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Efficiency Assessment through Hierarchical Network Data Envelopment Analysis Approach: Perspectives of University Faculties

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Abstract

This study presents a model for measuring university faculty efficiency within hierarchical structures using Hierarchical Network Data Envelopment Analysis (HNDEA). The model strategically evaluates diverse university faculty functions, leveraging shared inputs and incorporating new subunits to capture additional output variables. It emphasizes the crucial role of innovation in higher education efficiency, highlighting universities' responsibility in transforming research into innovation, with patents and other intellectual properties serving as key outputs. Analyzing data from 26 faculties in a Malaysian public university, the HNDEA model revealed that no faculty achieved optimal efficiency. Comparative analysis with conventional Data Envelopment Analysis (DEA) methods consistently showed lower efficiency scores in the HNDEA model, underscoring its superior discriminatory power. Significantly, the proposed model simplifies faculty ranking challenges. The HNDEA model is less flexible than conventional DEA, but its capability to disaggregate efficiency into specific functions provides critical insights for administrators. The study also compared efficiency scores and rankings between non-grouped and grouped faculties using the HNDEA model and found that grouping enhances the precision of efficiency assessments. In the globalized era, sustaining university performance necessitates continuous improvement. This model, therefore, offers top university management a valuable tool for identifying improvement areas within each unit, enabling targeted actions for overall performance enhancement.

Keywords: data envelopment analysis; efficiency; hierarchical network data envelopment analysis; higher education; shared inputs.

1 Introduction

Over the past century, Higher Education (HE) has undergone significant growth, driven by the dynamics of the knowledge economy, globalization, and environmental challenges. These factors have placed academia at a critical juncture regarding teaching, research, and societal contribution [8]. The global increase in HE enrollment has necessitated a more focused distribution of resources to meet growing demands. The United Nations Educational, Scientific and Cultural Organization (UNESCO) National Commission's report in 2022 reveals a notable 28% increase in enrollment in Malaysia between 2010 [25] and 2021 [11]. This surge underscores the need for the education sector to adapt to changes and address issues related to resource allocation and infrastructure.

Malaysia's 20 public universities are categorized into research, comprehensive, and technical institutions, collectively producing approximately 124,000 graduates annually. Research universities focus on research, comprehensive universities offer a well-rounded education, and technical universities specialize in practical, hands-on technical and technological programs. The sector has experienced substantial growth; however, it faces challenges in adapting to rapidly evolving demands in technology and innovation, further compounded by limited funds and infrastructure issues exacerbated by the COVID-19 pandemic. Innovations, such as the adoption of online learning during the pandemic demonstrate the sector's adaptability to these changing circumstances.

Efficient resource utilization is crucial for sustainable development in HE. An in-depth study of efficiency is essential not only for optimal resource use and waste reduction but also as a strategic imperative. A Universitas21 report (2020) ranks Malaysian Higher Education Institutions (HEIs) 27th among 50 countries, considering factors like resources, environment, connectivity, and output [32]. However, rankings in HNDEA by See et al. [27] with equal and relative weights assigned as 28 and 35, respectively, suggest a nuanced evaluation is crucial, especially for developing nations like Malaysia. The study further notes the comparable performance of Asian and Western cultures in HE systems, indicating the progression of the Asian HE system toward a more Westernized approach.

DEA has been widely used for performance evaluation across various fields, including energy [14], banking [9], aquaculture [33], and HE [3, 16]. Prior studies have employed various DEA techniques to assess HE performance, as shown in Table 1. Johnes [17] explored the advantages and limitations of different methods for measuring HEI efficiency, noting that while DEA is effective for handling multiple inputs and outputs, it also has drawbacks. Johnes applied DEA to measure the efficiency of HEIs in England. Kasim et al. [21] evaluated the efficiency and effectiveness of selected Malaysian HEIs using DEA. Lim et al. [13] compared the efficiency of public with private and foreign universities in Malaysia using DEA. Taleb et al. [29] applied the output-oriented integer-valued DEA model under conventional DEA to assess the efficiency and returns-to-scale of public universities in Malaysia. Ahmed et al. [5] measured the efficiency of University Malaya, one of Malaysia's research universities, using conventional DEA.

However, conventional DEA has a notable flaw in that it overlooks the interactions and dependencies within internal processes. By treating the system as a black box, conventional DEA considers only inputs and outputs, potentially identifying a system as efficient despite inefficiencies within its components [18]. NDEA addresses this limitation by examining the internal structures of network production systems, leading to more accurate efficiency measurements. NDEA expands on conventional DEA by accommodating various network structures, such as series, parallel, hierarchical, or combinations of these [26].

Table 1: Selected Literature on HE Evaluation.

Authors	Methods	Variables
Johnes [17]	DEA (output-oriented VRS, Pastor et al. (2002) test, Spearman's rank correlation coefficient)	**Inputs**: UGQUAL (number of undergraduates (UG) x average A-level score of UG entrants), number of postgraduate students, academic staff, CAPITAL (total depreciation and interest payable), LIBCOMP (total expenditure on central libraries and information services, and central computer and computer networks), and ADMIN (expenditure on central administration and central services). **Outputs**: GRADQUAL (total number of first degrees awarded weighted by degree classification), POSTGRAD (total number of doctorate and other higher degrees awarded), value of recurrent grant for research awarded.
Kasim et al. [21]	DEA	**Efficiency Measurement:** **Inputs**: Number of professors, associate professors, and lecturers. **Outputs**: Number of graduated undergraduate students, number of graduated master students, number of graduated PhD students, and total amount of research grants. **Effectiveness Measurement:** **Intermediate Input/Output**: Number of undergraduate graduates, master's graduates, PhD graduates, and total research grants. **Outcomes**: Number of employed degree graduates, employed master's graduates, employed PhD graduates, and publications.
Lim et al. [13]	DEA (input-oriented VRS)	**Inputs**: Government operating grant, total expenditure, academic staff, administrative staff, and total assets. **Outputs**: Income (excluding government grant), fees income, and graduates.
Taleb et al. [29]	DEA (CRS, VRS, RTS, scale efficiency)	**Inputs**: Number of postgraduate enrollments, number of undergraduate enrollments, and number of academic staff. **Outputs**: Number of postgraduate graduates, undergraduate graduates, and graduates who pursued further studies.
Ahmed et al. [5]	DEA (output-oriented CRS)	**Inputs**: Number of academic staff. **Outputs**: Total local graduates (undergraduate and postgraduate), total international graduates (undergraduate and postgraduate), and total employed six months after graduation.
Kao [18]	HNDEA	**Inputs**: Personnel and expenses. **Outputs**: Number of undergraduate graduates per year, total credit hours taught for undergraduate courses, number of postgraduate graduates per year, total credit hours taught for postgraduate courses, publications, grants, and income from services.
Shamohammadi and Oh [28]	2-stage NDEA	**Inputs**: Academic staff, non-academic staff, research fund, undergraduate enrollments, postgraduate enrollments (intermediate), and fixed assets. **Outputs**: Quality-adjusted publication, quality-adjusted patent, undergraduate-degree-awarded students (intermediate), and total degree-awarded students: undergraduate and postgraduate.

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Authors	Methods	Variables
Temoso et al. [30]	NDEA	**Teaching:** **Inputs**: Number of undergraduate enrollments, postgraduate enrollments, and total expenditure. **Outputs**: Undergraduate completion and postgraduate completion. **Research:** **Intermediate (Output of Teaching) / Input in Research**: Master research completion and PhD completion. **Inputs**: Academic staff responsible for research activities and research grants. **Output**: Total research outputs (Master's, PhD theses, and publications).
Kashim et al. [20]	HNDEA	**Inputs**: Number of professors, associate professors, senior lecturers, lecturers, foreign academic staff, non-academic staff, and expenses. **Outputs**: Number of undergraduate graduates, master's graduates, PhD graduates, publications, grant amounts, main researchers by grant type, expert lecturers, and collaboration activities under MoU/LoI.
Ahmad et al. [4]	DEA-based Malmquist Productivity Index	**Inputs**: Undergraduate student enrollment, postgraduate student enrollment, and academic staff. **Outputs**: Undergraduate degrees awarded, postgraduate degrees awarded, and publications in Scopus.
Ersoy [10]	DEA (CRS), super efficiency, TOPSIS	**Inputs**: General expenditure, professors, associate professors, assistant professors, lecturers, and research assistants. **Outputs**: Undergraduate students, postgraduate students, graduates from undergraduates, graduates from postgraduates.
Barra and Zotti [6]	DEA (VRS), bootstrap	**Inputs**: Staff (Professors, associate professors, researchers, assistant professors, non-academic staff), research activities spending, teaching activities allocations, students' enrollments. **Outputs**: Publications (Articles in international journals, national journals, international books, national books), total external research funding obtained by the university, scientific production indices (research productivity index, capacity of attracting resources index, research productivity per cost of the academic staff index), number of graduates weighted by their degree classification, indices related to questionnaires given to students (student satisfaction index and undergraduate satisfaction index).

NDEA offers several advantages over traditional DEA. For instance, Shamohammadi and Oh [28] highlighted that in a multi-objective production process, mixed-efficiency results could be calculated in a single model based on different processes using NDEA. They also added that neglecting the influence of factors between different stages could cause deviant results in conventional forms of DEA. Lee and Worthington [22] employed a two-stage NDEA model to measure the research efficiency of universities in Australia, arguing that conventional DEA results are often overstated compared to NDEA findings. Shamohammadi and Oh [28] used a two-stage NDEA model to evaluate efficiency changes in Korean private universities, classifying them based on efficiency patterns into research-oriented, teaching-oriented, and research-teaching-oriented categories. Similarly, Temoso et al. [30] utilized the NDEA method to examine the performance of South African HEIs within a network structure of teaching and research.

Despite these advancements, the use of HNDEA to assess faculty efficiency in universities remains limited. HNDEA, a specific extension of NDEA designed for hierarchical systems, provides a more refined method for evaluating multi-level processes within organizations. Kao [18] applied an NDEA model for hierarchical systems to evaluate the efficiency of physics departments across 20 Chinese universities. In another study, Kashim et al. [20] applied HNDEA to assess the efficiency of 14 faculties at a Malaysian university.

Both studies emphasize key university functions–teaching, research, and service–within their hierarchical models. Kao's model includes subordinate units only within the teaching function, while Kashim et al. [20] further divide the teaching function into undergraduate, master's, and PhD programs and split the services function into consultation and collaboration activities.

Although previous studies have provided valuable insights into faculty efficiency, they often address the research function in generalized terms without delving into its specific components. This limitation overlooks the multifaceted nature of research, which includes distinct elements such as publications, grants, and innovations-each playing a critical role in academic progress. This study contributes significantly to higher education research by extending the efficiency evaluation frameworks of Kao [18] and Kashim et al. [20]. It addresses this gap by developing a tailored efficiency assessment model for university faculties organized within a hierarchical structure. Using the HNDEA approach, the model evaluates faculty efficiency across key functions–teaching, research, and services–while breaking down the research function into specific subunits: publications, grants, and innovations. This refinement enhances the accuracy and depth of faculty efficiency evaluation.

In addition to developing this tailored efficiency assessment model, our study also aims to validate the HNDEA approach by evaluating the efficiency of all university faculties and comparing their performance with that determined by a conventional black-box DEA model. We further investigate how categorizing faculties into science and non-science groups affects their efficiency scores and rankings. Moreover, we analyze faculty efficiency both collectively and separately into science and non-science categories to understand the impact of these classifications on efficiency evaluations. Furthermore, existing HNDEA applications have not sufficiently explored how faculty classification into science and non-science disciplines affects efficiency evaluation. This aspect remains scarce despite its potential to offer valuable insights into faculty performance disparities.

The paper is structured to provide a comprehensive understanding of the proposed model and its implications. Section 2 covers the methodology and improvements made to existing models. Section 3 discusses the empirical results, offering insights into the proposed approach. Finally, Section 4 summarizes the findings and their significance in the field of higher education.

2 Methodology

Consider a hierarchical production or service system composed of a set of similar subunits, as illustrated in Figure 1. The efficiency evaluation of a Decision-Making Unit (DMU) j (where $j = 1, 2, \ldots, r$) within this system is examined. At the top level, system q includes three first-level units, labelled q_1, q_2, and q_3. Each first-level unit is further divided into multiple second-level subunits. For instance, unit q_1 consists of two second-level subunits, q_{11} and q_{12}.

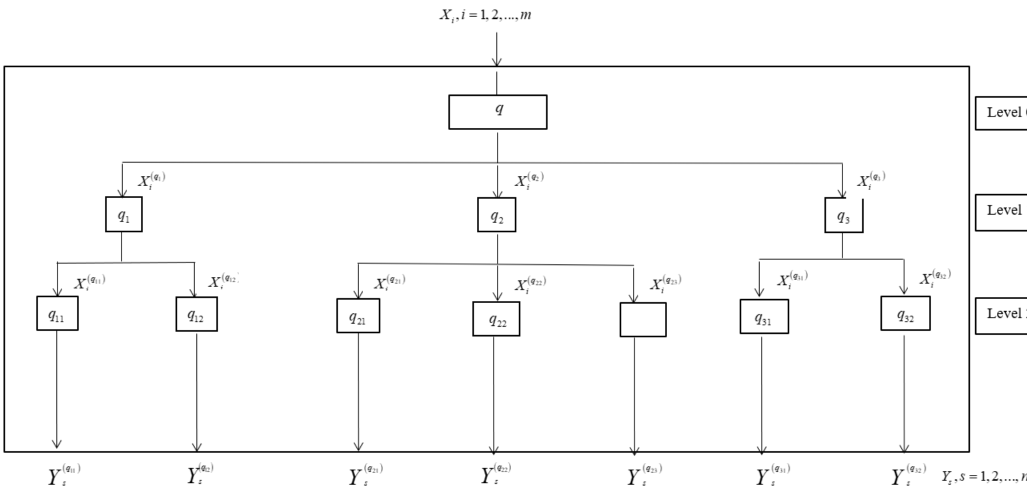


Figure 1: The structure of a two-level hierarchical system.

In this hierarchical structure, inputs are allocated by top level to the first-level units, which subsequently distribute them to their respective second-level subunits. This process continues through successive hierarchical levels, ensuring that inputs reach the lowest-level subunits where outputs are generated. For example, unit q_1 receives inputs from its parent unit q and allocates them to its subunits q_{11} and q_{12}, which then produce their respective outputs.

This hierarchical structure resembles the operational framework of university faculties. To assess the efficiency of university faculties, this study employs the NDEA method for hierarchical systems, known as HNDEA. This approach is tailored for structures where each DMU contains an equal number of first-level units, each performing distinct functions. If one unit has subordinate units at a lower level, all other DMUs must have the same number of subordinate units performing similar functions, ensuring a one-to-one correspondence across different DMUs [18].

Figure 2 illustrates the structure of a typical faculty system comprising three primary functions at the first level: teaching, research, and services. Building on the approaches of Kao [18] and Kashim et al. [20], this study extends the hierarchical structure by incorporating two, three, and two subordinate units under teaching, research, and services, respectively, at the second level. Inputs are shared between different functions and supplied to this faculty system. Each unit in level 1 distributes the inputs allocated to it from the top (level 0) to its subunits, where the inputs they receive are consumed to produce outputs. This means that it is assumed that the outputs of an intermediate unit come entirely from its subordinate units. In other words, it does not generate outputs itself. For example, the outputs of teaching function are those produced by undergraduate teaching and postgraduate teaching. Moreover, all inputs of an intermediate unit are fully allocated to its subordinate units. The efficiency of a hierarchical system is a weighted average of those of the units at the bottom of the hierarchy.

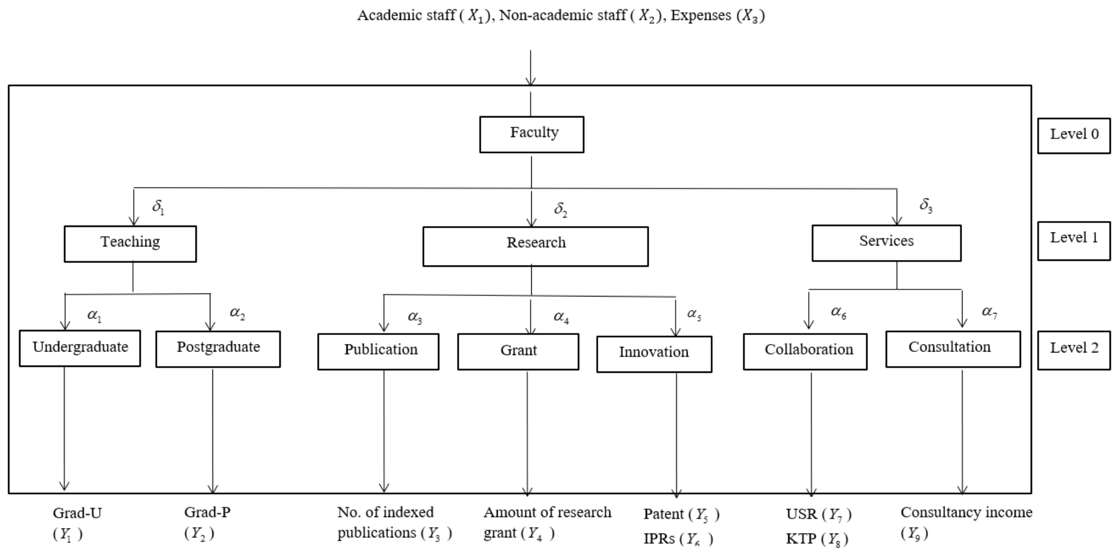


Figure 2: A two-level hierarchical structure of a university faculty.

3 Data and Sample

The study sample comprises faculties from a Malaysian public university, and the data were collected for the year 2020. The sample selection procedure resulted in a final count of 26 faculties after excluding one faculty with incomplete reports.

Agasisti et al. [2] highlighted that research productivity analysis in universities involves classifying inputs into human resources, financial resources, and structures, with outputs grouped into publications and financial support. Thus, as shown in Table 2, the inputs for this study encompass academic (X_1), non-academic (X_2), and expenses (X_3). Expenses include the maintenance of equipment and facilities, insurance, staff training costs, travel, salaries for part-time workers, and all other types of expenses. The outputs are associated with different functions. Teaching functions are divided into two subunits that are based on undergraduate and postgraduate teaching. The number of graduated undergraduate students in a year (Y_1) is the output of undergraduate teaching. Similarly, the number of graduated postgraduate students in a year (Y_2) is the output of postgraduate teaching.

The literature on research-related output is vast and diverse. However, concerning research, we distinguish various outputs and propose three subunits under research: publication, grant, and innovation. These additional subunits generate distinct outputs based on their specific functions. The number of indexed publications (Y_3) represents the output of research publication activities, aligning with previous literature that highlights publication as a key component of university research [11]. The indexed publications considered in this paper include scientific publications published in Web of Science, Scopus, and Excellence in Research for Australia (ERA). In addition to research publications, universities are increasingly focused on securing research grants, as the ability to attract funding is considered an important objective and a proxy for the quality and relevance of research. In particular, faced with tight budget constraints, universities allow more time for their researchers to conduct income-generating activities [2]. Here, we consider the amount of research grant (Y_4) to be the output of the research grant subunit. This includes the number of

Table 2: Efficiency measurement variables.

Input	Output
Academic staff	Number of undergraduate students graduated in a year (Grad-U)
Non-academic staff	Number of postgraduate students graduated in a year (Grad-P)
Expenses	Number of indexed publications
	Amount of research grant
	Patent
	Other intellectual properties (IPRs)
	University responsibility program (USR)
	Knowledge transfer program (KTP)
	Consultancy income

grants funded by universities, national, international, and industrial.

A study by Hu et al. [15] stated that the scientific research activities of universities are not only the power source of talent cultivation but also innovation, which is an important force in promoting regional innovation development. Considering this, patents (Y_5) and other intellectual properties (IPRs) (Y_6) are regarded as research innovation outputs. This study considers the number of new certificates of patents filed for the current year, and IPRs include commercialized products, technology know-how, trademarks, building plans, utility innovations, and many other IPRs.

The dynamics of knowledge production are changing, as is the way in which societies regard expectations and values. Thus, higher education has shifted from focusing primarily on teaching and performing research to adding an equivocal Third Mission, portrayed as "a contribution to society" or hereafter services. Universities engaged in service activities are becoming engines that contribute to the social, economic, and cultural development of the regions in which they operate by transferring knowledge and technologies to industry and society at large [8, 1]. In the two-level structure of our study, services are divided into two subunits: consultation and collaboration. We consider the university responsibility program (USR) (Y_7) and knowledge transfer program (KTP) (Y_8) to be the outputs of collaboration activities. The income received from consultation activities (Y_9) serves as the output of consultation.

4 Weight Restrictions

When confronted with multiple indicators, the challenge lies in incorporating their relative importance, necessitating the assignment of weights. To address this, weights based on expert opinions are assigned to both units and subunits to ensure comparability across faculties (see Table 3). These weights can be represented by the Type I Assurance Region (ARI) model, as proposed by Thompson et al. [31], where the ratio for each unit pair and subunit pair adheres to predefined bounds α_i and β_i:

$$\alpha_i \leq \frac{V_i}{V_{i+1}} \leq \beta_i. \tag{1}$$

Table 3: Weights of units and subunits of a university faculty.

	Units and subunits	Weights
q_1	**Teaching**	**50%**
	q_{11} Undergraduate students	85%
	q_{12} Postgraduate students	15%
q_2	**Research**	**30%**
	q_{21} Publication	50%
	q_{22} Grant	40%
	q_{23} Innovation	10%
q_3	**Services**	**20%**
	q_{31} Collaboration	70%
	q_{32} Consultation	30%

5 The Model

Let us consider a system whose structure is visually depicted in Figure 1 and Figure 2. In the given context, $X_{ij}^{(q)}$ represents the i-th input and $Y_{sj}^{(q)}$ the s-th output of the q-th unit of DMU j $(j = 1, \dots, r)$. By utilising m inputs, this system generates n outputs. Under the conventional black-box approach of Charnes-Cooper-Rhodes (CCR), the mathematical model for quantifying the efficiency of DMU k is:

$$E_k^{CCR} = \max \frac{\sum\limits_{s=1}^{n} u_s Y_{sk}}{\sum\limits_{i=1}^{m} v_i X_{ik}},$$

subject to:

$$\sum_{s=1}^{n} u_s Y_{sj} - \sum_{i=1}^{m} v_i X_{ij} \leq 0, \; j = 1, \dots, r, u_s, v_i \geq \varepsilon, \; s = 1, 2, \dots, n, \; i = 1, 2, \dots, m. \tag{2}$$

Where u_s, v_i represent the multipliers and ε is a small non-Archimedean number utilised to ensure that no factor is overlooked when calculating efficiency [18, 7].

In the academic domain, shared inputs serve diverse functions as academic staff allocate efforts among teaching, research, and services [18, 20]. Determining the precise effort allocation poses challenges, leading the upper management to assume approximate distributions of inputs at 50%, 30%, and 20% for teaching, research, and services, respectively. Let $\delta_1, \delta_2, \delta_3$ denote the proportions of shared inputs allocated to teaching, research, and services, respectively. Consequently, we have $\delta_1 + \delta_2 + \delta_3 = 1$, and these inputs have the relation of $\delta_1 \cong 1.67\delta_2$, $\delta_1 \cong 2.5\delta_3$, and $\delta_2 \cong 1.5\delta_3$. Given the approximative nature, these proportions are expressed as ranges [18]. Li et al. [23] contend that these lower and upper bounds on the proportions can mirror the decision maker's preferences. Thus, the proportions in ranges take the form of:

$$0.33\delta_2 \leq \delta_1 \leq 3\delta_2, \quad 0.5\delta_3 \leq \delta_1 \leq 4.5\delta_3, \quad \text{and} \quad 0.5\delta_3 \leq \delta_2 \leq 4.5\delta_3.$$

There are two types of teaching: undergraduate and postgraduate. We assume that the faculty allocates 85% of resources to undergraduate and 15% to postgraduate; that is, $\alpha_1 \cong 5.67\alpha_2$ and

$\alpha_1 + \alpha_2 = 1$, where α_1 and α_2 are the proportions of each resource allocated to undergraduate and postgraduate teaching. The relation of $\alpha_1 \cong 5.67\alpha_2$ is represented by $0.67\alpha_2 \leq \alpha_1 \leq 6\alpha_2$.

There are three subunits of research: publication, grant, and innovation. Every faculty is assumed to allocate 50%, 40%, and 10% of each input to publication, grants, and innovation, respectively. The relations are $\alpha_3 \cong 1.25\alpha_4$, $\alpha_3 \cong 5\alpha_5$, $\alpha_4 \cong 4\alpha_5$, and $\alpha_3+\alpha_4+\alpha_5 = 1$ and are represented by:

$$0.25\alpha_4 \leq \alpha_3 \leq 2.25\alpha_4, \quad \alpha_5 \leq \alpha_3 \leq 9\alpha_5, \quad \alpha_5 \leq \alpha_4 \leq 9\alpha_5.$$

Services are divided into collaboration and consultation activities. We assume that the faculty allocates 70% of the resources to collaboration and 30% to consultation activities; that is, $\alpha_6 \cong 2.33\alpha_7$ and $\alpha_6 + \alpha_7 = 1$, where α_6 and α_7 are the proportions of each resource allocated to collaboration and consultation services, respectively. The relation of $\alpha_6 \approx 2.33\alpha_7$ is represented by:

$$0.33\alpha_7 \leq \alpha_6 \leq 3\alpha_7.$$

Extending the work of Kao [18] and Kashim et al. [20], the proposed network model (HNDEA model) considers constraints on shared inputs and can be formulated as follows:

$$E_k^{HNW} = \max u_1Y_{1k} + u_2Y_{2k} + u_3Y_{3k} + u_4Y_{4k} + u_5Y_{5k} + u_6Y_{6k} + u_7Y_{7k} + u_8Y_{8k} + u_9Y_{9k},$$

subject to:

$$\begin{aligned}
&v_1X_{1k} + v_2X_{2k} + v_3X_{3k} = 1,\\
&u_1Y_{1j} - (v_1\delta_1\alpha_1X_{1j} + v_2\delta_1\alpha_1X_{2j} + v_3\delta_1\alpha_1X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&u_2Y_{2j} - (v_1\delta_1\alpha_2X_{1j} + v_2\delta_1\alpha_2X_{2j} + v_3\delta_1\alpha_2X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&u_3Y_{3j} - (v_1\delta_2\alpha_3X_{1j} + v_2\delta_2\alpha_3X_{2j} + v_3\delta_2\alpha_3X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&u_4Y_{4j} - (v_1\delta_2\alpha_4X_{1j} + v_2\delta_2\alpha_4X_{2j} + v_3\delta_2\alpha_4X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&(u_5Y_{5j} + u_6Y_{8j}) - (v_1\delta_2\alpha_5X_{1j} + v_2\delta_2\alpha_5X_{2j} + v_3\delta_2\alpha_5X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&(u_7Y_{7j} + u_8Y_{8j}) - (v_1\delta_3\alpha_6X_{1j} + v_2\delta_3\alpha_6X_{2j} + v_3\delta_3\alpha_6X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&u_9Y_{9j} - (v_1\delta_3\alpha_7X_{1j} + v_2\delta_3\alpha_7X_{2j} + v_3\delta_3\alpha_7X_{3j}) \leq 0, \quad j = 1,\dots,r,\\
&0.33\delta_2 \leq \delta_1 \leq 3\delta_2, \quad 0.5\delta_3 \leq \delta_1 \leq 4.5\delta_3, \quad 0.5\delta_3 \leq \delta_2 \leq 4.5\delta_3, \quad \delta_1 + \delta_2 + \delta_3 = 1,\\
&0.67\alpha_2 \leq \alpha_1 \leq 6\alpha_2, \quad \alpha_1 + \alpha_2 = 1,\\
&0.25\alpha_4 \leq \alpha_3 \leq 2.25\alpha_4, \quad \alpha_5 \leq \alpha_3 \leq 9\alpha_5, \quad \alpha_5 \leq \alpha_4 \leq 9\alpha_5, \quad \alpha_3 + \alpha_4 + \alpha_5 = 1,\\
&0.33\alpha_7 \leq \alpha_6 \leq 3\alpha_7, \quad \alpha_6 + \alpha_7 = 1,\\
&u_s, v_i \geq \varepsilon, \quad s = 1,\dots,9, \quad i = 1,2,3.
\end{aligned} \tag{3}$$

The optimal solution (u^*, v^*) will be obtained from the aforementioned equations, which will subsequently be used to calculate the efficiencies across all units and subunits.

According to Kao [18], when inputs are shared at the same level throughout a group of subunits, the unit's efficiency is a weighted average of those subunits' efficiencies. For example, the efficiency score of the teaching unit is calculated as the weighted average of the undergraduate and postgraduate subunits. The efficiency formulae are therefore described in detail below:

$$
\begin{aligned}
E_k^{(UG)} &= \frac{u_1^* Y_{1k}}{v_{111}^* X_{1k} + v_{211}^* X_{2k} + v_{311}^* X_{3k}},\\
E_k^{(PG)} &= \frac{u_2^* Y_{2k}}{v_{112}^* X_{1k} + v_{212}^* X_{2k} + v_{312}^* X_{3k}},\\
E_k^{(T)} &= \frac{(u_1^* Y_{1k} + u_2^* Y_{2k})}{v_{11}^* X_{1k} + v_{21}^* X_{2k} + v_{31}^* X_{3k}},\\
E_k^{(P)} &= \frac{u_3^* Y_{3k}}{v_{123}^* X_{1k} + v_{223}^* X_{2k} + v_{323}^* X_{3k}},\\
E_k^{(G)} &= \frac{u_4^* Y_{4k}}{v_{124}^* X_{1k} + v_{224}^* X_{2k} + v_{324}^* X_{3k}},\\
E_k^{(I)} &= \frac{(u_5^* Y_{5k} + u_6^* Y_{6k})}{v_{125}^* X_{1k} + v_{225}^* X_{2k} + v_{325}^* X_{3k}},\\
E_k^{(R)} &= \frac{(u_3^* Y_{3k} + u_4^* Y_{4k} + u_5^* Y_{5k} + u_6^* Y_{6k})}{v_{12}^* X_{1k} + v_{22}^* X_{2k} + v_{32}^* X_{3k}},\\
E_k^{(Col)} &= \frac{(u_7^* Y_{7k} + u_8^* Y_{8k})}{v_{136}^* X_{1k} + v_{236}^* X_{2k} + v_{336}^* X_{3k}},\\
E_k^{(Con)} &= \frac{u_9^* Y_{9k}}{v_{137}^* X_{1k} + v_{237}^* X_{2k} + v_{337}^* X_{3k}},\\
E_k^{(S)} &= \frac{(u_7^* Y_{7k} + u_8^* Y_{8k} + u_9^* Y_{9k})}{v_{13}^* X_{1k} + v_{23}^* X_{2k} + v_{33}^* X_{3k}}.
\end{aligned}
\tag{4}
$$

6 Results and Discussions

The results derived from DEA offer critical insights into the efficiency levels of university faculties. These insights enable robust comparisons with top-performing counterparts and provide actionable guidance for administrative alignment with higher standards. DEA utilises a scoring system ranging from 0 to 1, where a score of 1 indicates efficiency and a score of 0 indicates inefficiency [19, 12].

This section is structured into two parts, with each subsection presenting results from different models. The first subsection compares results obtained from the HNDEA model with those from the CCR model. In the second subsection, faculties are categorised, and their efficiency within each group is assessed. Subsequently, we compare the efficiency scores derived from the HNDEA model for all faculties in the first subsection with the scores and rankings obtained in the second subsection.

6.1 Efficiency assessment of all faculties via conventional DEA and HNDEA models

The efficiency scores and rankings of the 26 faculties using the CCR and HNDEA models reveal significant insights. The results, showcasing efficiency scores and rankings from both models, are outlined in Table 4. This table also presents efficiency scores for units within each faculty, as evaluated using the HNDEA model. To maintain confidentiality, the names of the faculties have been anonymised. Notably, our findings reveal a high degree of similarity in the rankings produced by the two models, with a Spearman's rank correlation coefficient of $r = 0.8022$.

Table 4: Efficiency scores and rankings of all faculties using the CCR and HNDEA models.

No	Fac	E^{CCR}	R^{CCR}	E^{HNW}	R^{HNW}	E^{UG}	E^{PG}	E^{T}	E^{P}	E^{G}	E^{I}	E^{R}	$E^{Col.}$	$E^{Con.}$	E^{S}
1	A	1.0000	1	0.7198	7	0.6746	0.7834	0.7364	0.5529	0.4197	1.0000	0.6445	1.0000	0.0459	0.7615
2	B	1.0000	1	0.7526	4	0.9675	0.7053	0.9301	0.2647	0.5517	0.0000	0.4507	0.5420	0.0000	0.4065
3	C	1.0000	1	0.8120	3	1.0000	0.6031	0.9433	0.6027	0.1386	0.0000	0.4270	0.2009	1.0000	0.8017
4	D	1.0000	1	0.6687	10	0.3526	0.2069	0.3318	1.0000	0.8431	0.6785	0.8923	0.2150	0.0072	0.1630
5	E	1.0000	1	0.5918	16	0.3717	0.4116	0.3956	0.8206	0.1761	1.0000	0.7112	0.3958	0.1952	0.3457
6	F	1.0000	1	0.7371	6	1.0000	0.5165	0.9309	0.4190	0.5551	0.0532	0.4833	0.3271	0.0000	0.2453
7	G	1.0000	1	0.9480	1	0.9799	1.0000	0.9919	1.0000	0.7873	1.0000	0.9500	0.9782	0.0312	0.7414
8	H	0.5937	25	0.3166	25	0.0441	0.0284	0.0419	0.5061	0.2157	0.5493	0.4294	0.2900	0.0000	0.2175
9	I	0.8869	20	0.4666	22	0.4507	0.5976	0.5387	0.5493	0.0421	0.0000	0.3652	0.5326	0.0000	0.3995
10	J	0.7419	22	0.4753	21	0.6622	0.4248	0.6283	0.2016	0.0697	0.0000	0.1495	0.3658	0.0034	0.2752
11	K	0.8779	21	0.4640	23	0.5655	0.2648	0.5225	0.5732	0.1564	0.4450	0.4449	0.3051	0.0000	0.2289
12	L	1.0000	1	0.5183	18	0.3421	0.1011	0.3077	0.3220	0.1431	0.2582	0.2652	1.0000	0.0008	0.7502
13	M	1.0000	1	0.7045	9	0.6749	1.0000	0.8696	0.6140	0.0615	0.0000	0.4123	0.5331	0.0000	0.3998
14	N	0.5555	26	0.3086	26	0.2882	0.0304	0.2514	0.1399	0.0770	0.2323	0.1498	0.5555	0.0000	0.4167
15	O	0.9546	19	0.6023	15	0.4994	0.8690	0.7208	0.2457	0.2470	0.0000	0.2289	0.8175	0.0000	0.6131
16	P	1.0000	1	0.6516	11	0.9587	0.5433	0.8994	0.1267	0.1371	0.0000	0.1243	0.3931	0.1302	0.3273
17	Q	1.0000	1	0.8504	2	0.5531	0.5635	0.5594	1.0000	1.0000	1.0000	1.0000	0.8129	0.0000	0.6096
18	R	1.0000	1	0.7466	5	0.2967	0.1879	0.2812	1.0000	1.0000	1.0000	1.0000	0.3962	0.0000	0.2971
19	S	1.0000	1	0.6303	13	0.7655	0.1730	0.6809	0.3334	0.0494	0.0000	0.2285	1.0000	0.0216	0.7554
20	T	0.7305	23	0.4758	20	0.6821	0.4137	0.6437	0.2258	0.1191	0.0825	0.1851	0.2074	0.0035	0.1565
21	U	1.0000	1	0.6491	12	0.4586	1.0000	0.7828	0.0000	0.0633	0.0000	0.0465	1.0000	0.0000	0.7500
22	V	1.0000	1	0.5148	19	0.7002	0.0499	0.6073	0.2422	0.0511	0.5543	0.2825	0.5965	0.0000	0.4474
23	W	1.0000	1	0.6098	14	0.1621	0.4381	0.3274	0.5220	0.7024	0.4197	0.6382	0.8768	0.2816	0.7280
24	X	1.0000	1	0.7191	8	0.3610	0.2328	0.3427	1.0000	1.0000	0.2050	0.9582	0.2585	0.0338	0.2023
25	Y	0.7270	24	0.4318	24	0.2453	0.0679	0.2199	0.6006	0.5371	0.2788	0.5429	0.3148	0.0422	0.2467
26	Z	1.0000	1	0.5531	17	0.4466	0.2601	0.4200	0.7272	0.5941	0.0801	0.6377	0.4811	0.0386	0.3705

Note: E^{CCR} = Efficiency scores using CCR, E^{HNW} = Efficiency scores using HNDEA, R^{CCR} = Ranking by CCR, R^{HNW} = Ranking by HNDEA, E^{UG} = Undergraduate Teaching Efficiency, E^{PG} = Postgraduate Teaching Efficiency, E^{T} = Teaching Efficiency, E^{P} = Publication Efficiency, E^{G} = Grant Efficiency, E^{I} = Innovation Efficiency, E^{R} = Research Efficiency, $E^{Con.}$ = Consultation Efficiency, $E^{Col.}$ = Collaboration Efficiency, E^{S} = Services Efficiency.

Under the CCR model, 18 faculties achieved a score of one, representing approximately 69% of the total, suggesting efficiency according to CCR criteria. All faculties rated as fully efficient achieve the same top ranking ($R = 1$), which presents a challenge in differentiating the rankings of efficient faculties. This finding is consistent with previous observations by Kao [18] and Kashim et al. [20]. This indicates that the CCR model does not adequately differentiate between the faculties' performance.

The HNDEA model, in contrast, offers a distinct ranking of faculties based on efficiency values, highlighting significant differences in performance among them. All faculties in this study were found to be inefficient when analysed using the HNDEA model. This result reflects the model's ability to identify nuances in performance that the CCR model might overlook. The inefficiencies were primarily concentrated in the consultation and innovation units across multiple faculties, which is critical for university administration to address. This detailed analysis helps administrators pinpoint specific units where performance can be improved, providing a more actionable framework for intervention.

For instance, while Faculty G secured top rankings in both the conventional DEA and HNDEA models, its efficiency value under the HNDEA model indicates inefficiency, particularly in the consultation subunit. This highlights that while overall performance may seem satisfactory, closer examination of individual components within the faculty reveals areas requiring attention. Conversely, Faculty N ranked lowest among all faculties, demonstrating subpar performance across all units and subunits, particularly in income generation from consultations. The identification of such inefficiencies presents an opportunity for targeted improvement strategies, such as enhancing consultation services or reallocating resources.

Our analysis of teaching efficiency revealed that undergraduate teaching outperformed postgraduate teaching. This finding is significant because it suggests that faculty members may be allocating more resources or adopting more effective methods for undergraduate programs. Regarding research units, innovation showed the lowest performance, while publication demonstrated the highest. Among service units, consultation was identified as the least efficient. This finding indicates that services beyond teaching and research, such as consultations with industry or the public, may not be receiving adequate attention or resources, which could limit their potential impact on faculty and university performance.

The efficiency scores were significantly impacted by the 2020 COVID-19 pandemic, which affected various factors. The nationwide Movement Control Order (MCO) implemented in Malaysia in March 2020 resulted in institutional closures and a swift transition to e-learning under resource constraints. These measures evolved over the next 19 months in response to changing pandemic conditions. The disruption caused by the pandemic likely contributed to inefficiencies across multiple units, particularly in consultation and innovation, where remote work and restricted interactions might have hindered performance.

6.2 Comparative efficiency assessment of university faculties: overall vs. group analysis using HNDEA models

To further explore the topic, all faculties were divided into science and nonscience disciplines, identifying 14 nonscience and 12 science faculties. The HNDEA model was then applied to each group. Table 5 presents the results for all faculties collectively, as well as within their respective groups, allowing for a comparative analysis of efficiency scores and rankings. This approach highlights differences in performance when analysing faculties as a whole versus within specific groups.

Table 5: Efficiency scores and rankings of faculties by group, with overall comparison.

No	Fac	$E^{(\mathrm{HNW})}_{\mathrm{ALL}}$	$R^{(\mathrm{HNW})}_{\mathrm{ALL}}$	$E^{(\mathrm{HNW})}_{\mathrm{NS}}$	$R^{(\mathrm{HNW})}_{\mathrm{NS}}$	$E^{(\mathrm{HNW})}_{\mathrm{S}}$	$R^{(\mathrm{HNW})}_{\mathrm{S}}$
1	A	0.7198	7	0.9014841	1	-	-
2	B	0.7526	4	0.8537348	3	-	-
3	C	0.8120	3	-	-	0.8516389	3
4	D	0.6687	10	-	-	0.7083071	6
5	E	0.5918	16	0.8377316	4	-	-
6	F	0.7371	6	0.8772825	2	-	-
7	G	0.9480	1	-	-	0.954676	1
8	H	0.3166	25	-	-	0.3411147	12
9	I	0.4666	22	0.6078816	9	-	-
10	J	0.4753	21	0.517537	13	-	-
11	K	0.4640	23	-	-	0.4873344	10
12	L	0.5183	18	0.5854403	10	-	-
13	M	0.7045	9	0.7694993	6	-	-
14	N	0.3086	26	0.3556568	14	-	-
15	O	0.6023	15	0.6580063	8	-	-
16	P	0.6516	11	0.7785759	5	-	-
17	Q	0.8504	2	-	-	0.9206976	2
18	R	0.7466	5	-	-	0.7614239	4
19	S	0.6303	13	-	-	0.6393219	8
20	T	0.4758	20	0.5462322	12	-	-
21	U	0.6491	12	0.6835719	7	-	-
22	V	0.5148	19	0.5771866	11	-	-
23	W	0.6098	14	-	-	0.6796607	7
24	X	0.7191	8	-	-	0.724866	5
25	Y	0.4318	24	-	-	0.4396925	11
26	Z	0.5531	17	-	-	0.5672523	9

Note:
$E^{(\mathrm{HNW})}_{\mathrm{ALL}}$ = Efficiency of all faculties with HNDEA,
$R^{(\mathrm{HNW})}_{\mathrm{ALL}}$ = Ranking of all faculties with HNDEA,
$E^{(\mathrm{HNW})}_{\mathrm{NS}}$ = Efficiency of nonscience faculties with HNDEA,
$R^{(\mathrm{HNW})}_{\mathrm{NS}}$ = Ranking of nonscience faculties with HNDEA,
$E^{(\mathrm{HNW})}_{\mathrm{S}}$ = Efficiency of science faculties with HNDEA,
$R^{(\mathrm{HNW})}_{\mathrm{S}}$ = Ranking of science faculties with HNDEA.

The results in Table 5 indicate that efficiency scores are generally higher for faculties within their respective groups than when all faculties are analysed collectively. Furthermore, differences in both rankings and efficiency scores were observed depending on whether the analysis was conducted on grouped or ungrouped faculties. For example, Faculty A, the top performer among nonscience faculties ($E^{(\mathrm{HNW})}_{\mathrm{NS}}$), has an efficiency score of 0.901484, which is higher than Faculty F's score of 0.877283. However, when comparing these scores with the efficiency scores of all faculties analysed together, Faculty F exhibits a higher efficiency score than Faculty A. These variations in efficiency scores result in differing rankings between the two models.

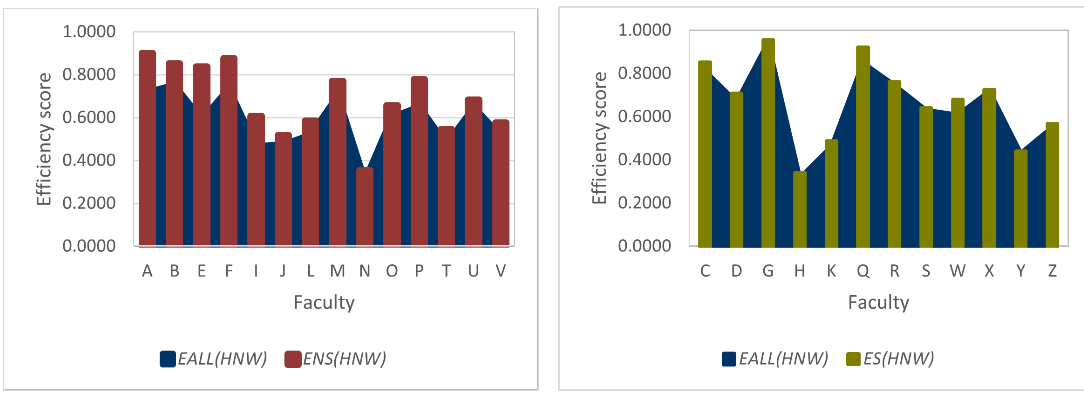
Next, we compare the rankings obtained using the HNDEA model for all faculties collectively and by discipline, as presented in Table 6. Column 3 represents the initial rankings of all faculties analysed without group distribution. Columns 4 and 6 present the reranked results based on nonscience and science groups, respectively, derived from the rankings in Column 3. Columns 5 and 7 show the rankings resulting from grouped analysis. This approach allows us to see how different evaluation methods capture and interpret faculty outcomes across diverse academic fields, especially between science and nonscience faculties. For example, nonscience disciplines might emphasise creative outputs, such as artwork, which may not receive the same recognition in university assessments as scientific publications. This disparity is significant; most universities prioritise scientific writing as the main output over other important contributions when evaluating performance.

Table 6: Comparing university faculty rankings based on the HNDEA analysis model for all faculties with the rankings based on the group.

No	Fac	$R_{\text{ALL}}^{(\text{HNW})}$	$R_{\text{ALL}}^{(\text{HNW})}$ re-rank by non-science group	$R_{\text{NS}}^{(\text{HNW})}$	$R_{\text{ALL}}^{(HNW)}$ re-rank by science group	$R_{\text{S}}^{(\text{HNW})}$
1	A	7	3	1	-	-
2	B	4	1	3	-	-
3	C	3	-	-	3	3
4	D	10	-	-	6	6
5	E	16	8	4	-	-
6	F	6	2	2	-	-
7	G	1	-	-	1	1
8	H	25	-	-	12	12
9	I	22	13	9	-	-
10	J	21	12	13	-	-
11	K	23	-	-	10	10
12	L	18	9	10	-	-
13	M	9	4	6	-	-
14	N	26	14	14	-	-
15	O	15	7	8	-	-
16	P	11	5	5	-	-
17	Q	2	-	-	2	2
18	R	5	-	-	4	4
19	S	13	-	-	7	8
20	T	20	11	12	-	-
21	U	12	6	7	-	-
22	V	19	10	11	-	-
23	W	14	-	-	8	7
24	X	8	-	-	5	5
25	Y	24	-	-	11	11
26	Z	17	-	-	9	9

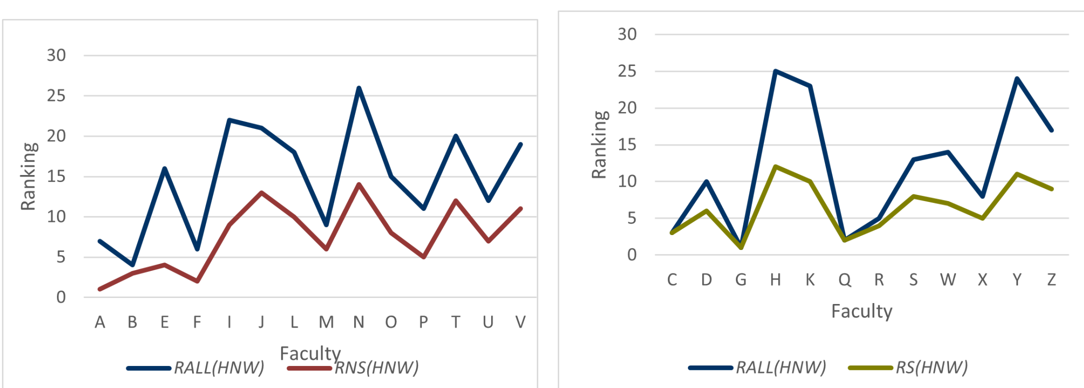
A comparison of faculty rankings from the overall and grouped analyses reveals significant differences. In the science group, the differences are less pronounced, except for faculties S and W. However, for the nonscience group, comparing Column 4 with Column 5 reveals substantial differences. This variation underscores the importance of grouped analysis, as nonscience disciplines may emphasize both scientific publications and other forms of output, which could affect how their contributions are recognized in university evaluations.

Figure 3 presents graphs comparing the efficiency scores of all faculties with those of grouped faculties: Figure 3(a) contrasts all faculties with the nonscience group, while Figure 3(b) contrasts all faculties with the science group. Figure 4 presents the corresponding rankings. When analyzed within their respective groups, faculties exhibit higher efficiency scores. This is most likely due to faculty similarities within each group, resulting in better efficiency scores. In contrast, when faculties are evaluated generally, they are compared to a broader, more diversified set of faculties, introducing more variation and typically resulting in lower efficiency scores. While higher efficiency scores within groups might suggest higher rankings, Figure 4 reveals a different trend. Faculties within their groups tend to have lower rankings compared to the overall analysis. This can be explained by the smaller sample sizes within each group.



(a) (b)

Figure 3: Efficiency scores comparison: All faculties vs. (a) nonscience and (b) science groups using the HNDEA model.



(a) (b)

Figure 4: Rankings comparison for all faculties and faculties grouped by (c) nonscience and (d) science using the HNDEA model.

7 Conclusions

In higher education, both nationally and internationally, institutions engage in benchmarking, policy analysis, and information disclosure efforts to enhance their competitiveness. However, the complex nature of HEIs, characterised by diverse inputs and outputs within a non-profit framework, poses significant challenges in performance measurement. In addressing this challenge, DEA emerges as a valuable approach renowned for its adaptability to handle such complexities. This paper proposes a model utilising HNDEA, tailored to measure faculty efficiency within the hierarchical structures prevalent in university faculties.

The inclusion of research subunits such as publication, grants, and innovation enhances the assessment of faculty efficiency. These additions are in line with the goals outlined in the Malaysia Education Blueprint $2015-2025$ (Higher Education) or MEB (HE), emphasising the promotion of innovation for national economic growth and overcoming challenges in engaging with industry and community [24].

To validate the proposed model, we assessed 26 faculties in a Malaysian university using 2020 data. A comparison with conventional DEA methods consistently showed lower efficiency scores under the HNDEA model, demonstrating its greater discriminatory power. While the HNDEA model may be less flexible than the conventional CCR model, it offers the advantage of evaluating efficiency at multiple levels, including units and subunits, enabling a more detailed identification of inefficiencies, which is valuable for administrators.

Specifically, our analysis of grouping faculties into science and nonscience disciplines using the HNDEA model showed higher efficiency scores for grouped faculties compared to analysing all faculties collectively. This approach provides a more tailored efficiency assessment by considering the distinct operational environments of each faculty group. Within the context of the studied faculties, inefficiencies in innovation and consultation subunits are evident, indicating a misalignment with the aspirations outlined in the MEB (HE). Addressing these inefficiencies requires future initiatives to strengthen university-industry collaboration and foster innovation at the institutional level.

In conclusion, this study discusses a network DEA model for evaluating faculty efficiency within a hierarchical structure. By capturing efficiency at multiple levels, the model offers valuable insights for targeted improvements, addressing limitations in conventional DEA approaches. Future research could explore a dual-model methodology that accounts for variable returns to scale and offers a complementary perspective on faculty efficiency within hierarchical structures.

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Conflicts of Interest The authors declare that there is no conflict of interest regarding the publication of this paper.

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