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Sustainable/Robust Supplier Selection in the Post-Pandemic Era: Using Data Envelopment Analysis

Mazyar Zahedi-Seresht, Ganisha Nayanathara Premarathna Athaudage, Wing Ki Lee, Shahrzad Khosravi

Department of Quantitative Studies, University Canada West, Vancouver, Canada
Email: Mazyar.zahedi@ucanwest.ca

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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 sustainable/robust suppliers. The results of this research have been implemented in the business intelligence system of a company.

Keywords

Data Envelopment Analysis (DEA), Supply Chain, Sustainable/Robust Supplier, Efficiency, Decision Making Unit (DMU)

1. Introduction

This paper introduces the crucial topic of Sustainable/Robust Supplier Selection post-pandemic, utilizing Data Envelopment Analysis (DEA). It emphasizes the importance of resilient supply chains, sets objectives for DEA adaptation, sustainability integration, and robustness assessment, and provides practical insights. The study's contributions lie in its innovative approach and comprehensive structure, despite limitations related to context and data availability. The subsequent sections cover literature review, methodology, empirical findings, practical implications, and conclusion. By structuring the paper in this manner, we offer a cohesive exploration of supplier selection considering sustainability and pandemic-related uncertainties.

1.1. 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; 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. Significantly, international companies are continuously improving to survive in the rapidly changing global market. As the supply chain (SC) plays a salient role in the entire business function, companies increasingly pay attention to continuous improvement.

With the increasing supply chain complexity, current supply chains encompass many players 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, supply uncertainties, and supply chain interruptions. 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).

1.2. 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. 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. Considering the shocking spread, severity, and inaction, WHO characterized Covid-19 as a pandemic on the 11th of March 2020 (World Health Organization, 2020).

According to the reports of WHO (**Figure 1**), 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

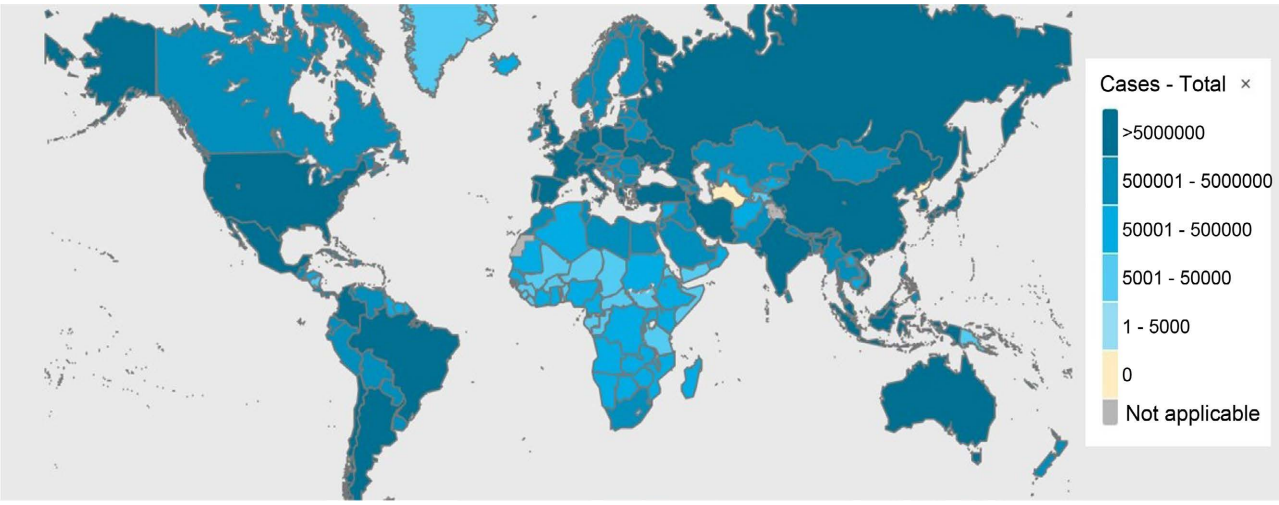

Figure 1. Note: Global Covid-19 spread as of 30th January 2023.

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 firmed 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 the 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 growth rate was anticipated to be 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 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.

1.3. How Did Covid-19 Affect the 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 customers (Raj et al., 2022; Xu et al., 2020; Ivanov et al., 2017). The supply chain activities 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). As per the 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 bar-

riers, 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 income loss and saving money for an uncertain and ambiguous future (Chiaramonti & Maniatis, 2020). Consequently, the prices of essential commodities have 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 restrictions 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, experienced delays, cancellations, and postponements due to travel restrictions and border closures. As the 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 the 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.

The existing literature on supplier selection often lacks a comprehensive integration of sustainability considerations and robustness assessment in the context of post-pandemic dynamics. This research seeks to bridge this gap by proposing a novel application of Data Envelopment Analysis (DEA) to simultaneously evaluate supplier efficiency, sustainability performance, and resilience against pandemic-induced uncertainties. By combining these factors within a single analytical framework, this study aims to offer a holistic solution that aligns with the contemporary needs of businesses striving for resilient and sustainable supplier selections.

2. Robust/Sustainable 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 disruptions, 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 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 disruptions 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 disruptions (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 disruptions (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/FOG computing, 3D printing, artificial intelligence (AI), Internet of Things (IoT), blockchain, and big data analytics are commonly used based on the business size.

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 be used 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).

3. 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 to 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., 2022a). 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; conversely, it enables a long-term business partnership and enhances performance by minimizing potential risk, accelerating mutual benefit, enhancing productivity, and optimizing profits. 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., 2022b). 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).

4. Data Envelopment Analysis (DEA)

Data Envelopment Analysis (DEA) is widely used to measure productivity and efficiency. This methodology is a practical approach popularly adopted in various industries, including healthcare, financial institutions, agriculture, armed services, sports, retail, etc. It facilitates decision-makers in evaluating an organization's efficiency and benchmarking. 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.

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 (Charnes et al., 1978). Initially, it was also called CCR since the model was developed by Charnes, Cooper, and Rhodes. Later, Banker, Charnes, and Cooper further developed the model, and it was called BCC in 1984. Today, DEA has become one of the most crucial analysis tools in decision-making. It helps to assess efficiency and identify production. DEA is a linear programming-based methodology 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 used 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., 2022b), 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 under optimal conditions with the maximum efficiency. The efficiency rate of a DMU can be expressed as the weighted sum of outputs/the weighted sum of inputs.

Maximize

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

Subject to;

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

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

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

v_i—Input weight of the ith input;

u_k—Output weight of the kth 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 inefficiency. Reducing the number of inputs helps to reach the efficient limit.

4.1. 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 is needed. Any resource consumed by a DMU is considered as 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, either 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.

4.2. Inputs

4.2.1. Geographical Distance

Sourcing activities play a vital role across industries since they directly impact 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. Geographical distance is vital in selecting robust suppliers as it impacts the procurement process and may cause undesired performance results.

4.2.2. 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, which is one of the assessment criteria for supply chain performance and warehouse operation performance.

4.2.3. 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.

4.2.4. 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; they focus 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 the financial burden and prioritizing trade partners that exhibit higher productivity.

4.3. Outputs

4.3.1. Sustainability/Robust 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 customers. 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.

4.3.2. 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 industrial Internet of Things (IoT) such as additive manufacturing, big data, artificial intelligence, blockchain, and cloud computing. Many companies use improved and collaborative technologies when dealing with suppliers based on the requirements of Industry 4.0.

4.3.3. UpToDate Technology Rank

Measuring the suppliers' capability to initiate innovations and develop existing technologies is crucial in supplier selection. Supplier innovation systematically leverages the innovative capabilities to accelerate the innovative capabilities, providing numerous benefits such as novel ideas, higher margins, and reduced time-to-market, leading to profit growth. As we study, very few indexes measure the company's innovation and potential. Most importantly, the Capacity For Innovation (CFI) index 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).

4.3.4. 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 a safe, robust, and sustainable business environment. Suppliers with highly improved technologies can quickly adapt to new business trends and recent technologies (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.

4.3.5. Number of Ports that Can Reach

The COVID-19 outbreak led to a negative impact on maritime transportation. The role and function of ports are essential as they are the central part and provide linkage in the global supply chain network. Circulation of goods dropped to around 60% of capacity due to the initial country lockdown and closure of international borders with COVID-19, creating a massive supply chain disruption worldwide (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. Ports faced numerous challenges as they could not maintain operations due to labor shortages and port congestions with the widespread coronavirus infections (Kim et al., 2022).

4.3.6. Percentage of Machinery

In response to the emergency of the contagious virus COVID-19, countries implemented different countermeasures, leading to a range of uncertainties in supply chains in all industries. Measures such as lockdowns, contact tracing restrictions, vaccination programs, social distancing, quarantines, port & airport closures, etc., impacted 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 relyon physical labor with minimal machine 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 (Sinniah et al., 2022).

5. Numerical Example

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 1.

However, due to a lack of existing data for the above new sets of input and output, 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. The industry generally accepts those three criteria (Davis et al., 2015). 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 for demonstrating the calculation of the efficiency score for the ten suppliers. Table 2 shows the list of inputs and outputs for processing the efficiency score calculation.

5.1. Inputs

Number of employees: As discussed in the preceding section, organizations with smaller workforces adhere less to formal procedures; this exhibits that they operate with a higher level of agility and flexibility during global crises. 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. Although the previous section mentioned that selecting a supplier solely by product price is insufficient, price still plays a significant role during supplier screening.

Table 1. List of new inputs and outputs.

Inputs	Outputs
Geographical distance	Sustainability Rank
Number of deliveries	Investment in information technology
Number of employees	UpToDate 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.

Table 2. 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 the efficiency score.

5.2. Outputs

Delivery grade: An organization's performance is greatly influenced by choosing the right supplier with excellent delivery performance. 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 the supply chain operation.

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.

Quality: Having the right supplier leads to business success, and customers are more emphatic about product quality. Quality applies to both service and product.

Step* 2: *Retrieving data for inputs/ outputs factors

The quantitative data for the selected input and output factors were collected from 10 key suppliers of company. Company has four decades of experience in the valves industry and receiving international certifications, 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 company are shown below in Table 3. The dataset contains two inputs and three outputs, measured in different scales.

Step* 4: *Data Normalization

Data presented in Table 3 comprise various input and output variables,

Table 3. Data of the inputs and outputs of 10 DMUs.

	Inputs		Outputs		
	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 from ten suppliers.

measuring 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 transforms variables or attributes from a dataset by scaling them down (Kotsiantis et al., 2007). 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 4** falls within the range of 0 to 1 despite variations in the measurement units.

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

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

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

Table 4. 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.

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 features into the same scale, ensuring they have an equal effect on the analysis.

Min-max normalization finds out the minimum and maximum values of the dataset. 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 4** demonstrates the values of the inputs and outputs of the 10 DMUs 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 the 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.

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 5**. **Figure 2** 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 2**, the third efficient supplier of Supplier Two's efficiency score is considerably less than the first two, accounting for 38% of efficiency.

Table 5. The efficiency score of suppliers.

	Efficiency Score	u1	u2	u3	v1	v2
Supplier 1	1.00	0.00	1.60	0.00	1.73	1.13
Supplier 2	0.38	0.00	2.82	0.00	3.04	1.99
Supplier 3	0.00	0.00	1.06	0.00	1.14	0.75
Supplier 4	0.10	0.00	1.21	0.00	1.30	0.85
Supplier 5	0.00	0.00	0.00	0.00	1.00	0.00
Supplier 6	0.00	0.00	0.97	0.00	1.05	0.69
Supplier 7	1.00	0.00	0.00	0.00	1.80	0.00
Supplier 8	0.00	0.00	0.00	0.00	1.50	0.00
Supplier 9	0.08	0.00	0.00	0.00	1.29	0.00
Supplier 10	0.00	0.00	0.00	0.00	1.13	0.00

Note: Efficiency score of ten suppliers.

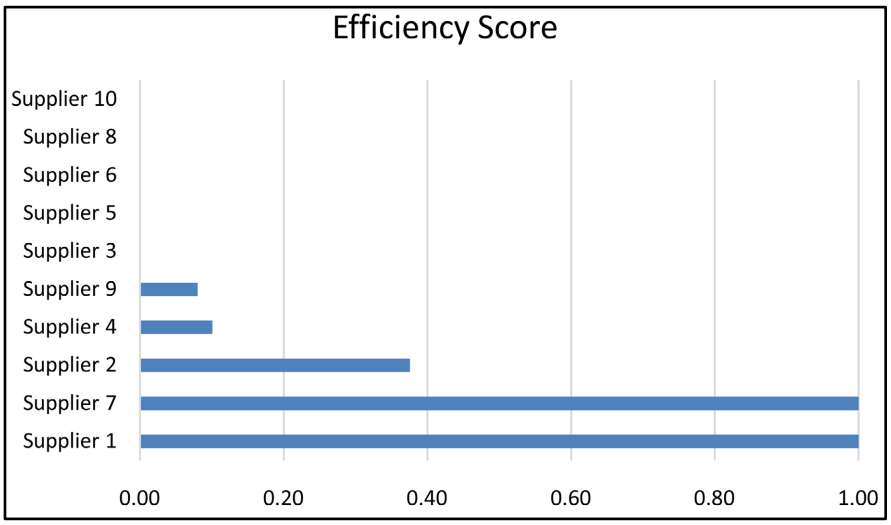

Figure 2. Efficiency scores of suppliers. Note: Bar chart of efficiency score of ten suppliers.

6. 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 company, 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.

Considering suppliers 1 and 7, both suppliers have an efficiency score of 1. We extracted the normalized input and output data from Table 6 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 Supplier1.

Table 6. 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 the top two suppliers after normalization.

As per the analysis, supplier 7 offers comparatively higher quality products at a lower price. Therefore, we recommend the selected Company, a well-known valve manufacturing company, to keep Supplier 7 as the leading supplier and Supplier 1 as the alternate supplier. Zahedi-Seresht and his team proposed Data Envelopment Analysis with different scenarios for inputs and outputs that can be helpful for future research even if we have suppliers with different scenarios (Zahedi-Seresht et al., 2017a, 2017b, 2021).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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