Robust Supplier Selection

Systematic Approach using Data Envelopment Analysis: In the Post-Pandemic Era

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ABSTRACT

With the existence of COVID-19, the whole economy experienced an unprecedented challenge. Organizations must be resilient to the ever-changing and unanticipated market to avoid being out of the fierce competition. In an era of information explosion, managers require a systematic, explicable, comparative, and traceable approach to evaluate and choose suppliers. In recent years, procurement strategies have been revamped due to the disruption in the global supply chain by the pandemic and war in Europe. A wrong supplier selection decision seriously damages the company's supply chain, operations, and reputation. Therefore, partnering with a sustainable supplier is a prerequisite for business success. With the rising importance of sustainability, choosing a competent supplier is one of the significant strategic management decisions. A sustainable supplier impacts business operations and accelerates long-term growth, enhancing efficiency and effectiveness. In the post-pandemic era, it is expected to have new approaches to define inputs and outputs to rank suppliers and logistics firms. This study uses Data Envelopment Analysis (DEA) to identify a sustainable supplier. Our approach involves selecting suitable inputs and outputs, improving the accuracy and relevance of the study to find more robust suppliers.

The results of this research were implemented in the business intelligence system of Miraab Company, which is known as a reliable industrial valve manufacturing company in Iran.

Key Words: Data Envelopment Analysis (DEA), Supply Chain, Robust Supplier, Efficiency, Decision Making Unit (DMU)

INTRODUCTION

Introduction to Supply Chain Management

As the definition by the Council of Supply Chain Management Professionals (CSCMP), supply chain management (SCM) involves planning and managing all activities encompassing procurement, conversion, and logistics-related services. It is a function of integrating the main business into the other business operations within or among the stakeholder companies. Most importantly, suppliers, intermediaries, and customers coordinate and collaborate on supply chain activities related to sales, marketing, finance, production, procurement, logistics, etc. Apart from that, previous literature also provided several definitions for SCM. Tang (2006) defined SCM as "the management of material, information, and financial flows through a network of organizations (i.e., suppliers, manufacturers, logistics providers, wholesalers/distributors, retailers) that aims to produce and deliver products or services for the consumers." Summing up the definitions given in the previous literature, a supply chain can be defined as an integrated network of resources, processes, and stakeholders who collaboratively manage the movement of materials, information, and money from the raw material acquisition, transforming materials to work-in-processed and finished goods to distributing finished products to the final customer to satisfy customer demand (Athaudage et al., 2022 and Tang, 2006).

With globalization, business processes have become more complex and advanced. Supply chain value and geographical range are immensely growing, and more stakeholders are joining worldwide. As a result, supply chains are also getting more vulnerable than before (Xu et al., 2020; Bier et al., 2020; Fagundes et al., 2020)). Not only that, but the market has also become more competitive. Companies are always looking for improvement opportunities with increasing competitiveness in the business context. International companies are on a continuous improvement

to survive in the rapidly changing global market. As the supply chain (SC) plays a salient role in the entire business function, companies pay more attention to continuous improvement.

With the increasing supply chain complexity, current supply chains encompass many players such as suppliers, manufacturers, distributors, and retailers at different tiers in various industries, which can sometimes be located across the world. Companies struggle to overcome many barriers and sustain in this striving global market (Vishnu et al., 2019). They frequently experience serious threats and many other risks. Some common instances are demand uncertainties, internal uncertainties, and supply uncertainties. Demand uncertainties such as product availability in the market, seasonality, trends, and affordability of consumers, refer to random and external factors that create unexpected demand incline or decline. Supply uncertainties are mainly capacity uncertainties, supply chain disruptions, and yield uncertainties, referring to the uncertainties in ordering quantity resulting from product defects etc. Recently, many disastrous events, such as terrorist attacks, pandemics, natural disasters, etc., have hugely interrupted supply chains. As Urciuoli & Hintsa (2018) explained, changing business trends, globalization, complexity, and specialization immensely drive risk and gradually decrease managerial power to control operations (Urciuoli & Hintsa, 2018).

About COVID-19

A 55-year-old woman from Hubei province was the first COVID-19 case reported in Wuhan, China, on 17th November 2019 (The Economic Times, 2020). The first media statement on ‘viral pneumonia’ was given to the WHO country office of the People’s Republic of China on the 31st of December 2019 by the Wuhan Municipal Health Commission (World Health Organization, 2020). On 11th February, the International Committee on Taxonomy of Viruses (ICTV) declared the name of the newly identified virus as the “Severe Acute Respiratory

Syndrome Corona Virus 2 (SARS-CoV-2)" since the virus was genetically related to SARS in 2003, however it is distinct and separate from SARS. On the same day, WHO named the new disease "COVID-19" (World Health Organization, 2020). The first case outside the People's Republic of China was recorded in Thailand on 13th January 2020. WHO characterized COVID-19 as a pandemic on the 11th of March 2020, considering the shocking spread, severity, and inaction (World Health Organization, 2020).

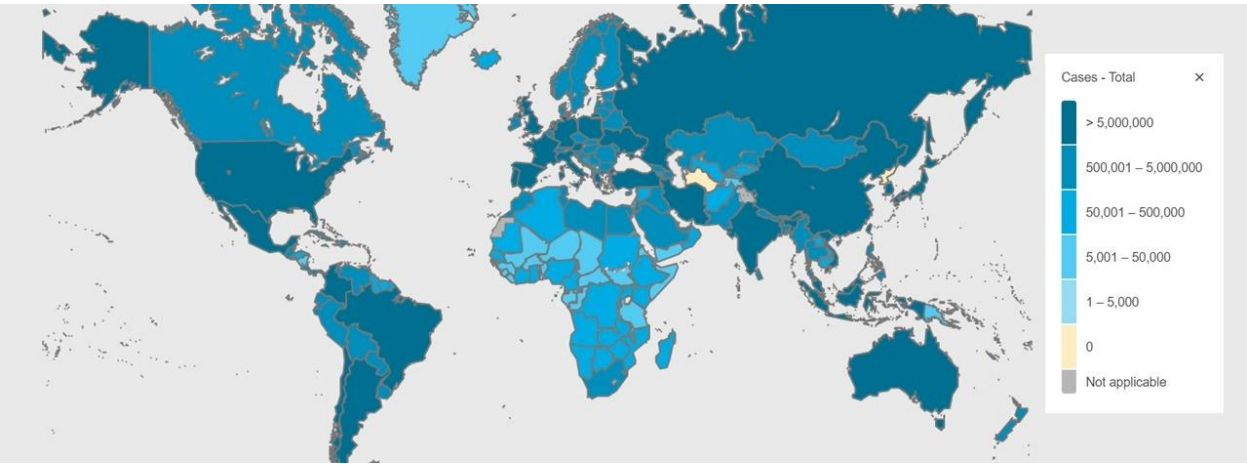
According to the reports of WHO, approximately 7.53 billion cases and 6.8 million deaths have been recorded by the date of 30th January 2023 (World Health Organization, 2023). So far, 229 countries and territories worldwide have been affected by the disease. Among all regions, Europe has recorded the maximum number of COVID-19 cases, which is about 2.71 billion with 2.18 million deaths. In contrast, the American region has the highest number of deaths, 2.90 million, with 1.99 billion cases (World Health Organization, 2023). Moreover, the US has accounted for over 1 billion confirmed cases. China and India remain after the United States with the confirmed cases of 98 million and 44 million, respectively. The top three countries which have the highest burden of the COVID-19 outbreak have recorded approximately 32 percent of global total confirmed cases (World Health Organization, 2023).

From the beginning of 2020, the pandemic engulfed the world. COVID-19 rapidly spread across the globe and formed a public health emergency among countries. In one aspect, fear of the disease pervades societies. Not only that, but strong economies of the world also downturned. World trade, capital flow, tourism, commodity prices, and remittances were abandoned. The global GDP rate was anticipated to slow down by nearly 2.3 percent due to COVID-19. Multilateral organizations estimated the global GDP deteriorated by 3% in April 2020, worse than the 0.1% shrinkage in 2009 (Alfaro & Jeong, 2020). Approximately 44 percent of 718 professionals and

world leaders interviewed in the Global Risks Perception Survey (GRPS) think that the 'erosion of global supply chains' is a risk for the economy, which would improve in 2020 compared to 2019 (World Economic Forum, 2020). The Institute for Supply Management (ISM) surveyed 600 supply chain professionals on the 10th March 2020. According to that, approximately 75% of surveyed companies reported that their supply chains are disrupted, and 16% of companies have experienced downward revenue targets (Industry Week, 2020).

Figure 1

Spread of COVID-19 - World map



Note. Global COVID-19 spread as of 30th January 2023. From WHO https://covid19.who.int/

How did COVID-19 affect on Supply Chain?

COVID-19 was unique among all disruptions as it has severely affected the global supply chains (GSCs), creating dynamic and diversified issues throughout (Chowdhury et al., 2021; Xu et al., 2020; Simchi-Levi, 2020). It was one of the most severe catastrophes in history (Raj et al., 2022; Ivanov et al., 2017). It proved the complexity and interconnectivity of GSCs as the upstream SCs are seriously affected due to the irregular and unpredictable behavior of downstream partners. As a result, the impact of the bullwhip effect was very sharp and significant in the upstream supply

chains, specifically small and medium-sized businesses. The COVID-19 pandemic disrupted all phases of GSC, from raw material acquisition to delivering products to the final customer (Raj et al., 2022; Xu et al., 2020; Ivanov et al., 2017). The activities within the supply chain were interconnected. Therefore, disrupting one function causes a ripple effect (Chowdhury et al., 2021) in several supply chains' supply, demand, and logistics side(Raj et al., 2022). According to a Fortune report released on the 21st of February 2020, out of 1000 Fortune companies, 94% of companies have experienced supply chain disruptions (Sherman, 2020). Furthermore, sudden demand and supply volatility, shortage of labor, international trade barriers, and vehicle movement restrictions were significant issues in all phases of the supply chain (Chowdhury et al., 2021) due to COVID-19 preventive measures such as quarantine restrictions, travel barriers, and temporary closures of some plants (Xu et al., 2020).

As a result of the pandemic, the gap between demand and supply increased (Raj et al., 2022). Some sectors have shown sudden demand spikes, while some have declined. Generally, products can be categorized into two types: functional products and innovative products. Functional products such as face masks have turned into innovative products, showing severe demand and supply fluctuations (Xu et al., 2020). For instance, the demand for face masks, Personal Protective Equipment (PPE), medical equipment, and canned and dried foods has significantly increased, creating a shortage in the market. Consumers experienced delays in online and traditional delivery services. They tend to buy more than they require due to uncertain supply chains, panic buying, and stockpiling behaviors (Chowdhury et al., 2021). At the same time, demand for non-essential products has drastically declined due to the income loss and saving money for an uncertain and ambiguous future (Chowdhury et al., 2021; Chiaramonti & Maniatis, 2020). Consequently, the price of essential commodities has increased, whereas non-essential

goods have decreased (Chowdhury et al., 2021). Many companies have adapted to Just-in-Time (JIT) inventory management systems to manage their inventories, optimizing the cost. As a result, those companies have struggled to maintain their inventory levels and realized that JIT is not a proper strategy to combat a global disruption such as a pandemic (Raj et al., 2022).

Furthermore, lockdowns have led to many constraints in accessing resources. The limited availability of labor, raw materials, and consumer goods suspended the functioning of some sectors (Xu et al., 2020). Approximately 25% of the world's population of around 2 billion workers belong to work in emerging economies. Due to the lockdown restriction and COVID-19 preventative measures, many workers failed to continue their jobs. Also, some of them lose their jobs because of temporary closures. As a result of their wage reductions and loss of employment, many migrant workers traveled back to their home countries. This reverse migration created enormous long-term issues, especially in agriculture and apparel supply chains. For example, India's largest food supplier, Azadpur Mandi has operated at only 25% of its standard capacity due to the labor shortage (Raj et al., 2022).

Moreover, logistics and transportation were disrupted and experienced delays, cancellations, and postponements due to travel restrictions and border closures. As World Trade Organization predicted, international trade has been fined by 13% to 32% in 2020 due to the pandemic (World Trade Organization, 2020). Commercial transportation was shut down, and air cargo transportation was limited to medical supplies (Xu et al., 2020). Furthermore, some countries imposed export and import restrictions. For instance, India, France, and the USA restricted medicine exports, leading to delayed transactions. Maritime freight is crucial in international logistics, representing 90% of global trade volume. The lack of truck drivers for container pick-ups, quarantine, and rigorous custom inspection caused delays in maritime cargo transportation

(Xu et al., 2020). This has increased the lead time, exceeding the timelines of the overall supply chain from raw material extraction to the final product (Hippold, 2020). According to Enteprenuer.com, lead times have risen by an average of 20 days for the suppliers of Anviln China (Raj et al., 2022).

As a result of the pandemic, many companies shifted to the blended distribution method of online-offline from physical channels. Due to preventative measures, many physical distribution channels had limited access or shut down (Dente & Hashimoto, 2020), causing multiple issues in the supply chain. However, many companies have improved their online service capabilities to survive this challenging time. Some retailers developed warehouses focusing exclusively on online sales, while others struggled to improve logistics functions to address new markets (Mollenkopf et al., 2021). Also, the relationship between supply chain partners has been significantly impacted due to the restrictions. As a result, the organizations failed to integrate and collaborate in supply decision-making, creating many adverse effects, including the impact of the bullwhip effect.

Robust Supply Chain

The coronavirus has created rapid changes in the business environment. Firms need to proactively take action to mitigate the issue by integrating and revamping their capabilities. After the pandemic, many organizations have improved supply chain resilience to strengthen operations and manage supply chain disruptions. Supply chain resilience allows organizations to maintain and enhance their market position (Birkie & Trucco, 2020). Previous research studies have proven that resilience is vital in directing other organizations to the right path in a catastrophe (Ponomarov & Holcomb, 2009). The collaborative research of Accenture and the World Economic Forum revealed that 80% of global companies considered supply chain resilience after the pandemic

(World Economic Forum, 2020). Many organizations have reconsidered their supply chain strategy, design, and dependencies to avoid adverse impacts in future situations.

Chowdhury & Quaddus (2016) discussed three main dimensions of supply chain resilience: preparedness, response, and recovery. The strategy considered preparedness for future disruption, readiness to respond quickly, minimizing adverse impacts, and recovering into the original or a better state (Chowdhury & Quaddus, 2016). As a result of the pandemic, organizations reconsider resource allocation to address a disruption successfully. They have prioritized the importance of tasks and allocated resources from non-prioritized activities to essential activities. Also, they have realized to increase production capacities, addressing demand spikes in the short run. However, researchers suggest utilizing temporary capabilities (Leite et al., 2021) by eliminating non-critical tasks. Also, it is recommended to share resources among supply chain partners to minimize the impact of disruption as the demand peaks at different points for different entities. Practically, the overall process will shut down in case of raw materials shortage. Therefore, maintaining and improving upstream supply chain resilience is crucial to continue the process. Supply chain mapping is commonly used to identify the bottlenecks and their consequences, enhancing visibility and formulating supplier-centric strategies. During COVID-19, most manufacturing companies temporarily closed production due to single sourcing. Thus, it is recommended to maintain a diversified supplier network and improve emergency sourcing procedures to address the disruption (Chowdhury et al., 2021).

Some scholars have proposed to improve and redesign logistics facilities to enhance responsiveness. Faster delivery methods, such as air transportation, are encouraged in the event of disruption (Chowdhury et al., 2021). Nearshoring and back shoring are also recommended to improve local capacities. Also, many entities adapted to offshoring strategies and equipped

production facilities with the required logistic support to deal with a future catastrophe. Over-dependency on international trading created multiple issues in the supply chain. Therefore, many companies tried to balance local and international trade as a lesson of the pandemic (Chowdhury et al., 2021). Selecting multiple suppliers near the primary production plant enhances the security and reserves stock levels in the short term (Raj et al., 2022). Redesigning short supply chains with a few partners also successfully maintains supply chain resilience. Furthermore, previous studies recommend developing ICT in supply chains is beneficial in the long term to deal with disruption. As a result of the pandemic, the popularity of adapting to technology was common. Consumers prefer online purchasing and home delivery due to travel restrictions. Digital technologies help to streamline, control, and monitor the process while mitigating the issues in a catastrophe (Ibn-Mohammed et al., 2021; Remko, 2020). The entities adapt to Industry 4.0 as the new long-term trend to deal with supply chain disruptions (Kumar et al., 2020). For instance, cloud and FOG computing, 3D printing, artificial intelligence (AI), Internet of Things (IoT), blockchain, and big data analytics are commonly used depending on the size of the business. According to Harvard Business Review, Walmart applied artificial intelligence technology to strengthen supply chain flexibility and resilience. By adopting the AI, Walmart automated the negotiation by chatbot with procurement suppliers to streamline the process while the pilot of the solution was conducted in January 2021 (Hoek et al., 2022).

Furthermore, some entities have developed automated systems to ensure smooth running with limited staff due to social distancing (Ivanov & Das, 2020). Organizations value real-time data in decision-making to gain a competitive advantage. Improving real-time transparency through control towers utilizing big data has become a new business trend. These approaches formulate business continuity plans and facilitate last-mile deliveries using autonomous vehicles

and drones (Raj et al., 2022). Digital transformation methodologies create real-time responsive and flexible supply chains to deal with external disruptions. New supplier partnerships are encouraged when revamping the supply chain, ensuring local proximity. Digital transformation technologies such as 3D printing and artificial intelligence can use to enhance production capabilities locally. Improving supply chain collaborations assists in mitigating adverse effects, speeding up the recovery, and preparing for the events (Sharma et al., 2022; Chowdhury et al., 2021). For instance, entities can implement knowledge management systems to share expertise and information among supply chain partners to mitigate information ambiguity. Furthermore, horizontal collaboration is encouraged at the national level, ensuring the continuous supply of essential products (Chowdhury et al., 2021).

Importance of supplier selection in the post-COVID-19 world

The COVID-19 pandemic enormously challenges the whole economy in every industry, affecting individuals and organizations (Mańkowski et al., 2022). It offers an opportunity for business transformation; companies switch their business model and how they operate their business (Naha & Nandy, 2022). Lockdowns, working from home, social distancing, panic buying, and rising demand in e-commerce created unexpected disruptions in supply chains. The pandemic exposes supply chain vulnerability with serious disturbance and delayed delivery (Sombultawee et al., 2022). The smooth transportation of goods or services, raw materials, components, semi-finished goods, or finished goods from a supplier to the customer on time and in the correct place is not inevitable. Each participates in the supply chain inextricably and executes activities at each stage to facilitate the cycle. In consequence, the performance of the supply chain is the crucial factor in achieving business success and enhancing a company's competitive edge (Čiković et al.,

2022). Simultaneously, the rivalry between companies from all industries is fierce in the digitalization era, and supplier selection is essential.

Choosing an ideal and reliable supplier is challenging; however, it enables a long-term business partnership and enhances performance by minimizing potential risk, accelerating mutual benefit, enhancing productivity, and optimizing profit. The selection of sustainable suppliers embraces economic criteria, ethical business practices, and environmental and societal impact with the raised awareness of corporative social responsibility (Čiković et al., 2022). Supplier evaluation includes an ecological commitment to reduce adverse environmental effects by integrating green supply chain management (Huang et al., 2022). The green concept is incorporated into the entire supply chain procedure from procurement, production, packaging, storage, and distribution (Shin & Cho, 2022). Successful supplier selection helps minimize operating costs, enhances customer satisfaction, and creates positive brand value. As a result, a quality supplier is a crucial part of an organization to achieve business success (Dutta et al., 2022)

Introducing Data Envelopment Analysis (DEA) and inputs and outputs to find a robust supplier

Data Envelopment Analysis (DEA)

Data Envelopment Analysis (DEA) is widely used to measure productivity and efficiency (Čiković et al., 2022). This methodology is a practical approach popularly adopted in various industries, including healthcare, financial institutions, agriculture, armed services, sports, retail, etc. (Čiković et al., 2022). It facilitates decision-makers in evaluating the efficiency of an organization and conducting benchmarking (Mozaffari et al., 2022). DEA is a non-parametric mathematical method for performance measurement. It is a data-oriented approach that directly

compares the available data without any pre-assumed parameters (Čiković et al., 2022). One of the biggest advantages of DEA is that it manages multiple input and output data. Also, DEA directly compares the DMU against the rest of the DMUs and provides efficiency scores separately for each DMU.

Farrell developed the traditional DEA method in 1957 (Hosseini-Nasab & Ettehadi, 2023). Charnes, Cooper, and Rhodes introduced the first DEA model in their seminal paper titled "Measuring the efficiency of decision-making units" in 1978 (Čiković et al., 2022; Charnes et al., 1978). Initially, it was also called CCR since the model was developed by Charnes, Cooper, and Rhodes (Mozaffari et al., 2022). Later, Banker, Charnes, and Cooper further developed the model, and it was called BCC in 1984 (Singh et al., 202). Today, DEA has become one of the most crucial analysis tools in decision-making. It helps to assess the efficiency and identify the production (Čiković et al., 2022). DEA is a linear programming-based methodology (Shafiee et al., 2021) used to calculate the production efficiency of suppliers by employing multiple input and output variables (Hosseini-Nasab & Ettehadi, 2023). By this, vendors can be distinguished by their efficiency levels. DEA is a mathematical method to calculate an economic unit's related productivity or efficiency, and it allows measuring the efficiency of a set of “Decision Making Units” (DMU).

A DMU refers to a homogeneous entity or productive unit offering similar products or services. It can include different entities such as doctors, energy providers, hospitals, restaurants, universities, banks, and countries. Besides, DMUs can generate multiple output variables based on various input variables. Applying the mathematical programming technique of DEA helps identify which DMU has the highest efficiency score and facilitates the selection of suppliers.

After establishing a set of DMUs, the next step is to define the input and output variables. The DEA model allows the incorporation of multiple input and output variables (Čiković et al., 2022), and the number of input variables can differ from the number of output variables, such as having two input variables with one output variable. The efficiency of DMU is affected by the proportional changes in the input or output variables. In DEA, all DMUs utilize the same set of input and output variables. To assess the efficiency of each DMU, a weighted ratio is assigned to each input and output variable for each DMU. By utilizing these weight ratios, the efficiency rate of each DMU can be calculated in the optimal condition with the maximum efficiency (Mozaffari et al., 2022). The efficiency rate of a DMU can be expressed as a weighted sum of outputs/ weighted sum of inputs.

In the DEA model, the efficiency score of each DMU is determined with respect to an efficiency frontier, which ranges from 0 to 1. The ratio of the weighted sum of outputs / weighted sum of inputs for each DMU cannot exceed 1 (Demircioğlu & Özgüner, 2022). If the efficiency score of a particular DMU is 1, it indicates that it operates at or very close to 100% efficiency. The productivity levels are relatively inefficient for DUMs with an efficiency score of less than 1 (but greater than 0). Furthermore, the DEA framework can identify the highest output level reached by a particular input level (Shafiee et al., 2021). This model allows inefficient DMUs to adjust their input and output levels to enhance efficiency and (Amirteimoori & Kordrostami, 2014) become comparable to their peer group (Ruiz & Sirvent, 2022).

The DEA model is a widely accepted mathematical programming technique that is being used in various industries. DEA model can be integrated with various multi-decision-making (MCDM) techniques to enhance its capability (Dutta et al., 2022). These techniques include Techniques for Order of Preference by Similarity to Ideal Solution (TOPSIS), Artificial neural

network (ANN), Analytic Hierarchy Process (AHP), Analytical Network Process (ANP), fuzzy DEA, etc. (Čiković et al., 2022). In addition, DEA can be combined with other methodologies such as fuzzy Analytic Network Process (FANP), super efficiency DEA, and DEA-Assurance Region (AR) model to attain more accurate results (Dutta et al., 2022).

Consider *n* number of DMUs with non-negative input vectors, $\mathbf{x_j} = (x_{1j}, x_{2j}, \ldots, x_{mj})$ and output vectors, $\mathbf{y_j} = (y_{1j}, y_{2j}, \ldots\ y_{rj})$, where x_{ij} denotes the value of the *i*th input and y_{kj} denotes the value of the *k*th output of the DMU_j, $j = 1, 2, \ldots, n$ in a typical DEA model. The efficiency score of DMUq is calculated by dividing the weighted sum of outputs by the weighted sum of inputs. They maximize the efficiency score of the evaluation unit (DMUq), assuming that the efficiency scores of all other units are less than or equal to 1. The linear version of the model is below.

Maximize

$$\theta_q = \sum_{k=1}^{r} u_k y_{kq}$$

Subject to;

$$\sum_{k=1}^{r} u_k y_{kj} - \sum_{i=1}^{m} v_i x_{ij} \le 0, \quad j = 1, 2, ..., n,$$

$$\sum_{i=1}^{m} v_i x_{iq} = 1,$$

$$u_k \ge \varepsilon, v_i \ge \varepsilon.$$

v_i – Input weight of the *i*th input

u_k – Output weight of the *k*th output

Non-Archimedean element $\varepsilon > 0$,

v_i and u_k represent input and output weights for the *i*-th input and *k*-th output. On the other hand, $\varepsilon > 0$ is a non-Archimedean element, smaller than any positive real number.

The optimal objective function value $q_q^* = 1$ shows the efficiency of the unit being evaluated. The units that are being assessed less than 1 indicate the inefficiency. Reducing the number of inputs helps to reach the efficient limit (Aswccfo et. al.).

For example, Assume that Ranch House, Inc is a fast-food restaurant chain operating in five locations. They have collected their inputs and output data to develop the DEA model to find the most efficient restaurant in the chain. Accordingly, they considered weekly hours of operation, full-time staff, and weekly supply expenses as the input measures. Their output measures include an average weekly contribution to profit, market share, and annual growth rate. The gathered input and output data are illustrated below in Tables 1 and 2, respectively (Aswccfo et.al.).

Table 1

Input measures

Restaurant	Hours of Operation	Full-time Staff	Supplies ($)
Bardstown	96	16	850
Clarksville	110	22	1400
Jeffersonville	100	18	1200
New Albany	125	25	1500
St. Matthews	120	24	1600

Note. Input measures in five locations.

Table 2

Output measures

Restaurant	Weekly Profit ($)	Market Share	Annual Growth Rate
Bardstown	3800	25	8.0
Clarksville	4600	32	8.5
Jeffersonville	4400	35	8.0
New Albany	6500	30	10.0
St. Matthews	6000	28	9.0

Note. Output measures in five locations

Developing the Mathematical Model for each DMU:

DEA model for Bradstown:

$Max\ \theta = 3800u_1 + 25u_2 + 8u_3$

Subject to

$$3800u_1 + 25u_2 + 8u_3 - 96v_1 - 16v_2 - 850v_3 \leq 0$$

$$4600u_1 + 32u_2 + 8.5u_3 - 110v_1 - 22v_2 - 1400v_3 \leq 0$$

$$4400u_1 + 35u_2 + 8u_3 - 100v_1 - 18v_2 - 1200v_3 \leq 0$$

$$6500u_1 + 30u_2 + 10u_3 - 125v_1 - 25v_2 - 1500v_3 \leq 0$$

$$6000u_1 + 25u_2 + 9u_3 - 120v_1 - 24v_2 - 1600v_3 \leq 0$$

$$96v_1 + 16v_2 + 850v_3 = 1$$

$$u_1, u_2, u_3, v_1, v_2, v_3 \geq \varepsilon$$

DEA model for Clarksville:

$Max\ \theta = 4600u_1 + 32u_2 + 8.5u_3$

Subject to

$$3800u_1 + 25u_2 + 8u_3 - 96v_1 - 16v_2 - 850v_3 \leq 0$$

$$4600u_1 + 32u_2 + 8.5u_3 - 110v_1 - 22v_2 - 1400v_3 \leq 0$$

$$4400u_1 + 35u_2 + 8u_3 - 100v_1 - 18v_2 - 1200v_3 \leq 0$$

$$6500u_1 + 30u_2 + 10u_3 - 125v_1 - 25v_2 - 1500v_3 \leq 0$$

$$6000u_1 + 25u_2 + 9u_3 - 120v_1 - 24v_2 - 1600v_3 \leq 0$$

$$110v_1 + 22v_2 + 1400v_3 = 1$$

$$u_1, u_2, u_3, v_1, v_2, v_3 \geq \varepsilon$$

DEA model for Jeffersonville:

$Max\ \theta = 4400u_1 + 35u_2 + 8u_3$

Subject to

$$3800u_1 + 25u_2 + 8u_3 - 96v_1 - 16v_2 - 850v_3 \leq 0$$

$$4600u_1 + 32u_2 + 8.5u_3 - 110v_1 - 22v_2 - 1400v_3 \leq 0$$

$$4400u_1 + 35u_2 + 8u_3 - 100v_1 - 18v_2 - 1200v_3 \leq 0$$

$$6500u_1 + 30u_2 + 10u_3 - 125v_1 - 25v_2 - 1500v_3 \leq 0$$

$$6000u_1 + 25u_2 + 9u_3 - 120v_1 - 24v_2 - 1600v_3 \leq 0$$

$$100v_1 + 18v_2 + 1200v_3 = 1$$

$$u_1, u_2, u_3, v_1, v_2, v_3 \geq \varepsilon$$

DEA model for New Alberny:

$Max\ \theta = 6500u_1 + 30u_2 + 10u_3$

Subject to

$$3800u_1 + 25u_2 + 8u_3 - 96v_1 - 16v_2 - 850v_3 \leq 0$$

$$4600u_1 + 32u_2 + 8.5u_3 - 110v_1 - 22v_2 - 1400v_3 \leq 0$$

$$4400u_1 + 35u_2 + 8u_3 - 100v_1 - 18v_2 - 1200v_3 \leq 0$$

$$6500u_1 + 30u_2 + 10u_3 - 125v_1 - 25v_2 - 1500v_3 \leq 0$$

$$6000u_1 + 25u_2 + 9u_3 - 120v_1 - 24v_2 - 1600v_3 \leq 0$$

$$125v_1 + 25v_2 + 1500v_3 = 1$$

$$u_1, u_2, u_3, v_1, v_2, v_3 \geq \varepsilon$$

DEA model for St. Matthews:

$Max\ \theta = 6000u_1 + 25u_2 + 9u_3$

Subject to

$$3800u_1 + 25u_2 + 8u_3 - 96v_1 - 16v_2 - 850v_3 \leq 0$$

$$4600u_1 + 32u_2 + 8.5u_3 - 110v_1 - 22v_2 - 1400v_3 \leq 0$$

$$4400u_1 + 35u_2 + 8u_3 - 100v_1 - 18v_2 - 1200v_3 \leq 0$$

$$6500u_1 + 30u_2 + 10u_3 - 125v_1 - 25v_2 - 1500v_3 \leq 0$$

$$6000u_1 + 25u_2 + 9u_3 - 120v_1 - 24v_2 - 1600v_3 \leq 0$$

$$120v_1 + 24v_2 + 1600v_3 = 1$$

$$u_1, u_2, u_3, v_1, v_2, v_3 \geq \varepsilon$$

Following table 3 shows the results taken by implementing and solving the mathematical model using Excel:

Table 3

Optimal Efficiency Score

Restaurant	Optimal Efficiency Score
Bardstown	1
Clarksville	0.96
Jeffersonville	1

New Albany	1
St. Matthews	0.99

Note. Optimal efficiency score of five locations

Obtaining a score of 1 shows a lack of evidence in determining whether the composite unit or the corresponding operating unit is relatively efficient. A score lower than one shows that the composite unit is more efficient than the corresponding operating unit.

The need for a powerful benchmark tool for supplier selection

With the existence of COVID-19, the entire economy has experienced an unprecedented challenge. Organizations need to be resilient to stay competitive and adapt to the ever-changing and unanticipated market. Continuously evaluating their supply chain business partners, including raw material vendors, manufacturers, distributors, logistic partners, retailers, etc., is indispensable. In an era of abundant information, managers require a systematic, explicable, comparative, and traceable approach to evaluate and choose suppliers. Making a wrong choice in supplier selection seriously damages the company's supply chain, operations, and reputation. Therefore, establishing partnership with a reliable suppliers is a prerequisite for business success.

Robust supplier

The concept of Triple Bottom Line (TPL) was raised by Freer Speckley in 1981 by claiming organizations need to maintain a balanced relationship of three areas, profit, people, and the planet. This principle became corporate social responsibility and later developed as the basis of sustainability (Wijonarko & Woro Astuti, 2022). In the 1990s, John Elkintong utilized the sustainability concept to measure the sustainability of cooperation in three aspects, economic, social, and environmental (Silva et al., 2022).

Sustainable suppliers should be conscious of society and the environment while operating their business (Čiković et al., 2022). Instead of solely pursuing profit maximization, it is important for suppliers to prioritize their daily operations and production outputs with the aim of mitigating negative impacts on both human beings and the environment.

Integrating social and environmental factor for selecting supplier after COVID-19

With the rising importance of sustainability, choosing a competent supplier is one of the significant strategic management decisions (Čiković et al., 2022). Solely focusing on price, quality, and delivery time is insufficient in supplier selection (Ferreira & Silva, 2022). Over the years, especially after experiencing the COVID-19 disaster, the traditional factors were found inadequate, and additional factors need to be included (Ferreira & Silva, 2022). The existing methods are reformulated, integrating social and environmental impact and developing a combination model in supplier selection (Ghamari et al., 2022). Economic and environmental factors are critical during the vendor selection process. (Ghamari et al., 2022). Sustainable suppliers enable a company to maximize profit while minimizing hazardous effects on the planet and people (Čiković et al., 2022).

Criteria of a robust supplier

A sustainable supplier requires engagement from top management for all green practices. It impacts business operations and accelerates long-term growth, enhancing efficiency and effectiveness (Čiković et al., 2022). Considering supplier location, resilience, flexibility, reliability, and long-term relationship are critical priorities during the selection process, although the significance of choosing suppliers differs by industry and product (Ghamari et al., 2022). Moreover, the evaluation of routine operations, packaging quality, warranty, and refund policy are significant factors in supplier selection (Javad et al., 2020). A sustainable supplier should obtain

professional knowledge of green practices. They perform regular environmental audits and acquire certificates such as ISO 14000, proving less environmental footprint (Silva et al., 2022).

In recent years, procurement strategies have been revamped due to the disruption in the global supply chain by the pandemic and war in Europe. On top of the three traditional concerns of quality, delivery, and price, intangible factors such as supplier reputation, continuous improvement, production responsiveness, technological development, and financial stability become part of the selection criteria (Ferreira & Silva, 2022). To cultivate sustainable principles, companies should consider environmental measures such as pollution control, carbon and dust emission, and treatment of wastewater (Ghamari et al., 2022), green product design (Xie et al., 2022), and R&D on environmental concerns utilizing latest technologies (Xie et al., 2022). Social responsibility (Sureeyatanapas et al., 2018), work safety procedures (Hasan et al., 2020), information disclosure (Banaeian et al., 2018), and labor relations (Xie et al., 2022) are taken into account in terms of social dimensions. Organizations are being cautious and devoting further resources to locating sustainable partners. A successful selection of suppliers expedites the final deliverables and increases customer satisfaction and the company's reputation.

Define Input and output variables on the DEA model

The DEA model measures the relative efficiency of decision-making units based on a group of inputs and outputs (Zhang & Li, 2017). To calculate the efficiency score, a set of input and output variables are needed. Any resource consumed by a DMU is considered as an input. The output represents the outcome or performance of transforming the input into either products or services (Wong, 2021). The input and output index selection varies by industry, product, or service type. The choice between input and output is based on the objective, whether input orientation or output orientation. An input-oriented DEA model investigates the ability to generate a specific output

level with minimal input and resources (Alidrisi, 2021). On the other hand, an output-oriented DEA model assesses how efficiently a DMU maximizes output with a particular input level..

There are no specific rules for identifying input and output variables in the DEA model. Operation indicators such as total assets, capital, current liabilities, operating expense number of staff, and overhead expenses can be considered as input variables. Similarly, operating income, net profit, net sales, or revenue can be regarded as output variables (Wong, 2021) when applying the DEA methodology to calculate the efficiency score for comparison.

Inputs

Geographical distance

Sourcing activities play a vital role across industries since it directly impact on business success.. Furthermore, strategic sourcing partners are essential for manufacturers, retailers or traders. Globalization accelerates a more complex and dispersed supply chain. The global supply chain network is more scattered and diffused with the growing number of warehouses, manufacturing and assembly factories, and subsidiaries (Wiengarten & Ambrose, 2017). Geographical distance is vital in selecting robust suppliers as it impacts the procurement process and may cause undesired performance results (Wiengarten & Ambrose, 2017).

Distance between supplier and buyer directly impactsthe accuracy of delivery lead-time and transportation time for goods or services from one stage to another. Unexpected shipment delays affect inventory management and production schedule. With COVID-19, companies experienced that any interruption of raw materials supply would damage the manufacturing process and the entire production line. This harmed the company’s reputation and customer satisfaction as the finished products failed to deliver as committed. In supplier selection, organizations now prioritize reliability instead of the traditional cost consideration (Fonseca &

Azevedo, 2020). Therefore, transitioning from global to local sourcing enhances the supply reliability and continuity of the production process (Juhász & Bányai, 2021).

Enterprises initiate efforts to lower risk and redundancy while enhancing resiliency and agility in their supply chains, adapting to the post-pandemic environment. The risk incurred is likely higher with a more significant geographic distance between suppliers and buyers (Fonseca & Azevedo, 2020). It increases the possibility of supply chain disruption caused by political instability, natural disasters, and unexpected events. Contingency plans, instant communication, and remedy action are hard to execute due to the inflexibility of long shipment routes and time zone differences. After the COVID-19 crisis, the finance minister from France urged French companies to assess their supply chains and reduce reliance on China and other Asian countries while preferring to switch to regional trade blocs (Fonseca & Azevedo, 2020). Therefore, cooperations mitigated risk by nearshoring, localization, and regionalizing in facing global trade uncertainty. The supply chain management trend focuses more on regionalization than globalization (Wang & Sun, 2021).

Number of deliveries

On top of being agile and resilient, logistics flexibility is crucial in the rapidly changing business economy. Logistic flexibility refers to a company's ability to modify and tailor the procedure of transport and storage of goods to meet the evolving requirement of each customer, which is necessary for establishing a sustainable competitive advantage (Sandberg, 2020). In response to the uncertainties of the global context, companies must enhance their flexibility (Hatmanto et al., 2022), which is one of the assessment criteria of supply chain performance (D'Aleo & Sergi Hatmanto, 2017) and warehouse operation performance (Dede & Çengel, 2020).

A logistic service provider with fewer deliveries can provide flexible service. Since the operation of these companies is not fully optimized, they have more resources available to deal with unexpected needs. They are well equipped to deal with an unforeseeable increase in demand to avoid delay, error, and quality issues compared to the companies with a high volume of orders. However, companies with substantial orders and at their maximum capacity spend much time and resources monitoring the current process to avoid supply chain disruption. Therefore, it can hardly provide reliable and timely service for a sudden surge in demand.

Companies with fewer deliveries are at a higher level of response flexibility. Adjustments to the current process are easily made. They react faster to market shifts, and customer needs as they have excess resources to address requirements and offer customized solutions to customers' specific needs. The ad hoc activities arranged will not have a negative impact and cause a burden on their existing business operation. The direct correlation between flexibility and performance suggests that greater flexibility leads to higher firm performance (Hatmanto et al., 2022).

Number of employees

The COVID-19 outbreak has greatly affected numerous segments of the global community. The pandemic has caused significant disruption in the supply chain. Many organizations faced difficulties during the crisis. Some companies were forced to halt their operations, while others laid off their staff (Ajripour, 2022). Being resilient and capable of reacting quickly to threatening disruption are suitable strategies for maintaining operational stability and sustainability during challenging times (Yang et al., 2022).

Suppliers or vendors with a smaller workforce allow operating with higher flexibility and agility. Many small-to-medium-size companies took the initiative to transform their business model after once under COVID-19 breakout by scaling up their e-commerce platforms. They

successfully leveraged the challenges and turned them into new business opportunities (Kien et al., 2023). Besides, companies with lesser employees and fewer layers of hierarchy can also work more efficiently and be easier to manage. They can have a fast response to the changing market and unexpected circumstances. The decision-making process is simple and streamlined, which is vital in times of crisis. In addition, these companies also offer more customized services and products to meet specific customer needs in the rapidly changing environment.

Numerous enterprises suffered a severe drop in business operations and profit during the COVID-19 pandemic. They face financial difficulties and either being forced to shut down or maintain their business with minimal gains or on the margins (Akingbade, 2021). However, enterprises with smaller workforces can operate with lesser expenses, such as salary, benefits, training and development, office spaces, equipment and supplies, and relative administrative costs. Having a supplier with less overhead costs makes them more reliable since they have a relatively stable financial position. Besides, they will be more flexible in offering competitive prices and payment terms, directly enhancing profitability.

After experiencing COVID-19, communication and information flow among trade partners are crucial. It is to increase transparency and minimize uncertainties and risks. Companies with a smaller workforce can build closer relationships with their trade partners, and their information flow is simple and more straightforward. They can communicate and share information through formal or informal meetings and anticipate potential risks. Trust and a close relationship are essential for a manufacturer's resilience (Yang et al., 2022).

Total health operating expenses

The outbreak of COVID-19 has adversely impacted many enterprises, resulting in financial losses and supply chain disruption. Enterprises are becoming more cautious about managing costs;

focusing on monitoring and minimizing operating expenses to optimize financial performance. Businesses are taking cost-cutting initiatives like reducing unnecessary utilities and marketing expenses. Financial resources were recognized as an essential asset for sustaining a business, and companies started to initiate new collaborations with suppliers (Bostan, 2021). Due to this, companies are being more meticulous in their supplier selection process while aiming to reduce financial burden and prioritizing trade partners that exhibit higher productivity.

Lower health operating expenses reflect the organizations investing less in employee health costs. Companies can be more flexible in allocating funding with lower health operating expenses. They can allocate saved expenditures on research and development, marketing and promotion, technology enhancement, etc., enhancing their product and service quality. Ultimately, their trade partners benefit from superior product quality and a higher level of services that fit the market needs.

Spending a lesser health cost in a cooperative reflects that their employees are relatively healthy, directly connected with a company's performance and sustainability. Health risk factors include excessive consumption of alcohol, obesity, high cholesterol, high blood pressure etc., taking around 25% of the employee's total healthcare expenditures (Street & Lacey, 2019). A healthy workforce team is regarded as one of the most desirable assets to an organization (Street & Lacey, 2019), and there is a direct relation between employee health and productivity.

Employees with a high risk of a modifiable health situation, including nutrition problems and tobacco and alcohol use, were 12.2% less productive than other colleagues (Street & Lacey, 2019). The more an organization spends due to employees' poor health, such as compensation, the lower morale, higher absenteeism and turnover (Street & Lacey, 2019). Major reasons for workplace absence are typically mental health problems, such as anxiety, stress, and depression.

The problem affects approximately 20% of the working population (Suter et al., 2022; Steel et al., 2014). It leads to an annual global productivity loss of USD1 trillion (Suter et al., 2022; Chisholm et al., 2016). Besides mental health issues, an example from the study by the American Diabetes Association in 2017 shows that diabetes impacts productivity since it causes an indirect cost of USD 90 billion while damaging work efficiency (Norwitz et al., 2022).

Despite profitability, maintaining stakeholders' well-being is vital to attain long-term success. Organizations are required to provide a healthy and safe working environment contributing to higher job satisfaction and engagement. A smaller proportion of spending on health operating costs reflects that the company can promote the well-being of their employees with a balance of financial performance and employees' well-being, which is a factor for achieving sustainability (Bosetti, 2022).

Outputs

Sustainability Rank

Companies should first evaluate themselves to identify their goals, business priorities, and sustainable initiatives to manage supplier selection criteria effectively. They should communicate their criteria to customers, ensuring that they have the potential to adhere to sustainability priorities as requested by the company. Companies should assess their supplier's performance by considering the environmental impact, social business dilemma, and ethical business practices. Sustainable supplier selection can be challenging as it requires organizations to identify and assess the suppliers' performance, aligning with sustainability. In order to overcome these challenges, companies can use different frameworks such as Global Reporting Initiatives (GRI), Standards defined by the Sustainability Accounting Standards Board (SASB), and International Organization for Standards (ISO 14001) system. Practicing sustainable supplier selection brings out many

advantages to a company. Most importantly, it improves the brand image, reduces the risks of unforeseen social and environmental impacts, and enhances business efficiency. Companies tend to build long-term relationships with suppliers who adapt to sustainable practices, reducing supply chain risks.

Investment in information technology

Information Technology (IT) has expanded business capacities in many aspects. As a result of globalization, IT plays a salient role in maintaining the interactions and information flow among upstream and downstream supply chain tiers (Tsai et al., 2021). Companies widely use digital transformation technologies integrated with Industry 4.0 in data exchange and collection, improving supply chains based on real-time technologies such as industrial Internet of Things (IoT), additive manufacturing, big data, artificial intelligence, blockchain, and cloud computing. Based on the requirements of Industry 4.0, many companies use improved and collaborative technologies when dealing with suppliers (Ferreira & Silva, 2022).

However, companies increasingly invest in information and communication technology to make their supply chain robust and resilient because of their learnings after the pandemic. Institute of Supply Chain Management (ISCM) found that 80% to 95% of supply chains were adversely impacted in March 2022 due to the COVID-19 pandemic. According to the survey done by Bassware, 60% of procurement managers of over 700 respondents claimed that they experience a lack of transparency in supply chains, causing a significant issue over supply chain resilience. Remko (2020) studied the risks and challenges reported by SC executives and recommended some strategies to reduce supply risks. Most importantly, he suggested initiating and accelerating projects related to digital transformation technologies to address the problem. Due to the pandemic, businesses increasingly moved toward e-commerce, online shopping, and self-checkouts,

promoting contactless purchasing practices. Also, many companies invested in logistics control towers to enhance business transparency and smoothen the information flow across the supply chains while reducing the Bullwhip effect. Therefore, the supplier's capacities and capabilities to invest in technologies are among the most influential factors in the supplier selection process.

The supplier selection process plays a significant role in reducing purchasing risks. Referring to the related literature, many authors have identified technology as one of the essential criteria in terms of supplier selection. Ferreira & Silva (2022) highlighted some significant aspects of supplier selection, including the delivery control system, improved communication, supplier involvement in the design, less paperwork, and long-lasted relationship, emphasizing the importance of investing in new technologies. Efficient communication channels significantly enhance the relationship between two parties (Ferreira & Silva, 2022). Tsai et al. (2021) studied the supplier selection in Taiwan's Thin-Film Transistor (TFT) Liquid-Crystal Displays (LCD) industry using DEMATEL (Decision Making Trial and Evaluation Laboratory) and ANP (Analytic Network Process) methods, evaluating the main factors in the supplier selection process. Accordingly, he also emphasized adapting to technologies is a crucial factor in tech industries as it strengthens the ability to minimize production time, develop the latest product designs and processes, and integrate business operations (Tsai et al., 2021).

Technology rank

Measuring the suppliers' capability to initiate innovations and develop existing technologies is crucial in supplier selection. Supplier innovation systematically leverages and accelerates innovative capabilities, providing numerous benefits such as novel ideas, higher margins, and reduced time-to-market, which leads to profit growth. McKinsey found that the externally sourced innovation are 40% more commercialized than the internally generated ideas as the supplier has

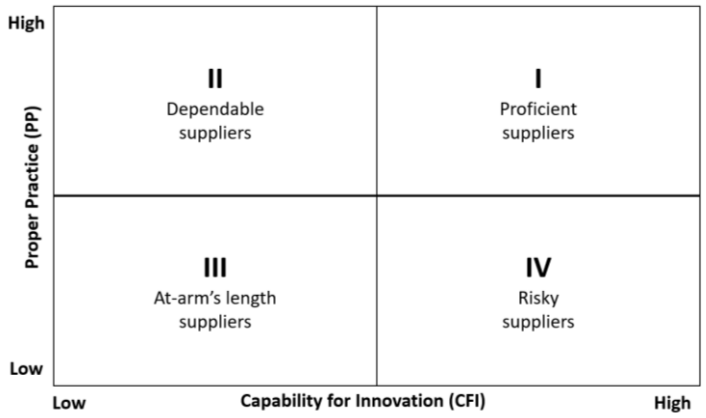
already validates (Göβwein et al., 2019). Aston Martin, the UK based car manufacturer has worked with US-based aerospace supplier, Flexsys to implement adjustable wings for high-end designs. The supplier used flexible materials to develop the component, offering a better appearance and performance than conventional designs. As we study, very few indexes measure the company's innovation and potential. Most importantly, the index for the Capacity For Innovation (CFI) measures the supplier's capability to improve innovation and technologies. The CFI index is mainly based on the existing industry and the resources allocated to research and development (R&D), which includes the variables in the workforce, budget allocation, and range of products offered. The main two variables in assessing the supplier's CFI index are (1) the amount of the R&D budget and (2) the R&D Staff ratio. The CFI index measures a supplier's potential based on the abilities in the R&D, depending on the industry sectors (Wu et al., 2013).

In addition to that, companies also use the index for Proper Practice (PP) to determine the supplier's attitude towards the client's Intellectual Property Rights and Resources (IP&R) and the supplier's practices to protect the client. The PP index is influenced by the external legal and cultural environment of the business and internally constrained by the influences of organizational culture, management, and administration (Wu et al., 2013). Wu et al. (2013) introduced three main variables to evaluate the PP index: Corporate Identity, IP rights index, and restraints index. Corporate identity is more subjective and considers the supplier's overall image. The IP rights index is an index that assesses suppliers' adherence to the terms and conditions of the agreement. Based on the CPI and PP index, the suppliers can be categorized into four segments; dependable suppliers, proficient suppliers, At-arm's-length suppliers, and risky suppliers, as explained in Figure 2. Maintaining a proper PP index determines the supplier's trustworthiness and reliability, adding extra value to the supplier selection process.

Furthermore, a few other indexes measure the supplier's innovative performance. For example, Master card and Harvard Business Review Analytic Services (HBRAS) introduced the "Business Innovators Index," considering five significant areas: process, human resource, funding, customer experience, and technology. This index is scaled from 0 to 100, whereas 100 represents the highest performance in an innovative strategy, frameworks, and behaviors (Mastercard, n.d.). This framework categorizes businesses into three segments: leaders, followers, and laggards. The study revealed that 17% of respondents were identified as leaders, while approximately half (41%) were laggards, with a mean index of 37 (Baker, 2019). Also, the Product Vitality Index (PVI) measures the company's innovation by evaluating the ability to introduce and deliver new products or services. This metric was created in 1988 by 3M, considering the company's revenue generated from the new product. The PVI is calculated by dividing the New Product Revenue by the Gross revenue in a pre-defined time (Manor, 2021). This index varies subject to the factors such as the nature of the product, the industry, and the product's current phase of the product lifecycle (Manor, 2021). Moreover, Sutardja Center for Entrepreneurship and Technology established a new index, named "Berkeley Innovation Index," which measures the innovation capabilities in a more holistic approach, considering four main aspects; (1) Strategy and Leadership, (2) Innovative culture from the organization's perspective, (3) Operations across the organization, (4) Mindset of people and (5) Tactical measures (Ikhlaq Sidhu et al., 2016).

Figure 2

Supplier Categorization based on the CPI and PP index



Note. Four supplier segments based on CPI and PP index

Research and Development (R&D) Personnel

R&D can be a vital consideration in supplier selection based on various factors. Companies prefer that their suppliers have an R&D division, ensuring proper technical capabilities and well-developed business practices in safety and environment to maintain a robust and sustainable business (Rajesh & Ravi, 2015). Suppliers with highly improved technologies can quickly adapt to new business trends and recent technologies (Rajesh & Ravi, 2015; Schiele et al., 2011), which rapidly change with Industry 4.0. It also assists suppliers to respond current market turbulence and supply chain disruptions, mitigating supply chain risks. Furthermore, R&D activities drive the product or service an extra mile by integrating technologies to maintain quality standards (Rajesh & Ravi, 2015). Having the required quality standards and certifications proves the quality and innovation capabilities of the company. Suppliers who obtain positive results in quality audits in the long term are likelier to have a culture of continuous innovation and improvement (Schiele et al., 2011).

Cousins et al. (2011) conducted a study to evaluate both skills and the resources available for R&D activities, utilizing the mechanisms to gain the advantage of external connections

(Cousins et al., 2011). The complexity of supply chain networks dramatically increases, reflecting the rise in R&D investment, complex products, shorter product lifecycles, challenges in managing the changes in technology, and the requirement of knowledge and resources for innovation. Therefore, companies cannot succeed alone; instead, they appreciate collaboration to withstand the fast-paced changes and gain a competitive advantage in the global market. Many organizations have redefined their boundaries and formed close and long-term supplier relationships, leveraging their strengths and achieving mutual benefits (Cousins et al., 2011). Wang et al. (2009) assessed supplier performance by considering the attributes such as R&D, cost, quality, service, and response and developed a multiple attribute matrix (Wang et al., 2009). In their study, R&D and improvements measure suppliers' involvement while the performance can be evaluated using delivery, damages, and quality (Wang et al., 2009). Moreover, Wu et al. (2013) assessed a supplier's suitability for outsourcing by measuring the supplier's potential for technological innovation, including the investment in R&D and the ratio of employees in the R&D division to the total number of employees (Wu et al., 2013).

Number of ports that can reach

In facing the serious disruptions caused by the COVID-19 outbreak, the ability to accessan expanded number of ports by logistic companies becomes more important. Ports play an essential role as they are the central part and provide linkage in the global supply chain network between countries. Circulation of goods dropped to around 60% capacity due to the initial country lockdown and closure of international borders with COVID-19, which created a vast supply chain disruption globally (Grater & Chasomeris, 2022). During the pandemic, ports implemented health and safety protocols such as health screening, social distancing, temperature checking, contact tracing, and quarantine requirement. With the widespread coronavirus infections, ports faced

challenges and could not maintain operations due to labor shortages and port congestions (Kim et al., 2022).

Regional hub ports are large-scale and significant ports that facilitating trade movement and connections for different countries. They are located close to major shipping routes and usually serve as the first or last station in a supply chain. A relatively large number of suppliers rely on them to transport products. In addition, these hub ports may impose stricter health screenings or quarantine measures, which leads to additional freight transportation delays. When a supplier has limited access to a single hub port that is already experiencing a high level of congestion, the supplier can only wait until the bottleneck is alleviated. Such a delay has severe implications for the shipment schedule. The scenario is similar if applied to transshipment ports, which handle the transportation of goods between vessels to the destination. Recently, companies have prioritized agility and responsiveness in supply chain management, especially in unpredictable circumstances. Suppliers who can access a greater number of ports are highly valued. Such support enables broader geographic coverage and enhances timely delivery by allowing the selection of the most efficient port and routes. As a result, addressing each customer's requirement under diverse situations.

Percentage of machinery

In response to the emergency of the contagious virus COVID-19, countries implemented different countermeasures, which led to a range of uncertainties in the supply chain in all industries. Measures such as lockdowns, restrictions contact tracing, vaccination programs, social distancing, quarantines, port & airport closures, etc., impacted on the labor supply market.

Manufacturing involves converting raw materials into finished goods, such as handling raw materials, prototype testing, production, assembly, packaging, quality control, inspection, goods

dispatch, and delivery. In traditional manufacturing, especially in developing countries, daily operations mainly relies on physical labor with minimal fmachines assistance for handling simple and repetitive tasks. The manufacturing processes require a substantial amount of labor, while the involvement of machinery is minimal. Consequently, many manufacturers have encountered a severe labor shortage problem during the pandemic crisis, which has disrupted the normal operations of factories. Manufacturing industries faced significant obstacles and complexities during COVID-19 (Suguna Sinniah et al., 2022)

The trend in manufacturing industries is toward automation which uses machinery to perform tasks that humans previously performed manually. Automation involves using advanced software and technology, together with an increased percentage of machinery involved in manufacturing. COVID-19 also expedites robotics adoption in services sectors; the service robots are machines equipped with artificial intelligence and controlled by a computer system without being impacted by social distancing or quarantine measures (Romero & Lado, 2021; Seyitoğlu & Ivanov, 2020).

Compared to machinery, human performance is more prone to fluctuation. Labor performance will be negatively affected when labor reaches a capacity over 70%. Workers may experience stress, burnout, decreased concentration, and fatigued leading to increased absenteeism or turnover (Cummings et al., 2022). Unlike humans, machines operate continuously and do not experience fatigue or require motivation. In the post-pandemic world, companies seek robust, reliable and consistent suppliers. Implementing automation into manufacturing processes mitigates output variability and enhances efficiency (Cummings et al., 2022). Therefore, suppliers who obtain a more significant proportion of machinery used in manufacturing are highly valued, particularly in the post-pandemic world.

FINDINGS AND DISCUSSION

Step 1: Determining inputs/ outputs factors of suppliers

As discussed in Section 3, we found the most appropriate set of inputs and outputs based on the literature review. The findings of inputs and outputs are summarized below in Table 4.

Table 4

List of new inputs and outputs

Inputs	Outputs
Geographical distance	Sustainability Rank
Number of deliveries	Investment in information technology
Number of employees	Technology rank
Total health operating expenses	Research and Development (R&D) Personnel
	Number of ports that can reach
	Percentage of machinery

Note. Inputs and outputs for supplier selection

However, due to a lack of existing data for the above input and output sets, the efficiency score calculation in the upcoming section will be based on the currently accessible data. Traditionally, price, delivery time, and quality were recognized as three major considering factors during the supplier selection process (Caristi et al., 2022). This paper has included these three traditional factors; price, quality and delivery grade, along with “number of employees” as an

additional input and "technology capability" as an additional output to demonstrate the calculation of the efficiency score for the ten suppliers. Table 5 shows the list of inputs and outputs for processing the efficiency score calculation.

Table 5

List of inputs and outputs that use for calculating efficiency score

Inputs	Outputs
Number of employees	Delivery grade
Price	Technological capability
	Quality

Note. Two Inputs and three outputs for calculating efficiency score

Inputs

Number of employees: As discussed in the preceding section, organizations with smaller workforces adhere less to formal procedures; this exhibits their higher level of agility and flexibility during global crises (Kraus et al., 2020). According to Haneberg (2021), the response to the crisis is quicker among smaller enterprises compared to larger enterprises. As a result, the number of employees is one of the critical considerations during the supplier selection process. It uses as one of the inputs for calculating the efficiency score.

Price: Enterprises have their supply chain strategy and have diverse factors in the supplier selection process (Ferreira & Silva, 2022). Although the previous section mentioned that selecting a supplier solely by product price is insufficient, price still plays a significant role during supplier screening. Companies have assessed price as one of the critical supplier selection criteria over an

extended period (Ferreira & Silva, 2022). As one of the common purchasing strategies is to minimize cost, having suppliers that offer a favorable price directly influences the cost of raw materials, components, delivery cost, service charges, etc. Suppliers provide a relatively low price impact directly on the enterprise's financial performance, such as cost of goods sold, business expenses, cash flow, profit margin, etc. Therefore, the price offered by the supplier is one of the essential factors during the vendor selection process, which improves financial performance and competitiveness (Sariaji & Juarna, 2022). During supplier assessment phase, companies must consider various factors to ensure having the most appropriate supplier according to their requirement. The ideal option is with the best and most accurate delivery timing at a better price (Ferreira & Silva, 2022). However, as discussed, price alone cannot be the only determinating factor. For example, while selecting a lower-priced supplier may have cost benefits for companies, it also comes with a trade-off:a longer and less reliable delivery service, as well aslower product quality. These factors, namely the delivery factor and quality factor, discussed in the upcoming section. Therefore, organizations need to carefully evaluate and balance the input elements to achieve an optimal outcome.

Outputs

Delivery grade: An organization's performance is greatly influenced by choosing the right supplier with excellent delivery performance. Research from Mirani et al. (2021) indicated that 86 percent of the companies prioritized timely delivery service by their suppliers. Timely delivery directly impacts the efficiency of a company's supply chain operation. On-time delivery is an essential aspect of supply chain management; it is measured by the supplier's ability to ship goods or services within the committed timeframe, as agreed upon by both parties (Mantos et al., 2023). An accurate delivery time enhances customer satisfaction and loyalty as customers are often

willing to pay a higher price for a product with better quality and faster delivery time (Wen & Wang, 2022). Failing to fulfill the delivery schedule caused delays in shipment and resulted in customer dissatisfaction (Pajić et al., 2022). Without reliable suppliers that are able to deliver products on time, there can be a severe disruption not only in the procurement process but also in the production and distribution of goods and services. Organizations experience many obstacles in inventory planning. Overstocking results in extra holding costs and a higher risk of obsolescence. On the other hand, understocking occurs, and companies do not have enough inventory to meet the market demand. The above phenomenon was more evident during the COVID-19 pandemic, where delays in shipment caused severe disruption to the entire supply chain. Inventory levels were low, organizations faced challenges finding substitutes, and certain kinds of products and components were not even available for an extended period.

Technological capability: As highlighted in the preceding section, investment in information technology is another critical aspect of supplier selection. It reflects the organization's ability to adapt to technology and foster innovation. During the digital economy, advanced technology facilities the exchange of knowledge, information sharing, and communication among different parties within the supply chain network (Xie et al., 2022). The growing prevalence of new technologies and digitalization drive notable changes in supply chain practices, enhancing transparency, flexibility, communications, and productivity (Tavana et al., 2021). Supply chain stakeholders can interact and collaborate more efficiently across geographic boundaries without time constraints. Digitalization integrated the entire supply chain and enhanced the visibility to all parties (Tavana et al., 2021). The utilization of advanced technology such as automation, artificial intelligence (AI), machine learning, Internet of Things (IoT), blockchain technology (BCT) and big data analytics (BDA), etc., provides significant support in logistic management, manufacturing

system, and supply chain management. These technologies facilitate better responsiveness, efficiency, and accuracy and mitigate internal and external disruption (Xie et al., 2022).

Upon experiencing supply chain vulnerability due to the COVID-19 pandemic, firms widely entered the digital transformation era by adopting new technologies and methodologies into their business operations for future challenges (Wang et al., 2022). Nowadays, technology capability is one of the top ten criteria during the supplier selection process (Kayani et al., 2023). Therefore, technological capability is considered one of the output factors in the presented DEA model.

Quality: Having the right supplier leads to business success, and customers are more emphatic about product quality (Wen & Wang, 2022). Quality applies to both service and product. According to Iqbal et al. (2020), Magdalena (2012), and Toloo & Nalchigar (2011), service quality can be evaluated by the degree of adherence to the committed specification, and product quality can be assessed on factors including durability, correctness, user-friendliness, and reliability (Mantos et al., 2023). The first supplier selection research conducted by Dickson (1966) states that quality has been recognized as the most crucial criterion by managers from 273 manufacturing companies out of the 23 standards during the supplier selection process (Ulutaş et al., 2022). This finding remains pertinent and applicable to this day. One of the studies by Mirani et al. (2021) mentioned that quality was ranked as the most crucial supplier selection requirement. Besides, having suppliers that are able to offer high-quality products and services mitigates risks (Liu et al., 2023). With superior quality in products and services from suppliers, organizations can minimize the chances of errors and associated costs for rectifying them. This enables organizations to maintain a consistent production schedule, conduct accurate planning, and enhance inventory management without encountering disruptions caused by inconsistent products or services.In the

vendor evaluation process, companies consider the trade-off between the input factor "price" and the output factor "quality." Suppliers whooffer lower costs may provide low-quality products, and choosing a low-quality product can result in higher opportunity costs (Saputro et al., 2021). Extra expenses are incurred for conducting quality control measures such as inspection, testing & repairs. As defective items keep separately from other products, it incurs additional handling and holding costs (Saputro et al., 2021). Moreover, lower-quality supplies may adversely impact the quality of the final product and reduce customer satisfaction, company reputation, and brand loyalty. Hence, organizations must evaluate their alternatives and weigh their options to attain equilibrium between these input and output factors.

Step 2: Retrieving data for inputs/ outputs factors

The quantitative data for the above discussed input and output factors were collected from 10 key suppliers of Miraab company. Miraab has four decades of experience in the valves industry and has received international certificates, including product quality certificates from Lloyds Register of England and DVGW of Germany, as well as IMS certificates including 2015:OHSAS 18001:2007, ISO 9001, and 2015:ISO 14001 from TÜVNORD.

Step 3: Efficiency score calculation

The retrieved data from Miraab company are shown below in Table 6. The dataset contains two inputs and three outputs; however, they are measured in different scales.

Table 6

	Inputs		Outputs		
Data of the inputs and outputs of 10 DMUs	No. of employees Grade (Out of 10)	Price (Out of 10)	Delivery grade (Out of 20)	Technological Capability (Out of 100)	Quality (Out of 100)

Supplier 1	1	9	13	70	10
Supplier 2	3	10	20	57	13
Supplier 3	5	8	17	40	60
Supplier 4	4	7	20	44	20
Supplier 5	6	3	4	40	90
Supplier 6	7	6	3	80	70
Supplier 7	2	4	18	57	90
Supplier 8	8	1	9	58	16
Supplier 9	10	2	6	88	22
Supplier 10	9	5	5	80	77

Note. Inputs and outputs grades form ten suppliers

Data Normalization

Data presented in Table 6 is comprised of various input and output variables, being measured in different scales. The disparity in measurement scales among the data creates discrepancies that lack comparability. Therefore, normalization is essential to standardize the values into a consistent format for comparison and further analysis.

Normalization is a procedure of transforming variables or attributes from a dataset by scaling them down (Kotsiantis et al., 2006). It refers to the process of scaling numerical data from different features into a common scale. It is crucial to allow data to be comparable and combined in a way that can be analyzed and presented (Muhammad & Peshawa, 2022). Various normalization techniques include min-max normalization, z-score, softmax, sigmoid, and decimal scaling (Kumar et al., 2022). “Min-Max Normalization” is being employed in this research paper. The inputs and outputs are weighted equally and carry an equivalent impact during the decision-making process by applying min-max data normalization. After completing min-max normalization, the resulting values fall into a specific range of either [0,1] or [-1, 1]. By

implementing this process, it is to ensure that the normalized value of all inputs and outputs shown in Table 7 falls within the range of 0 to 1 despite variations in the measurement units.

The mathematical formulation of Min-Max normalization is as below,

$$X_{norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

X_{norm} = Min-Max normalized value of X

X_i = i^{th} value of X

X_{min} = Min. value of the dataset

X_{max} = Max. value of the dataset

The Min-Max normalization approach is one of the methods that is frequently used (Srijiranon et al., 2021). It is one of the most common normalization techniques and ensures data are given in the identical range based on the minimum and maximum values. The technique establishes a new baseline for each data point by taking the difference between the minimum and maximum values as a base. The main goal of this normalization technique is to bring all the dataset's features into the same scale, ensuring they weigh in a same way, providing a fair comparison.

Min-max normalization finds the dataset's minimum and maximum values. Next, the difference between the actual and minimum values is divided by the difference between the maximum and minimum values, generating a normalized value between 0 to 1 or -1 to 1. Table 7 demonstrates the values of the inputs and outputs of the 10 DMUs after normalization.

Table 7

Data of two inputs and three outputs of 10 DMUs after normalization

	Input		Output		
	No. of employees Grade	Price	Delivery grade	Technological Capability	Quality
Supplier 1	0.00	0.89	0.59	0.63	0.00
Supplier 2	0.22	1.00	1.00	0.35	0.04
Supplier 3	0.44	0.78	0.82	0.00	0.63
Supplier 4	0.33	0.67	1.00	0.08	0.13
Supplier 5	0.56	0.22	0.06	0.00	1.00
Supplier 6	0.67	0.56	0.00	0.83	0.75
Supplier 7	0.11	0.33	0.88	0.35	1.00
Supplier 8	0.78	0.00	0.35	0.38	0.08
Supplier 9	1.00	0.11	0.18	1.00	0.15
Supplier 10	0.89	0.44	0.12	0.83	0.84

Note. Inputs and outputs grades form ten suppliers after normalization

Data Envelopment Analysis (DEA) measures the relative efficiency of each supplier compared to other suppliers. Supplier performance is calculated using the weighted input and output ratios in the supplier selection. The DEA model calculates weights that maximize the relative efficiency score of a DMU, ensuring that the efficiency scores of all DMUs are less than or equal to one, preventing the challenge of determining the weights of different DMUs. The objective is to find the best suppliers from the ten available options. We have developed ten equations, considering the problem in linear programming.

DEA model for Supplier 1:

Max $\theta = 0.59u_1 + 0.63u_2$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.89v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 2:

Max $\theta = u_1 + 0.35u_2 + 0.04u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.22v_1 + v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 3:

Max $\theta = 0.82u_1 + 0.63u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.44v_1 + 0.78v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 4:

Max $\theta = u_1 + 0.08u_2 + 0.13u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.33v_1 + 0.67v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 5:

Max $\theta = 0.06u_1 + u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.56v_1 + 0.22v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 6:

Max $\theta = 0.83u_2 + 0.75u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.67v_1 + 0.56v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 7:

$\text{Max } \theta = 0.88u_1 + 0.35u_2 + u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.11v_1 + 0.33v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 8:

$\text{Max } \theta = 0.35u_1 + 0.38u_2 + 0.08u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.78v_1 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 9:

Max $\theta = 0.18u_1 + u_2 + 0.15u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$v_1 + 0.11v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

DEA model for Supplier 10:

Max $\theta = 0.12u_1 + 0.83u_2 + 0.84u_3$

Subject to;

$0.59u_1 + 0.63u_2 - 0.89v_2 \leq 0$

$u_1 + 0.35u_2 + 0.04u_3 - 0.22v_1 - v_2 \leq 0$

$0.82u_1 + 0.63u_3 - 0.44v_1 - 0.78v_2 \leq 0$

$u_1 + 0.08u_2 + 0.13u_3 - 0.33v_1 - 0.67v_2 \leq 0$

$0.06u_1 + u_3 - 0.56v_1 - 0.22v_2 \leq 0$

$0.83u_2 + 0.75u_3 - 0.67v_1 - 0.56v_2 \leq 0$

$0.88u_1 + 0.35u_2 + u_3 - 0.11v_1 - 0.33v_2 \leq 0$

$0.35u_1 + 0.38u_2 + 0.08u_3 - 0.78v_1 \leq 0$

$0.18u_1 + u_2 + 0.15u_3 - v_1 - 0.11v_2 \leq 0$

$0.12u_1 + 0.83u_2 + 0.84u_3 - 0.89v_1 - 0.44v_2 \leq 0$

$0.89v_1 + 0.44v_2 = 1$

$u_1, u_2, u_3, v_1, v_2 \geq \varepsilon$

In order to find out the most efficient suppliers, we used the Excel solver function to determine the efficiency scores of each supplier, as shown in Table 8. Figure 3 further illustrates the findings of our study. Accordingly, two suppliers, supplier one and supplier seven, reported the highest efficiency score 1. As depicted in Figure 3, the third efficient supplier of Supplier 2 shows an efficiency score of 38%, which is considerably less than the first two.

Table 8

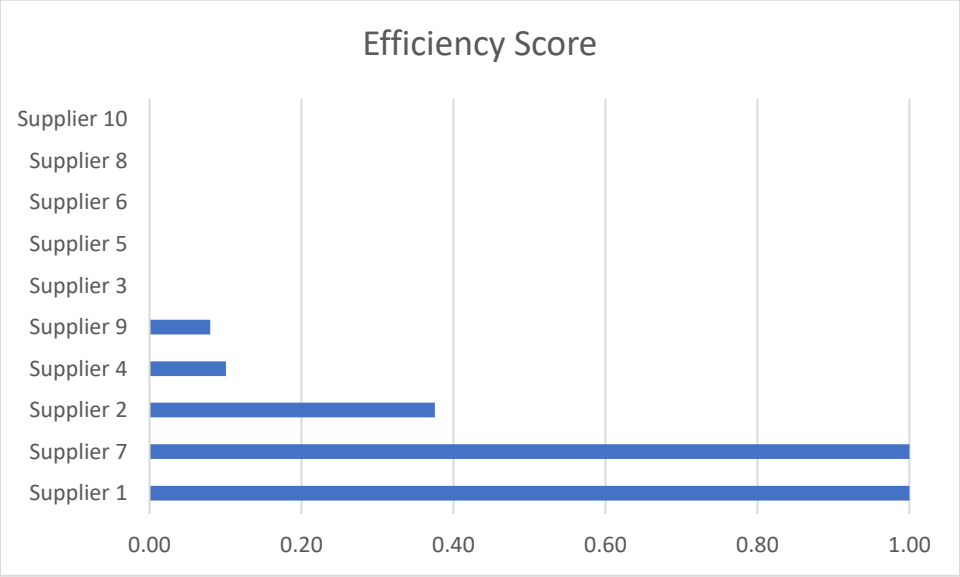
The efficiency score of suppliers

	Efficiency Score	u1	u2	u3	v1	v2
Supplier1	1.00	0.00	1.60	0.00	1.73	1.13
Supplier2	0.38	0.00	2.82	0.00	3.04	1.99
Supplier3	0.00	0.00	1.06	0.00	1.14	0.75
Supplier4	0.10	0.00	1.21	0.00	1.30	0.85
Supplier5	0.00	0.00	0.00	0.00	1.00	0.00
Supplier6	0.00	0.00	0.97	0.00	1.05	0.69
Supplier7	1.00	0.00	0.00	0.00	1.80	0.00
Supplier8	0.00	0.00	0.00	0.00	1.50	0.00
Supplier9	0.08	0.00	0.00	0.00	1.29	0.00
Supplier10	0.00	0.00	0.00	0.00	1.13	0.00

Note. Efficiency score of ten suppliers

Figure 3

Efficiency scores of suppliers



Note. Bar chart of efficiency score of ten suppliers

CONCLUSION

Supplier selection is one of the most crucial components in a manufacturing and logistics operation. It significantly influences the end-to-end supply chain functions, from sourcing raw materials to producing final products and delivering them to the final consumer. After reviewing related literature, we identified geographical distance, number of deliveries, number of employees, and total health operating expenses as the few most impactful inputs in supplier selection. Moreover, we found sustainability rank, information technology investment, up-to-date technology rank, research and development (R&D) personnel, numbers of ports that can reach, and percentage of machinery as significant outputs. Based on the context and data availability, we selected two inputs; the number of employees and price, and three outputs; delivery grade, technological capability, and quality, to develop the model.

This study used the Data Envelopment analysis model to determine the most suitable supplier for Miraab, which is known as a reliable industrial valve manufacturing company in Iran, based on the collected input and output data. Additionally, the decision-makers can rank the suppliers and prioritize them based on the context. Ranking and prioritizing suppliers is crucial in supply chain disruption, such as a pandemic, to mitigate the risk of production interruption.

Table 9

Comparing top-ranked suppliers

	Inputs		Outputs		
	No. of employees	Price	Delivery Grade	Technological Capability	Quality
Supplier 1	0.00	0.89	0.59	0.63	0.00
Supplier 7	0.11	0.33	0.88	0.35	1.00

Note. Inputs and outputs grades of top two suppliers after normalization

Considering suppliers 1 and 7, both suppliers have an efficiency score of 1. We extracted the normalized input and output data from Table 9 to select the most appropriate supplier. In comparing suppliers 1 and 7, the value of no. of employees for supplier 7 is significantly greater than supplier 1. However, the price paid by Supplier 7 is considerably lower than Supplier 1. Regarding the outputs, the quality of supplier 7 is also higher. In addition, the delivery grade is higher for Supplier 7 compared to Supplier 1. Also, Supplier 7 performs better in deliveries, even though its technological capability is less advanced than Supplier 1. As per the analysis, supplier 7 offers comparatively higher quality products at a lower price. Therefore, we recommend the selected company, Miraab, a well-known valve manufacturing company, to keep Supplier 7 as the leading supplier and Supplier 1 as the alternate supplier.

In this research, we consider a few input and output variables, however we found there are many other variables that directly influence the supplier's efficiency score. Therefore, we suggest future research to integrate many input and output variables in the analysis as it increases the accuracy of the results. Moreover, this research considers 10 DMUs with restrictions in gathering data within the given time frame. In future research efforts, we suggest expanding the same research by considering more DMUs, assisting companies inmaking clearer decisions on supplier selection. Furthermore, we conduct general research without considering specific industry, and apply it in an organization to validate the applicability of the model. However, we recommend conducting the same research, focusing on particular industries. Future research can find out specific input and output variables related to the industry, develop the model, and apply it in a few companies in the related industry, proving the applicability of the model. This proposed research methodology is expected to encourage companies to consider DEA in supplier selection process

as a benchmarking tool, increasing the reliability, continuity, and robustness of the overall supply chain.

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