provider collaboration within a specific geographic area.

By analyzing group efficiency, researchers can evaluate the effectiveness of coordination mechanisms such as telemedicine, referrals, and centralized decision-making. Research on group efficiency in cluster-based hospital management reveals the synergistic effects of collaboration, coordination, and contextual factors on healthcare delivery. See Thomas, et al. (1981), Sikka, et al. (2009), Delamater, et al. (2013), and Shay (2014) for further discussions on the cluster-based hospital system. On 23 January 2020, Hong Kong reported its first confirmed COVID-19 case. Since then, the city has implemented restrictive measures to keep daily confirmed COVID-19 cases below 150 in 2020 and 2021. However, a severe outbreak occurred in late February 2022, resulting in over 75,000 confirmed cases in a single day, which posed significant challenges to the city's public hospital sector. This dramatic situation has prompted us to investigate the changes in efficiency within the Hong Kong public hospital sector.

Most existing literature on group efficiency has focused on the potential of increasing outputs without adding input resources (see, for example, Li & Ng, 1995; Li & Cheng, 2007). However, the situation in the public hospital sector is different. In this sector, outputs are exogenous, and the primary objective is to minimize the use of input resources. Therefore, an input-oriented efficiency measure is more appropriate, as demonstrated in the studies by Kamel and Mousa (2021) and Androutsou, et al. (2022). While some types of literature utilize input-oriented structural efficiency measures (see, for example, Zhang & Duan, 2016), to the best of our knowledge, this methodology with subgroups has not yet been documented in the literature.

This paper has a twofold focus. First, the paper examines management practices within individual hospitals. The pandemic measures implemented to cope with COVID-19 introduced numerous restrictions on daily hospital operations, significantly increasing the pressure on each facility's internal operations. Effective management is essential to mitigate this pressure. If hospital management teams cannot guide their staff in adapting to these measures, the quality of patient services will decline, leading to a decrease in technical efficiency.

Second, the paper studies the allocation of resources in the hospital sector. The outbreak of this pandemic caused a shortage of hospital resources. Effective planning is necessary to achieve the efficient allocation of resources. Additionally, the pandemic reduced the availability of these resources. The market force is confined to the public hospital sector in Hong Kong, which is managed by the HA. If the HA cannot effectively plan and allocate its limited resources among hospitals, these resources will not be utilized in the best way possible. This, in turn, would result in lower allocative efficiency.

To address the research questions, this paper utilizes Tsang and Li's (2020) structural efficiency measure that accommodates the presence of subgroups to evaluate the hospital cluster system.

However, based on the discussions above, input-oriented efficiency measures are more suitable for modeling the operations of the public hospital sector. This highlights the necessity to develop an input-oriented efficiency measure that also considers the presence of subgroups.

3 Methodology

Most existing literature on group efficiency focused on the potential of increasing outputs without adding input resources (see, for example, Li & Ng, 1995; Li & Cheng, 2007). However, the operation of the public hospital sector is different. During the pandemic, policymakers must adapt their plans to address new situations. The number of patients is mainly uncontrollable. In other words, the outputs are determined externally, while public hospitals aim to minimize the use of inputs. In this case, an input-oriented efficiency measure is more suitable, as Kamel and Mousa (2021) and Androutsou, et al. (2022) demonstrated. While a limited number of studies utilize input-oriented structural efficiency measures (see, for example, Zhang & Duan, 2016), to the best of our knowledge, no existing literature has documented this methodology in the context of subgroups. Therefore, the objective of this study is to develop this measurement by considering the presence of subgroups and exploring their decomposition.

3.1 Input-oriented Structural Efficiency Measure

Suppose there is a group of K hospitals. Each hospital employs N inputs/ resources ($\boldsymbol{x} \in \mathbb{R}_+^N$) to provide M outputs/ services ($\boldsymbol{y} \in \mathbb{R}_+^M$). The kth hospital produces an output vector $\boldsymbol{y}^k = (y_{1k}, \cdots, y_{Mk})$ by employing input vector $\boldsymbol{x}^k = (x_{1k}, \cdots, x_{Nk}), k = 1, \cdots, K$. The relation between inputs and outputs can be characterized by the *production set* $\Im \coloneqq \{(\boldsymbol{x}, \boldsymbol{y}): \boldsymbol{x} \text{ can produce } \boldsymbol{y}\}$. Let $(\boldsymbol{x}^{k0}, \boldsymbol{y}^{k0})$ be the observed input-output vector for hospital k, $k = 1, \cdots, K$. Denote the observed aggregate input-output vector be $(\boldsymbol{X}^0, \boldsymbol{Y}^0) = \sum_{k=1}^K (\boldsymbol{x}^{k0}, \boldsymbol{y}^{k0})$. Following Li and Ng (1995), if resource reallocation among hospitals is allowed, the group production set for all J hospitals is,

$$\Im^g \coloneqq \left\{(\boldsymbol{X}, \boldsymbol{Y}): \boldsymbol{X} = \sum_{k=1}^{K} \boldsymbol{x}^k, \boldsymbol{Y} = \sum_{k=1}^{K} \boldsymbol{y}^k, (\boldsymbol{x}^k, \boldsymbol{y}^k) \in \Im, k = 1, \cdots, K\right\}. \tag{1}$$

Given the output targets, the potential of reduction in inputs can be estimated by the following *input-oriented structural efficiency measurement* of the whole group:

$$H^g \coloneqq \{\lambda: (\lambda \boldsymbol{X}^0, \boldsymbol{Y}^0) \in \Im^g\} \leqq 1. \tag{2}$$

If $H^g = 1$, the whole group is structurally efficient. If $H^g < 1$, the whole group is structurally inefficient, and the inputs utilized by all hospitals can be reduced by $(1 - H^g) \times 100\%$. Let the structurally efficient group input vector be $\boldsymbol{X}^H \coloneqq H^g \boldsymbol{X}^0$. For a convex production set, there exists a shadow price vector of inputs $\boldsymbol{w}^s \in \mathbb{R}_+^N$, such that the cost of the whole group is minimized at $\boldsymbol{X}^H$ with respect to $\boldsymbol{w}^s$ for the aggregate output vector $\boldsymbol{Q}^0$. Like Li and Ng (1995) and Li and Cheng (2007), the losses to the whole group can be expressed by a ratio between two shadow costs. By the definition of $\boldsymbol{w}^s$ and $\boldsymbol{X}^H$.

$$\frac{\text{minimum shadow cost at } \boldsymbol{X}^H}{\text{observed shadow cost at } \boldsymbol{X}^0} = \frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^H}{\boldsymbol{w}^s \cdot \boldsymbol{X}^0} = \frac{\boldsymbol{w}^s \cdot (H^g \boldsymbol{X}^0)}{\boldsymbol{w}^s \cdot \boldsymbol{X}^0} = H^g. \tag{3}$$

The shadow prices reflect the input values of the whole group. Given the outputs of unit k ($\boldsymbol{y}^k$), the hospital should minimize the shadow cost from the whole sector's point of view, i.e., $tc^{k*} = \min_{\boldsymbol{x}}\{\boldsymbol{w}^s \cdot \boldsymbol{x}: (\boldsymbol{x}, \boldsymbol{y}^k) \in \Im\}$. Let the observed shadow cost be $tc^{k0} = \boldsymbol{w}^s \cdot \boldsymbol{x}^{k0}$. The total minimum shadow cost and total observed cost are $TC^* = \sum_k tc^{k*} = \boldsymbol{w}^s \cdot (\sum_k \boldsymbol{x}^{k*})$ and $TC^0 = \sum_k tc^{k0} = \boldsymbol{w}^s \cdot (\sum_k \boldsymbol{x}^{k0})$. The inefficiency of the whole group due to inefficiency within units is called *aggregate cost efficiency.*[5],

$$ACE \coloneqq \frac{\boldsymbol{w}^s \cdot (\sum_k \boldsymbol{x}^{k*})}{\boldsymbol{w}^s \cdot (\sum_k \boldsymbol{x}^{k0})} = \frac{TC^*}{TC^0}. \tag{4}$$

By definition, $TC^* \leqq TC^0$ and hence $ACE \leqq 1$. Since outputs are fixed within each hospital in (4), the measure of aggregate cost efficiency captures the inefficiency of management and operations within individual hospitals. If the changes of inefficiency are due to COVID-19, then the change of ACE captures the inefficiency due to the adverse effects of COVID-19 on management and operations within individual hospitals.

In the computation of ACE in Equation 4, outputs are assumed to be fixed in each hospital, whereas output targets are allocatable among hospitals in the computation of H^g in Equation 2. The differences between H^g and ACE must be due to hospitals' reallocation of output targets. This is called *reallocative efficiency:*

$$RAE = \frac{H^g}{ACE}. \tag{5}$$

Planning the output targets of hospitals is the job of the Hong Kong Hospital Authority. Thus, the change of *RAE* captures the adverse impacts of COVID-19 on the planning and cooperation of the public hospital sector. It follows from Equations 2, 4, and 5 that,

$$H^g = RAE \times ACE. \tag{6}$$

Let the rate of change of item *i* be $g_i = di/i$, $i = H, RAE, ACE$. It is easy to derive that

$$g_H = g_{RAE} + g_{ACE}. \tag{6a}$$

In summary, treating the public hospital sector as a collection of production units allows us to assess the overall impact of COVID-19 on this sector through input-oriented structure efficiency (H^g). The overall effects can be broken down into two sources: the impact on planning and cooperation, which is measured by reallocative efficiency (RAE), and the impact on the management and operations of

[5] One may further decompose ACE into aggregate allocative efficiency (AAE) and aggregate technical efficiency (ATE), similar to that in Tsang and Li (2020). However, this is not the primary focus of the present paper.

individual hospitals, represented by aggregate cost efficiency (ACE).

3.2 The Efficiency Measures of Inter- and Intra-subgroup Reallocation

Suppose all hospitals in the whole group can be classified into T subgroups (clusters). Let the number of elements in the tth subgroup be n_t. So $n_1 + n_2 + \cdots + n_T = K$. Define $s_t = \sum_1^t n_t$. The hospitals are denoted as follows: hospitals $1, 2, \ldots, n_1$ ($n_1 = s_1$) are in subgroup 1; hospitals $n_1 + 1, n_1 + 2, \ldots, n_1 + n_2$ ($n_1 + n_2 = s_2$) are in subgroup 2; and so on. Denote the quantity variables of group t as follows: input vector $\boldsymbol{X}^t \coloneqq \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{x}^k$, output vector $\boldsymbol{Y}^t \coloneqq \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{y}^k$, where $t = 1, \ldots, T$ and $s_0 = 0$.[6] Similar to the group production set defined in (1), if output target reallocation among hospitals is allowed in subgroup t, the *group production set of subgroup* t is,

$$\mathfrak{J}^t := \left\{ \begin{matrix} (\boldsymbol{X}, \boldsymbol{Y}) \colon \boldsymbol{X} = \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{x}^k, \boldsymbol{Q} = \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{y}^k, (\boldsymbol{x}^k, \boldsymbol{y}^k) \in \mathfrak{J}, \\ k = s_{t-1} + 1, \cdots, s_t \end{matrix} \right\}. \tag{7}$$

Assume that there is a decision-maker in each subgroup. The objective of each subgroup is to be consistent with the objective of the whole group. Let the observed values of aggregate inputs and aggregate outputs in subgroup t be $\boldsymbol{X}^{t0} \coloneqq \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{x}^{k0}$ and $\boldsymbol{Y}^{t0} \coloneqq \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{y}^{k0}$, respectively. Recall that the shadow wages ($\boldsymbol{w}^s$) reflect the input values of the whole group. When output targets are reallocatable among hospitals within subgroup t but are fixed in this subgroup, each subgroup decision-maker t aims to achieve the minimum cost of subgroup t at the input price vector $\boldsymbol{w}^s$.

$$C^t(\boldsymbol{w}^s, \boldsymbol{Y}^{t0}) \coloneqq \min_{\boldsymbol{X}} \{\boldsymbol{w}^s \cdot \boldsymbol{X} \colon (\boldsymbol{X}, \boldsymbol{Y}^{t0}) \in \mathfrak{J}^t\}. \tag{8}$$

Let $\boldsymbol{X}^{tC} \in \mathbb{R}_+^N$ be a total input vector of subgroup t such that $\boldsymbol{w}^s \cdot \boldsymbol{X}^{tC}$ is at the minimum for the given aggregate output vector $\boldsymbol{Q}^{t0}$. Then $\boldsymbol{w}^s \cdot \boldsymbol{X}^{tC} = C^t(\boldsymbol{w}^s, \boldsymbol{Q}^t)$ Qt. If $\boldsymbol{w}^s \cdot \boldsymbol{X}^{t0} > \boldsymbol{w}^s \cdot \boldsymbol{X}^{tC}$, the observed cost is higher than the minimum cost for the total output vector $\boldsymbol{Q}^{t0}$. Thus, there is inefficiency within subgroup t. In the same spirit as computing the structural efficiency measure in Tsang and Li (2020), the *cost measure of structural efficiency for subgroup t* is hereby defined as follows:

$$h^t = \min_{\lambda, \boldsymbol{X}} \{\lambda \colon \boldsymbol{w}^s \cdot (\lambda \boldsymbol{X}^{t0}) \geqq \boldsymbol{w}^s \cdot \boldsymbol{X}, (\boldsymbol{X}, \boldsymbol{Y}^{t0}) \in \mathfrak{J}^t\} = \frac{C^t(\boldsymbol{w}^s, \boldsymbol{Y}^{t0})}{\boldsymbol{w}^s \cdot \boldsymbol{X}^{t0}}. \tag{9}$$

The quantity vector $\boldsymbol{X}^{tC}$ defined before is a solution to (9). Subgroup t is cost-structurally efficient at the input vector $\boldsymbol{X}^{tC}$ for all t. Let the corresponding total input vector of the whole group be $\boldsymbol{X}^{s*} = \sum_{t=1}^T \boldsymbol{X}^{tC}$. To achieve $\boldsymbol{X}^{s*}$, total output targets ($\boldsymbol{Y}^{t0}$) in each subgroup are fixed, but they can be reallocated among hospitals in the subgroup. When output targets are fixed in each subgroup, the minimum aggregate shadow cost is $\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}$. The difference between $\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}$ and $\boldsymbol{w}^s \cdot \boldsymbol{X}^0$ reflects the inefficiency of the whole group when reallocation of outputs is allowed within each subgroup but not among subgroups. The *intra-subgroup cost measure of structural efficiency measure* is:

[6] Note that the way Tsang and Li (2020) define elements in subgroups is inconsistent when $t > 2$, and here is a modified definition.

$$h^{intra} = \frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}}{\boldsymbol{w}^s \cdot \boldsymbol{X}^0} = \frac{\boldsymbol{w}^s \cdot \sum_{t=1}^{T} \boldsymbol{X}^{tC}}{\boldsymbol{w}^s \cdot \boldsymbol{X}^0}. \tag{10}$$

In general, $h^{intra} \leqq 1$. When $h^{intra} < 1$, reallocating output targets among hospitals within each subgroup can improve the efficiency of the whole group.

Recall that the minimum shadow cost for all hospitals is $\boldsymbol{w}^s \cdot \boldsymbol{X}^H$. Their difference between the shadow costs at $\boldsymbol{X}^{s*}$ and $\boldsymbol{X}^H$ reflects the efficiency losses due to the reallocation of resources among subgroups. This type of inefficiency is called *inter-subgroup reallocative efficiency*:

$$RAE^{inter} = \frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^H}{\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}}. \tag{11}$$

By definition, $RAE^{inter} \leqq 1$. When $RAE^{inter} < 1$, reallocating output targets among subgroups can improve the efficiency of the whole group.

The combination of Equations 3, 10, and 11 results in the following equation:

$$H^g = RAE^{inter} \times h^{intra}. \tag{12}$$

Recall that $\boldsymbol{w}^s \cdot (\sum_k \boldsymbol{x}^{k*})$ is the cost of the whole group when all individual hospitals have minimized cost at $\boldsymbol{w}^s$ without reallocation among them. Further, $\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}$ is the group's minimum cost when reallocating output targets within a subgroup is available, so the difference between these two must be due to the reallocation of output targets among production units within subgroups. Accordingly, the *intra-subgroup reallocative efficiency measure* is hereby defined as follows:

$$RAE^{intra} = \frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}}{TC^*} = \frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^{s*}}{\boldsymbol{w}^s \cdot (\sum_k \boldsymbol{x}^{k*})}. \tag{13}$$

The following equation is obtained by combining Equations 4, 10, 12 and 13:

$$H^g = RAE \times ACE = RAE^{inter} \times RAE^{intra} \times ACE. \tag{14}$$

The input-oriented structure efficiency (H^g) measures the degree to which the whole group achieves minimum group cost at the shadow price vector $\boldsymbol{w}^s$. The efficiency losses are due to (i) inefficient allocation of output targets among subgroups (inter-subgroup reallocative efficiency; RAE^{inter}); (ii) inefficient allocation of output targets within subgroups (intra-subgroup reallocative efficiency; RAE^{intra}); (iii) aggregate inefficient production at the hospital level (aggregate cost efficiency; ACE). Let $g_{inter} = dRAE^{inter}/RAE^{inter}$ and $g_{inter} = dRAE^{intra}/RAE^{intra}$. Then Equation 14 implies

$$g_H = g_{inter} + g_{intra} + g_{ACE}. \tag{14a}$$

If the impacts of COVID-19 were significant, then the value of g_H is considerable. This decomposition helps us to identify which component contributes more to the impacts.

3.3 The Efficiency Measures at the Subgroup Level

Decomposition in Equation 14 emphasizes the effects of each component on the whole group. It does not show the situations in subgroups. Including the structural efficiency of each subgroup may provide information from another angle. Similar to Equation 4, define the *aggregate cost efficiency for subgroup* t[7],

$$ace^t := \frac{\boldsymbol{w}^s \cdot \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{x}^{k*}}{\boldsymbol{w}^s \cdot \sum_{k=s_{t-1}+1}^{k_t+k_{t-1}} \boldsymbol{x}^k}. \tag{15}$$

Define the reallocative efficiency measure for subgroup t,

$$rae^t := \frac{C^t(\boldsymbol{w}^s, \boldsymbol{Q}^t)}{\boldsymbol{w}^s \cdot \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{x}^{k*}}. \tag{16}$$

This measure indicates the degree of improvement that can be achieved by reallocating output within subgroup t. Recall the cost measure of structural efficiency for subgroup t at the shadow price $\boldsymbol{w}^s$ in Equation 9, it follows that

$$h^t = rae^t \times ace^t. \tag{17}$$

Using Equation 9 and the definition of h^{intra} in Equation 10, let $\omega_t = \boldsymbol{w}^s \cdot \boldsymbol{X}^{t0}/\boldsymbol{w}^s \cdot \boldsymbol{X}^0$,

$$h^{intra} = \frac{\boldsymbol{w}^s \cdot \sum_{t=1}^{T} \boldsymbol{X}^{tC}}{\boldsymbol{w}^s \cdot \boldsymbol{X}^0} = \sum_{t=1}^{T} \left(\frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^{t0}}{\boldsymbol{w}^s \cdot \boldsymbol{X}^0} \times \frac{\boldsymbol{w}^s \cdot \boldsymbol{X}^{tC}}{\boldsymbol{w}^s \cdot \boldsymbol{X}^{t0}} \right) = \sum_{t=1}^{T} \omega_t h^t. \tag{18}$$

Note that $\sum_{t=1}^{T} \omega_t = 1$. The combination of Equations 12, 17, and 18 results in the following equation:

$$H^g = RAE^{inter} \times \sum_{t=1}^{T} \omega_t (rae^t \times ace^t). \tag{19}$$

This decomposition shows that the efficiency losses of the whole group are due to (i) inefficient allocation of output targets among subgroups (inter-group reallocative efficiency; RAE^{inter}); (ii) inefficient allocation of output targets among firms within each subgroup (reallocative efficiency; RAE^t); (iii) aggregate inefficient production at the hospital level in each subgroup (aggregate cost efficiency; ACE^t). Similar to Equation 14a, Equation 19 implies

$$g_H = g_{inter} + \sum_{t=1}^{T} \omega_t (g_{rae^t} + g_{ace^t}). \tag{19a}$$

Let the observed inputs and outputs in a particular year be $(\boldsymbol{x}^{k0}, \boldsymbol{y}^{k0}), k = 1, \cdots,$ K. The empirical production technology is the conventional VRS frontier in DEA literature.

---

[7] Similar to ACE, one may further decompose ace^t into aggregate allocative efficiency (aae^t) and aggregate technical efficiency (ate^t) for subgroup t.

$$T = \left\{(\boldsymbol{x}, \boldsymbol{y}): \sum\nolimits_{k=1}^{K} z_k \boldsymbol{y}^k \geqq \boldsymbol{y}; \sum\nolimits_{k=1}^{K} z_k x^k \leqq \boldsymbol{x}; \sum_{k=1}^{K} z_k = 1;\ z_k \geqq 0, k = 1, \cdots, K\right\}. \tag{20}$$

Let $(\overline{\boldsymbol{x}}, \overline{\boldsymbol{y}}) = \sum_{k=1}^{K} (\boldsymbol{x}^{k0}, \boldsymbol{y}^{k0})/K$. Similar to Li and Ng (1995) and Li and Cheng (2007), the computation of Equation 2 can be simplified as

$$H^g = \min_{\lambda, z} \lambda$$

subject to

$$\sum_{k=1}^{K} z_k \boldsymbol{y}^{k0} \geqq \overline{\boldsymbol{y}};\ \sum_{k=1}^{K} z_k \boldsymbol{x}^{k0} \leqq \lambda \overline{\boldsymbol{x}};\ \sum_{k=1}^{K} z_k = 1;\ \ z_k \geqq 0, k = 1, \cdots, K. \tag{21}$$

Let $\overline{\boldsymbol{x}}^t = \frac{1}{n_t} \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{x}^{k0}$ and $\overline{\boldsymbol{y}}^t = \frac{1}{n_t} \sum_{k=s_{t-1}+1}^{s_t} \boldsymbol{y}^{k0}$. By Tsang and Li (2020), the computation of Equation 9 can also be simplified as

$$h^t = \min_{q, x, z} \lambda\ ;$$

subject to

$$\lambda \boldsymbol{w}^s \cdot \overline{\boldsymbol{x}}^t \geqq \boldsymbol{w}^s \cdot \boldsymbol{x};\ \sum_{k=1}^{K} z_k \boldsymbol{x}^k \leqq \boldsymbol{x};\ \sum_{k=1}^{K} z_k \boldsymbol{y}^k \geqq \overline{\boldsymbol{y}}^t;$$

$$\sum_{k=1}^{K} z_k = 1;\ \ z_k \geqq 0, k = 1, \cdots, K. \tag{22}$$

Similarly, the computation of minimum cost for unit j is

$$tc^{j*} = \min_{x, z} \boldsymbol{w}^s \cdot \boldsymbol{x}\ ;$$

subject to

$$\sum_{k=1}^{K} z_k \boldsymbol{y}^k \geqq \boldsymbol{y}^j;\ \sum_{k=1}^{K} z_k \boldsymbol{x}^k \leqq \boldsymbol{x};\ \sum_{k=1}^{K} z_k = 1;\ z_k \geqq 0, k = 1, \cdots, K. \tag{23}$$

Then, all the components presented in this section can be computed accordingly.

4 Empirical Estimations

The model discussed in Section 3 is applied to the 38 public hospitals in Hong Kong, covering the fiscal years from 2017-18 to 2022-2023. This application aims to evaluate the impact of the COVID-19 pandemic on the efficiency of the public hospital sector in Hong Kong.

4.1 Data

The paper analyzes data from 38 public hospitals spread across 7 clusters managed by the Hong Kong

Hospital Authority (HA) for the fiscal years 2017-18 to 2022-2023. Each fiscal year runs from April to March of the following year. It is important to note that these hospital clusters represent the official management structure of the Hong Kong public hospital sector. Each cluster has its own Chief Executive (CCE), who is responsible for allocating resources within that specific hospital cluster. For the sake of convenience, the fiscal year 2017-18 is referred to as 2018, and so forth. The data has been sourced from various years of the HA Annual Report. The data source utilised in this study is documented in Appendix 1.

The HA Annual Report data encompasses hospitals and related institutions. For this report, hospitals are defined as those that offer both inpatient and outpatient services. Institutions that do not provide both services, such as blood transfusion centers, elderly care homes, and general clinics, are excluded from the present analysis. A list of the public hospitals included in this study, along with their respective clusters, can be found in Appendix 2. There are a total of 38 hospitals organized into 7 clusters. Each cluster is considered a subgroup, while all hospitals are part of the overall group. It is important to note that Tin Shui Wai Hospital and Hong Kong Children's Hospital were fully operational in 2019. Therefore, for the purposes of this study, only 36 hospitals were considered in 2018.

Due to the extensive number of input and output variables in the raw data, along with a limited number of observations, some of these variables are combined. This approach helps to mitigate the well-known curse of dimensionality, which could otherwise lead to an overly optimistic evaluation of hospital efficiency (Ünsal, et al., 2022). Table 1 presents the input and output variables used in the study, along with their respective compositions.

Table 1: Variables Included in the Analysis

Variables	Compositions
Inputs	
Hospital Bed (BD)	● No. of hospital beds
Medical-related Staff (MS)	No. of Full-time Equivalent Staff ● Medical ● Nursing ● Allied Health
Other Staff (OS)	No. of Full-time Equivalent Staff ● Others
Outputs	
Inpatient & Day inpatient (IP)	● Total Inpatient & Day inpatient discharges and deaths
Outpatient (OP)	● Total Accident & Emergency attendances ● Total Specialist Outpatient (clinical) attendances ● Family Medicine Specialist Clinic attendances ● Total Allied Health (Outpatient) attendances ● General Outpatient attendances

In total, the study includes three input variables and two output variables. It is also important to note that, as reported in the literature, the production process in hospitals typically involves inputs such as staff and beds, and outputs that represent different types of patients treated (see, for example, Henriques & Gouveia, 2022; Kamel & Mousa, 2021).

The descriptive statistics of public hospitals in the study period are shown in Table 2.

Table 2: Descriptive Statistics of Public Hospitals in 2018 to 2023

		BD	MS	OS	IP	OP
2018 (n=36)	Average	768.7	1097.3	930.0	50472.2	524996.5
	SD	603.1	1153.9	946.1	62948.8	604930.7
	Max	1994.0	3754.0	3286.0	202191.0	2110871.0
	Min	26.0	37.0	31.0	227.0	88.0
2019 (n=38)	Average	736.2	1084.8	919.6	48289.7	507030.0
	SD	625.8	1155.2	945.1	63010.2	601025.1
	Max	2016.0	3809.0	3393.0	211090.0	2118001.0
	Min	26.0	43.0	31.0	15.0	99.0
2020 (n=38)	Average	756.7	1145.2	979.7	47157.6	485267.5
	SD	613.5	1198.9	993.5	60460.1	570758.7
	Max	2034.0	3942.0	3599.0	202023.0	2039885.0
	Min	26.0	43.0	32.0	199.0	82.0
2021 (n=38)	Average	767.6	1183.8	1045.6	43073.6	460142.4
	SD	615.3	1232.9	1056.0	54808.1	541355.7
	Max	2036.0	4102.0	3808.0	177636.0	1962637.0
	Min	26.0	42.0	31.0	171.0	89.0
2022 (n=38)	Average	776.0	1185.7	1070.1	46217.4	494555.9
	SD	616.5	1223.2	1076.9	57937.3	576953.3
	Max	2049.0	4124.0	3821.0	193874.0	2075458.0
	Min	26.0	41.0	30.0	294.0	138.0
2023 (n=38)	Average	786.5	1191.5	1071.1	45400.5	477352.5
	SD	623.9	1219.2	1074.6	56006.5	550415.7
	Max	2093.0	4056.0	3817.0	184129.0	1968609.0
	Min	26.0	43.0	28.0	462.0	221.0

Note: BD: hospital bed; MS: medical-related staff; OS: other staff; IP: inpatient & day inpatient; OP: outpatient. Please refer to Table 1 for a detailed definition of variables.

Recall 2020 refers to fiscal year 2019-2020, which ended in March 2020. This means the COVID-19 pandemic has impacted Hong Kong since 2020, and Hong Kong's public hospital sector was significantly affected in 2022 and 2023. There was an increasing trend in inputs before the COVID-19 pandemic. However, while the increase in inputs continues, outputs decrease during the COVID-19 pandemic. In this particular case, it is anticipated that the efficiency of the public hospital sector in Hong Kong will experience a deterioration during the period of the COVID-19 Pandemic.

4.2 Results at the Public Hospital Sector Level

The model discussed in Section 3 is applied to data from 38 public hospitals managed by the Hong Kong Hospital Authority (HA) between 2018 and 2023. All observations are grouped together, with each cluster considered a subgroup. The primary focus is H^g, the input-oriented structural efficiency for all observations where hospital resource allocation is allowed. This reflects the potential annual improvements for public hospitals if the reallocation of output targets among them is feasible. The estimation results of the model are shown in Table 3. In order to provide a broader perspective, the years are categorised as follows: The years 2018 and 2019 represent the pre-pandemic period, 2020 and 2021 correspond to the initial phase of the pandemic, and 2022 and 2023 reflect the subsequent phase. Additionally, the geometric average for each period is included for reference. It is important to note that the year 2020 corresponds to the fiscal year 2019-2020, which concluded in March 2020. Hong Kong reported its first confirmed COVID-19 case in January 2020, followed by a significant outbreak in January 2022. As a result, the COVID-19 pandemic had minimal impact during the first stage of the crisis, while its effects intensified during the second stage.

Table 3: Input-oriented Structural Efficiency Measure and Its Decompositions at the Public Hospital Sector Level

Year N	2018 36	2019 38	GM (2018-2019)	2020 38	2021 38	GM (2020-2021)	2022 38	2023 38	GM (2022-2023)
H^g	0.7643	0.7629	0.7636	0.7687	0.7415	0.7550	0.6265	0.5649	0.5949
RAE	0.9095	0.9215	0.9155	0.9358	0.9227	0.9292	0.9697	0.9023	0.9354
ACE	0.8404	0.8280	0.8342	0.8215	0.8036	0.8125	0.6461	0.6261	0.6360

Note: GM: geometric mean. H^g: input-oriented structural efficiency measure; RAE: reallocative efficiency; ACE: aggregate cost efficiency. 2018-2019: pre-COVID-19 period; 2020-2021: first stage of the COVID-19 period; 2022-2023: second stage of the COVID-19 period.

According to Table 3, the input-oriented structural efficiency measure (H^g) for the pre-COVID-19 period is approximately 0.76 and was reduced to around 0.59 in the stage two COVID-19 period. This indicates that if all inefficiencies in the public hospital sector were eliminated, inputs could be reduced by about 24% while still meeting the same output targets. Before the pandemic, the sector's excess resource usage was estimated to be around 24%. This value remained relatively stable during the first stage of the COVID-19 pandemic. However, in the second stage, it increased significantly, rising to approximately 40%. This means that during the second stage, the excess resource usage of the sector changed from around 24% to about 40%. In comparison to the pre-COVID-19 period, it is found that the COVID-19 pandemic reduced the structural efficiency of the hospital sector by less than 1% in the first stage of the COVID-19 period. However, a significant decline in efficiency was observed in the second stage, where COVID-19 resulted in a reduction of approximately 16% in the structural efficiency of the hospital sector compared to the pre-COVID-19 period. In response to the first research question, the findings confirm that the efficiency of the hospital sector declined during the COVID-19 pandemic, primarily due to the significant increase in confirmed COVID-19 cases.

The new model further decomposes these inefficiencies into two parts: aggregate cost efficiency (ACE) and reallocative efficiency (RAE). A major factor contributing to excess capacity in hospitals is the inefficiency within individual hospitals, known as ACE. Before the COVID-19 pandemic, the value of ACE was approximately 0.83, indicating that the sector experienced an excess resource usage of around 17% due to inefficiencies. During the Stage One COVID-19 period, this value decreased to about 0.81 and further declined to approximately 0.64 in 2022. The increased resource usage in the sector was largely due to inefficiencies within individual hospitals caused by COVID-19. This inefficiency is estimated to account for approximately two percentage points of the observed inputs during the first stage of COVID-19 and about 19 percentage points during the second stage. The results suggest a finding consistent with studies in other countries and regions (see, for example, Mishra, et al., 2023; Henriques & Gouveia, 2022; Androutsou, et al., 2022). The restrictions to cope with COVID-19 have significantly impacted hospital operations. As a result, hospitals are required to allocate additional resources to maintain service during the pandemic. In response to the second research question, the findings indicate that the COVID-19 pandemic has negatively affected the efficiency of individual hospital operations in Hong Kong. This finding highlights an important policy implication:

during future pandemics, the HA should focus more on the internal operations of each hospital. This calls for a review of the current measures in place to handle sudden outbreaks of infectious diseases within hospitals.

The changes in RAE are surprising. RAE represents the efficiency of resource allocation among hospitals in the sector. This topic is relatively underexplored in the existing literature. The figures presented in Table 3 indicate that resource allocation among hospitals was generally efficient compared to the management and operations within the hospitals throughout the entire study period. During the pre-COVID period, the average RAE value was 0.92. This suggests that the excess resource usage in hospitals due to inefficient resource allocation amounted to approximately 8% of the observed inputs. However, the value of RAE increased slightly to 0.93 during stage one of the COVID-19 period and to 0.94 during stage two of the COVID-19 period. This reflects that HA has adjusted its planning to allocate limited resources among hospitals in the most effective manner during COVID-19. In response to the third research question, the findings show that the allocation of resources within the Hong Kong hospital sector was not negatively affected by COVID-19. On the other hand, there was a slight improvement following the outbreak.

4.3 Results at the Hospital Cluster Level

The new model also offers a breakdown of the input-oriented structural efficiency measure at the hospital cluster level. It is important to note that the hospital clusters are categorized not only by region but also according to the official management structure of the Hong Kong public hospital sector. Each hospital cluster has its CCE, responsible for allocating resources within that cluster. The findings are summarized in Tables 4 and 5. Overall, the trends observed are similar to those seen at the sector level. Therefore, only key results are mentioned in this section, and the reporting of less significant details is omitted.

Table 4: Inter- and Intra-subgroup Reallocative Efficiency

Year	2018	2019	GM (2018-2019)	2020	2021	GM (2020-2021)	2022	2023	GM (2022-2023)
N	36	38		38	38		38	38	
RAE	0.9095	0.9215	0.9155	0.9358	0.9227	0.9292	0.9697	0.9023	0.9354
RAE^{inter}	0.9979	1.0000	0.9989	1.0000	1.0000	1.0000	1.0000	0.9956	0.9978
RAE^{intra}	0.9114	0.9215	0.9165	0.9358	0.9227	0.9292	0.9697	0.9063	0.9375

Note: GM: geometric mean. RAE: reallocative efficiency; RAE^{inter}: inter-subgroup reallocative efficiency; RAE^{intra}: intra-subgroup reallocative efficiency. 2018-2019: pre-COVID-19 period; 2020-2021: first stage of the COVID-19 period; 2022-2023: second stage of the COVID-19 period.

Table 4 decomposes the reallocative efficiency for the whole group into two components: inefficiency due to allocation among subgroups (RAE^{inter}) and inefficiency due to allocation within subgroups (RAE^{intra}). It is evident that the inter-subgroup reallocative efficiency (RAE^{inter}) is close to 1 in the entire study period. It reflects that resource allocation at the central level, i.e., among hospital clusters, was highly efficient both before and during the COVID period. The data shows that the intra-subgroup reallocative efficiency (RAE^{intra}) improved from 0.9165 in the initial period to 0.9292 during the first stage of the COVID-19 pandemic and reached 0.9375 in the second stage. In response to the fourth research question, the findings indicate that the enhancement in resource allocation during the COVID-

19 pandemic primarily results from improvements at the cluster level, meaning better resource distribution among hospitals within each cluster.

Table 5: Input-oriented Structural Efficiency Measure and Its Decompositions at the Hospital Cluster Level

Year		2018	2019	GM (2018-2019)	2020	2021	GM (2020-2021)	2022	2023	GM (2022-2023)
N		36	38		38	38		38	38	
RAE^{inter}		0.9979	1.0000	0.9989	1.0000	1.0000	1.0000	1.0000	0.9956	0.9978
HKE	h^t	0.7281	0.7302	0.7291	0.7496	0.7024	0.7256	0.5799	0.4926	0.5345
	rae^t	0.9490	0.9724	0.9606	0.9637	0.9556	0.9596	0.9620	0.8723	0.9161
	ace^t	0.7668	0.7510	0.7588	0.7777	0.7351	0.7561	0.6028	0.5646	0.5834
HKW	h^t	0.8069	0.8506	0.8285	0.8337	0.8149	0.8242	0.7137	0.5869	0.6472
	rae^t	0.9504	0.9653	0.9578	0.9596	0.9369	0.9482	0.9587	0.8505	0.9030
	ace^t	0.8490	0.8811	0.8649	0.8688	0.8697	0.8693	0.7445	0.6902	0.7168
KLC	h^t	0.7474	0.7178	0.7325	0.7255	0.6781	0.7014	0.5964	0.5159	0.5547
	rae^t	0.8876	0.9048	0.8962	0.9215	0.8787	0.8998	0.9448	0.8562	0.8994
	ace^t	0.8420	0.7934	0.8173	0.7873	0.7716	0.7794	0.6313	0.6026	0.6167
KLE	h^t	0.7667	0.7640	0.7653	0.7668	0.7438	0.7552	0.6843	0.6747	0.6795
	rae^t	0.8502	0.8342	0.8422	0.8891	0.8977	0.8934	0.9800	0.9604	0.9702
	ace^t	0.9261	0.9159	0.9210	0.8624	0.8286	0.8454	0.6982	0.7025	0.7004
KLW	h^t	0.7656	0.7786	0.7721	0.7751	0.7565	0.7657	0.6441	0.6160	0.6299
	rae^t	0.9327	0.9590	0.9458	0.9710	0.9689	0.9699	0.9894	0.9619	0.9756
	ace^t	0.8208	0.8120	0.8164	0.7982	0.7808	0.7894	0.6509	0.6404	0.6456
NTE	h^t	0.7924	0.8023	0.7973	0.8007	0.7841	0.7924	0.6236	0.5751	0.5989
	rae^t	0.9561	0.9726	0.9643	0.9656	0.9554	0.9605	0.9739	0.8908	0.9314
	ace^t	0.8287	0.8249	0.8268	0.8293	0.8207	0.8250	0.6402	0.6456	0.6429
NTW	h^t	0.7562	0.7247	0.7403	0.7542	0.7423	0.7482	0.5846	0.5402	0.5620
	rae^t	0.8616	0.8514	0.8565	0.8825	0.8823	0.8824	0.9841	0.9542	0.9690
	ace^t	0.8778	0.8512	0.8644	0.8546	0.8413	0.8479	0.5940	0.5661	0.5799

Note: GM: geometric mean. RAE^{inter}: inter-subgroup reallocative efficiency; h^t: input-oriented structural efficiency measure pf subgroup t; rae^t: reallocative efficiency of subgroup t; ace^t: aggregate cost efficiency of subgroup t. HKE: Hong Kong East cluster; HKW: Hong Kong West cluster; KLC: Kowloon Central cluster; KLE: Kowloon East cluster; KLW: Kowloon West cluster; NTE: New Territories East cluster; NTW: New Territories West cluster. 2018-2019: pre-COVID-19 period; 2020-2021: first stage of the COVID-19 period; 2022-2023: second stage of the COVID-19 period. Hospital clusters that declined in resource allocation are highlighted in yellow, and hospital clusters that improved in resource allocation are highlighted in green.

Table 5 estimates the efficiency level of the seven hospital clusters. In general, the patterns of aggregate cost efficiency in the cluster (ace^t) are similar to that of the whole sector; all clusters have a worsened ace^t. Tables 3 and 5 show that the aggregate cost efficiency values, both for the overall sector and for individual clusters, show a declining trend over the studied period.

Furthermore, the investigation revealed disparate patterns of reallocative efficiency within the clusters (rae^t). There has been a noticeable decline in resource allocation within the hospital clusters of Hong Kong East (HKE), Hong Kong West (HKW), and New Territories East (NTE). In contrast, Kowloon East (KLE), Kowloon West (KLW), and New Territories West (NTW) have experienced an improvement in resource allocation. This disparity highlights the need for further research to identify the causes of inefficient resource allocation in hospital management by comparing these two groups of hospital clusters.

In response to the fifth research question, the findings suggest that hospital operation efficiency in all clusters declined during the studied period. However, a deterioration in resource allocation within three of the clusters was observed, while the other three clusters demonstrated an improvement in resource allocation.

4.4 Robustness Checks

To illustrate that the findings of this paper are not dependent on the classification of inputs, a robustness check using two inputs and two outputs (by combining all staff) is presented in Table 6. The results of this robustness check are consistent with the main findings. For instance, the efficiency of the hospital sector declined during the COVID-19 pandemic, primarily affecting individual hospital operations. Additionally, resource allocation within the Hong Kong hospital sector saw a slight improvement during this period, mainly due to better distribution of resources among hospitals within each cluster. Since the robustness check results for individual hospital clusters align closely with the main findings, detailed discussions are skipped to conserve space.

Table 6: Robustness Checks for Efficiency Scores

Year N	2018 36	2019 38	GM (2018-2019)	2020 38	2021 38	GM (2020-2021)	2022 38	2023 38	GM (2022-2023)
H^g	0.7638	0.7649	0.7643	0.7643	0.7386	0.7513	0.6231	0.5632	0.5924
RAE	0.9133	0.9216	0.9174	0.9402	0.9253	0.9327	0.9686	0.9027	0.9351
ACE	0.8363	0.8277	0.8320	0.8129	0.7983	0.8055	0.6433	0.6239	0.6336
RAE^{inter}	0.9986	0.9995	0.9990	1.0000	1.0000	1.0000	1.0000	0.9957	0.9978
RAE^{intra}	0.9146	0.9221	0.9183	0.9402	0.9253	0.9327	0.9686	0.9066	0.9371

Note: GM: geometric mean. H^g: input-oriented structural efficiency measure; RAE: reallocative efficiency; ACE: aggregate cost efficiency.; RAE^{inter}: inter-subgroup reallocative efficiency; RAE^{intra}: intra-subgroup reallocative efficiency. 2018-2019: pre-COVID-19 period; 2020-2021: first stage of the COVID-19 period; 2022-2023: second stage of the COVID-19 period.

Finally, it is important to note that DEA is a non-parametric method that can be influenced by outliers. Some studies have suggested conducting sensitivity analyses by removing potential outliers. However, this approach is not applicable to the current study, which aims to assess the efficiency of Hong Kong's public hospital sector. Removing any observations would compromise this objective, as the data would no longer represent the entire sector. Instead, it is recommended that future research consider other types of sensitivity analyses, such as bootstrapping.

5 Conclusion

In December 2019, a new coronavirus known as SARS-CoV-2 emerged, causing COVID-19. The first cases were recorded in Wuhan, China, and the virus rapidly spread globally. This pandemic significantly impacted healthcare systems, drawing the attention of numerous scholars to its effects on service delivery. However, previous studies have primarily focused on assessing the efficiency of individual healthcare units rather than evaluating the efficiency of the healthcare system as a whole, particularly in terms of resource allocation.

This paper assesses the efficiency of Hong Kong's public hospital sector during the COVID-19 pandemic. A key feature of this sector is its cluster-based management model. To account for the effects of the pandemic, the paper adapted the structural efficiency model outlined by Tsang and Li (2020), transforming it into an input-oriented model that evaluates the productive performance of the hospital sector across different years. To the best of our knowledge, this subgroup methodology has not yet been documented in the literature.

Data from 38 public hospitals managed by the Hong Kong Hospital Authority (HA) covering the fiscal years 2017-18 to 2022-23 were analyzed, encompassing both pre-COVID-19 and COVID-19 periods. The findings provide clear insight into how the efficiency of the Hong Kong public hospital sector changed during the pandemic. The results indicate that COVID-19 negatively impacted hospital services, with the extent of these impacts increasing over time. Specifically, excess resource usage in the hospital sector rose from 24% just before the pandemic to 40% during the second stage of COVID-19. This suggests that the pandemic accounts for an additional 16% of the observed inputs to society each year.

These losses can be categorized into two main sources. The most significant impact arises from the internal management and operations of individual hospitals, which account for approximately 36% of the total inputs in the hospital sector. The second source of inefficiency is excessive resource usage stemming from the planning and cooperation among hospitals, accounting for less than 7%. Additionally, the results reveal that resource allocation among hospital clusters is highly efficient both before and during the pandemic. However, different patterns of reallocative efficiency were observed within the hospital clusters. Specifically, three clusters experienced a decline in resource allocation, while another three showed improvement.

This study contributes to the field of Decision Sciences by applying and extending DEA, a core operations research technique, to provide actionable insights for strategic planning and resource allocation in public health systems. The analyses indicated that individual hospitals primarily managed the negative impacts of COVID-19. This finding highlights an important policy implication: during future pandemics, the HA must focus more on the internal operations of each hospital, necessitating a review of current measures to handle sudden outbreaks of infectious diseases.

The study has several limitations. Given the relatively small number of hospitals in Hong Kong, inputs and outputs are combined in the analysis. Additionally, the influence of potential outliers may necessitate extensive robustness checks. Questions remain regarding whether the observed impacts stem from planning and coordination efforts by the HA or are influenced by the effects of COVID-19 on the resource allocation system. These uncertainties open avenues for future research, such as comparing cluster management strategies or applying the model to other sectors.

Acknowledgment
The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (UGC/FDS15/E02/21).

References

Allen, D. E., & McAleer, M. (2020). Predicting Cases and Deaths in Europe from Covid-19 Tests and Country Populations. *Annals of Financial Economics*, 15(4), 2050017.

Androutsou, L., Kokkinos, M., Latsou, D., & Geitona, M. (2022). Assessing the Efficiency and Productivity of the Hospital Clinics on the Island of Rhodes during the COVID-19 Pandemic. *International Journal of Environmental Research and Public Health*, 19(23), 15640.

Delamater, P. L., Shortridge, A. M., & Messina, J. P. (2013). Regional Health Care Planning: A Methodology to Cluster Facilities Using Community Utilization Patterns. *BMC Health Services Research*, 13, 333. PMCID: PMC3766152

Guo, H., Zhao, Y., Niu, T., & Tsui, K. L. (2017). Hong Kong Hospital Authority resource efficiency evaluation: via a novel DEA-Malmquist model and Tobit regression model. *PloS one*, *12*(9), e0184211. https://doi.org/10.1371/journal.pone.0184211

Henriques, C. O., & Gouveia, M. C. (2022). Assessing the Impact of COVID-19 on the Efficiency of Portuguese State-owned Enterprise Hospitals. *Socio-Economic Planning Sciences*, 84, 101387–101387

Hong Kong Hospital Authority. Various years. *Hospital Authority Annual Report. Hong Kong Hospital Authority*, HKSAR Government.

Kamel, M. A., & Mousa, M. E. S. (2021). Measuring Operational Efficiency of Isolation Hospitals During COVID-19 Pandemic Using Data Envelopment Analysis: A Case of Egypt. Benchmarking: *An International Journal*, 28(7), 2178–2201.

Li, S. K., & Cheng, Y. S. (2007). Solving the Puzzles of Structural Efficiency. European Journal of Operational Research, 180, 713 – 722.

Li, S. K., & Ng, Y. C. (1995). Measuring the Productive Efficiency of a Group of Firms. International *Advances in Economic Research*, 1, 377-390.

Mishra, V., Singh, J., Kulkarni, S., & Yadav, S. (2023). Analysis of Profit Efficiency of Corporate Hospitals in India during COVID-19 - An DEA-MPI Based Approach. *International Journal of Healthcare Management*, ahead-of-print(ahead-of-print), 1–9.

Ng, Y. C., & Li, S. K. (2022). Can Clustering Improve the Efficiency of Resource Allocation: A Case of Hospital Sector. *Paper presented at Western Economic Association International (WEAI) 97th Annual Conference*, Portland, Oregon, United States.

Shay, P. D. (2014). *More than just hospitals: an examination of cluster components and configurations (Doctoral dissertation)*. Virginia Commonwealth University. Retrieved from https://scholarscompass.vcu.edu/etd/3331/

Sikka, V., Luke, R. D., & Ozcan, Y. A. (2009). The efficiency of hospital-based clusters: Evaluating system performance using data envelopment analysis. *Health Care Management Review*, *34*(3), 251-261.

Thomas, J. W., Griffith, J. R., & Durance, P. (1981). Defining Hospital Clusters and Associated Service Communities in Metropolitan Areas. Socio-Economic Planning Sciences, 15(2), 45–51.

Tsang, C. K., & Li, S. K. (2020). Allocation of Resources within Subgroups of an Industry: A Case Study in the Chinese Industrial Sector. *Journal of Productivity Analysis*, 53, 125-139.

Tuan, B. A., Pho, K. H., Pan, S. H., & Wong, W. K. (2022). Applications in Sciences in the prevention of COVID-19. *Advances in Decision Sciences*, 26(4), 1-16.

Ünsal, M. G., Friesner, D., & Rosenman, R. (2022). The curse of dimensionality (COD), misclassified DMUs, and Bayesian DEA. *Communications in Statistics-Simulation and Computation*, *51*(8), 4186-4203.

Zhang, S., & Duan, Y. (2016). Structural Efficiency Research of Chinese Regional Economy Based on Data Envelopment Analysis. *Advances in Economics, Business and Management Research*, 16, 65–70.

Appendix 1: Data and Source

Data	Source
• No. of hospital beds • Total Inpatient & Day inpatient discharges and deaths • Total Accident & Emergency attendances • Total Specialist Outpatient (clinical) attendances • Family Medicine Specialist Clinic attendances • Total Allied Health (Outpatient) attendances • General Outpatient attendances	HA Annual Report Appendix 9 Statistics on Number of Beds, Inpatient, Accident & Emergency, and Outpatient Services
No. of Full-time Equivalent Staff • Medical • Nursing • Allied Health • Others	HA Annual Report Appendix 11(a) Manpower Position – by Cluster and Institution

Appendix 2: Public Hospitals Included in this Study

Hospital	Cluster
Cheshire Home, Chung Hom Kok	Hong Kong East (HKE)
Pamela Youde Nethersole Eastern Hospital	
Ruttonjee & Tang Shiu Kin Hospitals	
St. John Hospital	
Tung Wah Eastern Hospital	
Grantham Hospital	Hong Kong West (HKW)
MacLehose Medical Rehabilitation Centre	
Queen Mary Hospital	
The Duchess of Kent Children's Hospital at Sandy Bay	
Tung Wah Group of Hospitals Fung Yiu King Hospital	
Tung Wah Hospital	
Hong Kong Buddhist Hospital	Kowloon Central (KLC)
Hong Kong Children's Hospital*	
Hong Kong Eye Hospital	
Kowloon Hospital	
Kwong Wah Hospital	
Our Lady of Maryknoll Hospital	
Queen Elizabeth Hospital	
Tung Wah Group of Hospitals Wong Tai Sin Hospital	
Haven of Hope Hospital	Kowloon East (KLE)
Tseung Kwan O Hospital	
United Christian Hospital	
Caritas Medical Centre	Kowloon West (KLW)
Kwai Chung Hospital	
North Lantau Hospital	
Princess Margaret Hospital	
Yan Chai Hospital	
Alice Ho Miu Ling Nethersole Hospital	New Territories East (NTE)
Bradbury Hospice	
Cheshire Home, Shatin	
North District Hospital	
Prince of Wales Hospital	
Shatin Hospital	
Tai Po Hospital	
Castle Peak Hospital	New Territories West (NTW)
Pok Oi Hospital	
Tin Shui Wai Hospital*	
Tuen Mun Hospital	

Note: *Tin Shui Wai Hospital and Hong Kong Children's Hospital were established in full function in 2019.