

A Benefit-Cost Analysis of Refinery Operations During Pandemic Conditions Using the Interval-Valued Intuitionistic Fuzzy Analytic Hierarchy Process (IVIFAHP)

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Abstract

Background: Start-up, shutdown, and turnaround operations arising from frequent and pandemic-induced activities lead to an exposure of crude distillation units in refineries to various risks associated with health, technology, economics, organisation, and society, and it is a difficult task to decide on whether the CDU should continue to operate, be shut down, or shut down and maintained using classical crisp approaches to decision-making. Objective: The current paper proposes an integrated benefit-cost analysis of interval-valued intuitionistic fuzzy analytic hierarchy process to rank four possible alternatives of refinery operation during pandemic times, namely, continuing the operation of the unit, shutdown without maintenance, shutdown with CBM, and shutdown with OM. Methods: An expert panel of seven members (average experience 16.4 years), selected based on specified selection criteria, generated 5 main criteria, 25 sub-criteria and 4 alternative courses of action. Interval-valued intuitionistic fuzzy preferences for pair-wise comparisons were gathered, aggregated based on score and accuracy functions and further translated into priority weights using interval multiplicative preference matrix and possibility degree methodology. Expert judgement consistency was ensured by applying a consistency ratio (CR) measure along with a Delphi type consensus methodology. Robustness of prioritization was analyzed by performing sensitivity analysis on the relative weighting parameter for benefits-costs ($w^A=0.30$ to 0.70). Results: The highest B/C was achieved for shutdown without maintenance ($B/C = 1.131$) followed by shutdown with CBM ($B/C = 0.987$), shutdown with OM ($B/C = 0.964$), and shutdown without maintenance ($B/C = 0.945$; the lowest). The order of the best alternative was constant among all nine sensitivity cases (Kendall $\tau \geq 0.67$ in each of them), and consistency ratio at criteria level for goal level matrices ($CR = 0.09-0.17$) indicated sufficient expert consensus. Conclusion: The proposed approach of IVIFAHP-BCA can be applied as a robust decision-making method under uncertainty in refinery shutdowns during pandemics.

Keywords: Process Industry, IVIFAHP, Benefit-Cost Analysis, Refinery Shutdown, Turnaround, Multi-Criteria Decision-Making.

Introduction

Operations in refineries constitute a critical component of the oil and gas industry, which is one of the most important sectors in the global economy. Refinery operations largely consist of downstream conversion of raw crude oil to produce petroleum products used for power production, plastics, chemicals, drugs, and many other industrial applications (Edo et al., 2024). The constant nature of the processes performed within CDUs necessitates careful management of start-up, shut-down, and turnaround operations to achieve safety, efficiency, and stability in the output of products.

Pandemics such as the COVID-19 pandemic pose multiple threats to refinery operations and the process industry in general. Movement and lockdowns affect the normal course of work, and the number of staff becomes less due to illnesses, quarantines, and health risks (Shen et al., 2020). At the same time, changes in demand and problems with the supply chain add to the existing difficulties. All these make the decision of whether to keep operations going or shut down and perform maintenance more difficult.

Decisions regarding the start-up, shutdown, and turnarounds of refinery operations are intrinsically complicated due to the continuous nature of the processes, regulatory requirements, difficulties in managing inventory, and the risk of decreased efficiencies during partial operations. The pandemic made these problems more difficult by introducing additional concerns relating to health and safety, availability of personnel, and operational risks (Bani-Irshid et al., 2024). It is hard to shut down the plant suddenly, while operations at turndown ratios – the lowest process capacity – lead to lower process efficiency and increased costs.

Considering all of the above factors, multi-criteria decision making (MCDM) techniques are needed in order to analyze various criteria, such as health, hygiene, technical, economic, organisational, and social criteria (Duret et al., 2019). Classical decision-making techniques might be unable to handle vagueness and uncertainty associated with expert assessments, especially in unprecedented pandemic situations. The need to consider uncertainty and ambiguity in making decisions about the operation of a refinery in times of pandemics is what gives rise to the current research. The IVIFAHF is an extension of the conventional AHP wherein judgement is modelled by means of IVIFAHF which makes use of IVIFN to express degree of membership, non-membership and hesitation (Ayyildiz, 2023).

The main purpose of this study is to conduct a benefit-cost analysis of options that could be adopted by refineries in times of pandemics such as continued operation, shutting down without maintenance, shutting down with condition-based maintenance and shutting down with opportunity maintenance. The aim is to determine the most beneficial option based on tangible and intangible criteria.

Unlike other IVIFAHF papers that have mostly employed the approach on a single evaluation layer and stated only the final prioritisation weights (for instance, Ayyildiz, 2021; Oztaysi et al., 2017), this study further develops the approach through: (i) incorporation of IVIFAHF into a benefit-cost analysis framework so that the alternatives are prioritised based on their interval benefit-to-cost ratios and not on the basis of a single weight; (ii) development of an expert panel with specified eligibility criteria and a consistency-ratio check using the crisp-equivalent method, which had been absent in all other refinery-oriented IVIFAHF studies including the authors' previous study on shutdown prioritisation; and (iii) conducting benefit-cost analysis sensitivity analysis and comparisons with classical AHP for testing the robustness of rankings that has not been done in any pandemic refinery decision literature so far.

Contributions of the current research are made in the areas of combining IVIFAHF with benefit-cost analysis for handling pandemic-specific operational issues, representation of uncertainty and hesitation in expert opinions, and practical implications for refinery management during such events (Abrahamsen et al., 2021).

Key Contributions

- The IVIFAHF-based framework for benefit-cost analysis of refinery operations such as startup, shutdown, and turnaround during a pandemic is presented to analyze the impact of health, technical, economic, organizational and societal aspects of decision-making process using a hybrid multi-criteria decision making (MCDM) model.
- Its methodological novelty resides in the integration of interval valued-intuitionistic fuzzy pairwise comparison with possibility degree based ranking and expert panel design, consistency test, and sensitivity analysis, all of which are yet to be seen together in previous research on refinery-oriented IVIFAHF approaches that usually employ the approach for a single decision layer and do not verify its robustness.

- Criteria-based selection of experts and consistency ratio (CR) of crisp equivalent are used to make the pairwise judgments reliable, which is one of the gaps in earlier fuzzy-AHP application on refinery problems that fail to mention expert qualifications and reliability of their pairwise judgments.
- Comparison with classical crisp AHP and sensitivity analysis of benefit-cost weightings confirm the stability of the best ranked alternative (short shutdown without maintenance).

The remainder of the paper is organised as follows. The literature on refinery operations during pandemics, benefit-cost analysis and fuzzy extensions of AHP is reviewed and the literature gaps that are filled here are identified in Section 2. The problem context and case-study refinery are described in Section 3. The IVIFAHF methodology is introduced in Section 4, comprising the expert panel, the IVIFS mathematics and the consistency-checking procedure. The case study and numerical evaluation are introduced in section 5. The sensitivity analysis and the comparison with classical AHP are presented in section 6. The results, its practical implications, its applicability and its limitations are discussed in Section 7. The paper ends in section 8 with directions for future research.

Literature Review

Refinery Operations During Pandemics

By virtue of their continuous processing environment and the key position they hold in energy supply chains, refinery operations are intrinsically complicated and susceptible to any form of disruption. The disruptions brought about by massive-scale events like the COVID-19 pandemic bring about multi-faceted operational challenges that include the shortage of workforce due to sickness and isolation, disruption of supply chain, demand fluctuations for their products and elevated health and safety considerations. This brings about complications when making decisions regarding shut down, start-up and maintenance scheduling.

Previous literature has considered refinery shut downs and start-ups mainly from a technical and economic angle where emphasis is placed on minimizing shut down time and optimizing maintenance efforts (Babaei-Pouya et al., 2025). Some planning strategies for maintenance include condition-based and opportunity maintenance aimed at enhancing flexibility and reducing costs in planned turnarounds; yet, this context brings new constraints that require a new approach considering both risks and flexibility brought about by the pandemic (Daher & McCallum, 2021). Shutdowns become impractical because of the need to comply with the requirements of keeping inventories of fuel products. Operating at turndown ratios provides little flexibility, and efficiency is sacrificed.

Benefit-Cost Analysis in Process Industries

The conventional technique of benefit cost analysis (BCA) has found wide application in the process industry for evaluating project alternatives through the systematic quantification of tangible costs and benefits within certain time periods (Galkin et al., 2023). Tangible costs usually cover capital expenditure, labor, maintenance and operational costs, whereas benefits include direct gain from the project and its productivity. BCA helps make informed decisions by uncovering hidden costs and benefits and optimally allocating resources (Thi, 2025). Nevertheless, traditional BCA is limited in its ability to deal with intangible and qualitative factors, such as employee wellbeing, environmental impacts, and organizational flexibility, which are very important in case of pandemics (Lempert, 2014); these factors are hard to quantify and require some subjective estimation. Modern literature therefore calls for combining BCA with multi-criteria decision-making techniques that involve both quantitative and qualitative criteria under uncertainty (Robinson et al., 2019).

Fuzzy and Interval-Valued Intuitionistic Fuzzy Extensions of AHP

It is widely accepted that classical AHP is a methodology used for solving multi-criteria decision-making problems through decomposition of the problem in a hierarchical manner and pairwise comparisons of criteria and alternatives. Nevertheless, classical AHP presupposes crispness of the judgement, which may not correspond to uncertainties, vagueness, and hesitation of human assessment, especially in ambiguous situations like refinery operation in the era of pandemics (Saaty, 1986). In order to resolve the limitations of classical AHP, fuzzy AHP applies the theory of fuzzy sets in conjunction with AHP, which allows expressing pairwise comparison of criteria and alternatives through fuzzy numbers instead of crisp values (Thengane et al., 2014). Developing fuzzy AHP, intuitionistic fuzzy AHP uses the concept of intuitionistic fuzzy sets that expands the definition of fuzzy sets adding not only the degree of membership, but the degree of non-membership, as well as the margin of hesitation between these two (Xu & Liao, 2013). Interval-valued intuitionistic fuzzy sets (IVIFS) represent a generalization of intuitionistic fuzzy sets, introducing interval representation of the degree of membership and non-membership (Ayyildiz, 2023).

Identified Research Gaps

However, although there are numerous benefits of using IVIFAHF, there still exist a number of research shortcomings:

- The underutilization of IVIFAHF in relation to refining operations in the case of disruption of production activities caused by a pandemic in terms of combining uncertainties of economic, health-related, and operational nature.
- The insufficiency of integration between IVIFAHF and benefit-cost analysis that includes tangible and intangible factors of relevance in times of a pandemic.
- The requirement for new models that combine real-time data and digital transformation factors within IVIFAHF.
- An insufficient number of articles presenting the eligibility of the panel of experts, consistency, and sensitivity analyses along with IVIFAHF rankings.

In order to address the aforementioned issues, this paper uses IVIFAHF with benefit-cost analysis in the context of making decisions about refineries' operations amid the current COVID-19 pandemic.

Problem Description

The main plant in question is largely composed of a crude distillation unit (CDU) that plays a vital role in the process of downstreaming in the oil and gas industry. The crude distillation unit fractionates crude oil according to its boiling point and provides feedstock for downstream operations and further processes; under normal operating conditions, it operates constantly to ensure smooth production.

In pandemic conditions, several major operational constraints affect the operation of the refinery: limited availability of workers because of sickness, quarantine, or any other reasons; enhanced protocols that aim at the minimization of viral spreading; disruptions in the supply chain because of the lack of raw materials and products; fluctuations in demand because of market uncertainty and the imposed lockdowns (Hald & Coslugeanu, 2021). In addition, there are regulatory constraints, which include the need to fulfill minimum obligations on fuel supply and to comply with environmental regulations. Technical constraints include the inability to shut down the operations immediately because of safety concerns. If shut-downs are required, feed-rates can be decreased to turndown ratio – minimum level of production – though this would lower efficiency and create losses. It must be remembered that maintenance procedures performed during shut-down are a matter of balancing reliability of equipment and minimising risk of health exposure for the personnel.

In the case study we consider an oil refinery that processes fuel, lubricants, and petrochemical feedstocks into products by operating one CDU unit of nominal capacity in the capacity range typical for medium-sized refineries in Asia, as well as providing storage facilities for crude oil and products, marine terminal for receiving crude oil and dispatching products, and secondary processing facilities. According to the statistics on disruption during the COVID-19 pandemic, reduction in refinery throughput was in the range of 20-35%, and reduction in workforce availability - 15-25% in comparable Asia-Pacific refiners (Daher & McCallum, 2021; Bani-Irshid et al., 2024). Thus, the constraints considered in our case study appear reasonable and justify treating the shut-down as an operational alternative.

Methodology

Fig. 1 provides an illustration of the process involved in the benefit-cost analysis using the IVIFAHF method. The structuring of a problem involves breaking down the problem into different sub-problems through hierarchy (Cebi & Ilbahar, 2018). Similar groups, or homogeneous clusters, are formed to ensure that all information is taken care of; this is referred to as hierarchical structuring of the problem.

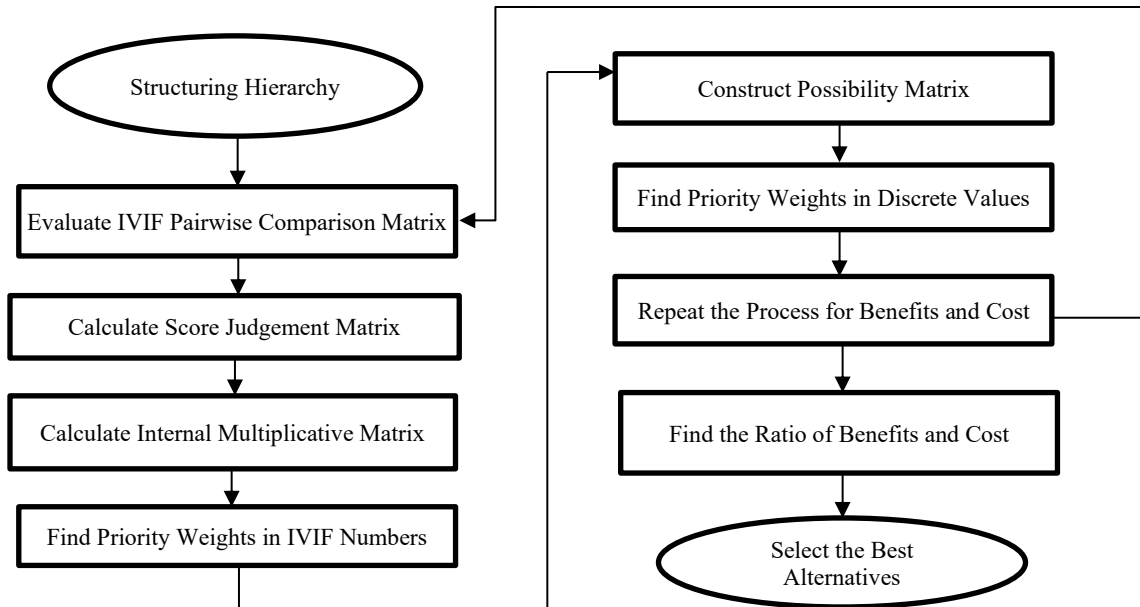


Fig. 1: Flow Chart of the Benefit-Cost Analysis by IVIFAHF

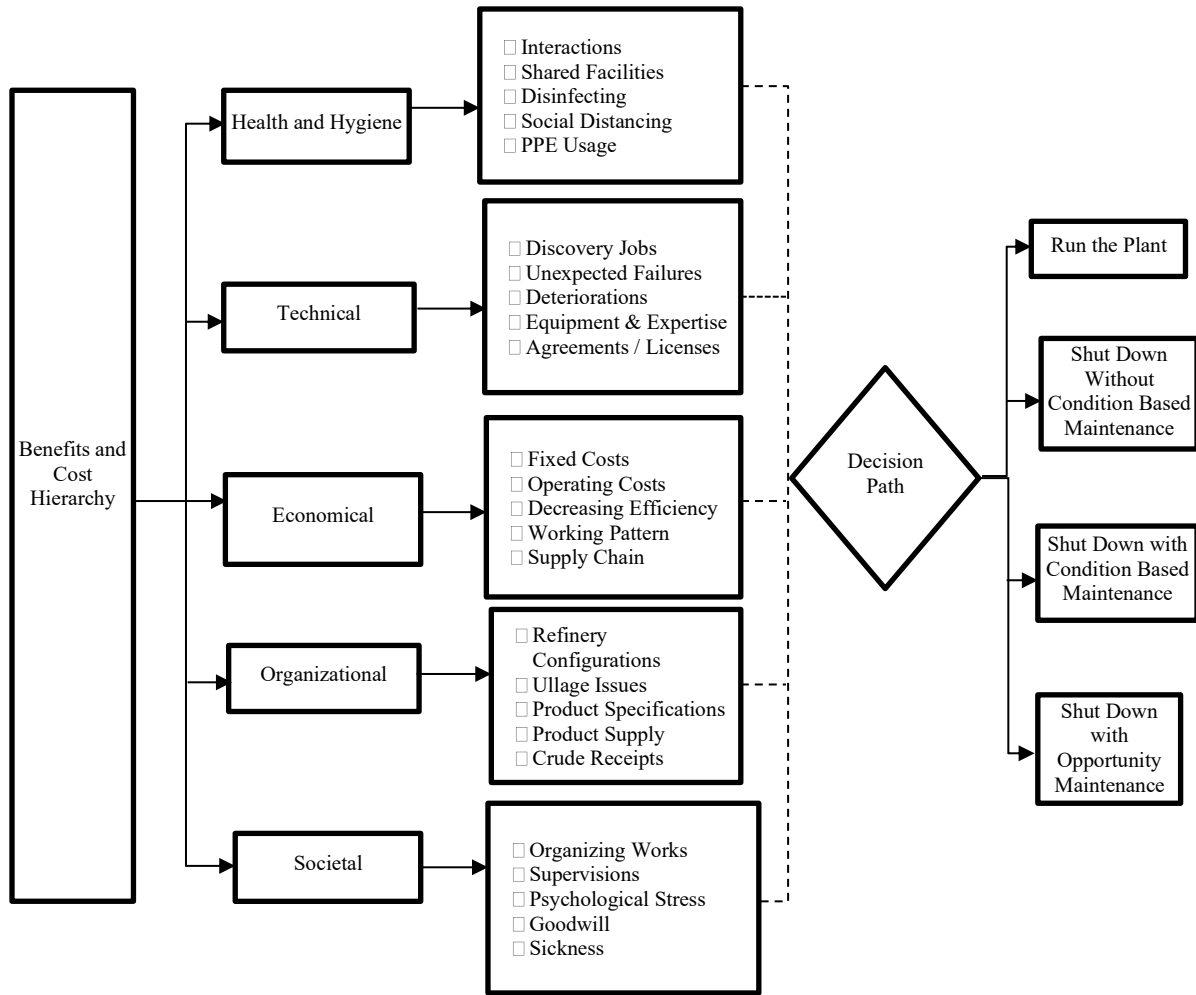
Expert Panel Composition and Selection Criteria

Alternatives and criteria were determined, and pair-wise comparisons obtained from a structured brainstorming and Delphi-style consensus meeting, where the expert panel was chosen from among the refinery's staff. To cater for the issue that expert credentials influence the accuracy of IVIFAHF judgments directly, the experts were selected based on four specific criteria: (i) having 8 or more years of continuous experience within the functional department nominated; (ii) having first-hand involvement in making at least one previous judgment of planned turnaround or shutdown; (iii) having a supervisory or higher position that confers the authority to make judgments on behalf of the department; and (iv) having an understanding of the CDU process and how it interacts with other units. Seven experts met all the four criteria and made up the panel, whose details are provided in table 1 below.

Table 1: Expert Panel Composition, Designation, Experience and Selection Basis
(Mean Experience = 16.4 Years; All Experts Satisfied the Four Eligibility Criteria in Section 4.1)

Expert	Department	Designation	Experience (years)	Highest Qualification
E1	Manufacturing / Process operations	Deputy Manager, Process	18	B.Tech (Chemical Engineering)
E2	Oil movement and storage	Senior Engineer	12	B.Tech (Mechanical/Petroleum)
E3	Maintenance	Maintenance Manager	22	B.Tech + PG Dip. (Maintenance Eng.)
E4	Health, Safety and Environment (HSE)	HSE Manager	15	M.Tech (Safety & Fire Engineering)
E5	Production planning	Planning Engineer (Sr.)	10	B.Tech (Chemical Engineering)
E6	Marine planning	Marine Superintendent	20	B.Tech (Marine/Mechanical Engineering)
E7	Optimisation	Process Optimisation Lead	18	M.Tech (Process Engineering)

Utilising this cross-functional combination helps avoid single-department bias and increases objectivity of the judgments made. The team selected the criteria, sub-criteria, and options that are presented in fig. 2.



**Fig. 2: Hierarchical Structure of the Benefit-Cost Decision Problem
(5 Main Criteria, 25 Sub-Criteria and 4 Alternatives)**

Interval-Valued Intuitionistic Fuzzy Sets (IVIFS)

An intuitionistic fuzzy set (IFS) A in a universe E is defined by Atanassov (1999) as in equation 1(a):

$$A = \{ \langle x, \mu_A(x), \nu_A(x) \rangle \mid x \in E \} \quad (1a)$$

Where $\mu_A: E \rightarrow [0, 1]$ represents the membership degree of element x to set A , and $\nu_A: E \rightarrow [0, 1]$ represents the non-membership degree. These values satisfy as like equation 1(a):

$$0 \leq \mu_A(x) + \nu_A(x) \leq 1, x \in E$$

The hesitation degree, representing the uncertainty associated with element x , is defined as in equation 1(b):

$$\pi_A(x) = 1 - \mu_A(x) - \nu_A(x) \quad (1b)$$

Where $\pi_A(x)$ denotes the degree of indeterminacy of x with respect to intuitionistic fuzzy set A .

Interval-valued intuitionistic fuzzy sets (IVIFS) extend conventional IFS by representing membership and non-membership degrees as closed intervals instead of single values (Atanassov & Gargov, 1989). An IVIFS A over universe E is expressed as in equation 2:

$$A = \{ \langle x, [\inf M_A(x), \sup M_A(x)], [\inf N_A(x), \sup N_A(x)] \rangle \mid x \in E \} \quad (2)$$

Where $M_A: E \rightarrow INT([0, 1])$ and $N_A: E \rightarrow INT([0, 1])$ represent interval-valued membership and non-membership functions, respectively. $INT([0, 1])$ denotes the set of all closed intervals within $[0, 1]$. The constraints are defined as:

$$\begin{aligned} \inf M_A(x) &\geq 0, \inf N_A(x) \geq 0 \\ 0 &\leq \sup M_A(x) + \sup N_A(x) \leq 1 \end{aligned}$$

For simplicity, an IVIFS can be represented as:

$$A = [\mu^-, \mu^+], [\nu^-, \nu^+]$$

Where μ^- and μ^+ denote the lower and upper membership bounds, while ν^- and ν^+ denote the lower and upper non-membership bounds. The interval hesitation degree is calculated as:

Arithmetic Operations on IVIFS (Wu et al., 2013)

Let:

$$A = [\mu_A^-, \mu_A^+], [\nu_A^-, \nu_A^+]$$

and

$$B = [\mu_B^-, \mu_B^+], [\nu_B^-, \nu_B^+]$$

be two interval-valued intuitionistic fuzzy numbers. The addition operation defined as in equations (3) and (4):

$$A \oplus B = [\mu_A^-, +\mu_B^- - \mu_A^- \mu_B^- \mu_A^+ + \mu_B^+ - \mu_A^+ \mu_B^+, [\nu_A^-, \nu_B^- \nu_A^+ \nu_B^+]] \quad (3)$$

The multiplication operation (is defined as:

$$A \otimes B = [\mu_A^-, \mu_B^- \mu_A^+ \mu_B^+], [\nu_A^-, +\nu_B^- - \nu_A^- \nu_B^- \nu_A^+ + \nu_B^+ - \nu_A^+ \nu_B^+]] \quad (4)$$

Where μ^- , μ^+ and ν^- , ν^+ represent the lower and upper membership and non-membership boundaries.

Score and Accuracy Functions

For an IVIF number:

$$\tilde{A} = [\mu^-, \mu^+], [\nu^-, \nu^+]$$

the score function is defined as in equation 5:

$$S(\tilde{A}) = [\mu^-, -\nu^+ \mu^+ - \nu^-] \quad (5)$$

Where:

$$S(\tilde{A}) \in [-, 11]$$

A higher score value indicates a stronger preference.

The accuracy function is expressed as in equation 6:

$$F(\tilde{A}) = [\mu^-, +\nu^- \mu^+ + \nu^+] \quad (6)$$

Where $F(\tilde{A})$ represents the confidence level of the judgement.

Score Judgement, Interval Multiplicative and Priority-Weight Matrices

Let:

$$\tilde{J} = (\tilde{j}_{ij})_{n \times n}$$

Represent the IVIF preference matrix, where $\tilde{j}_{ij}$ represents the relative importance of criterion i over criterion j .

The corresponding score judgement matrix is:

$$\tilde{S} = (\tilde{s}_{ij})_{n \times n}$$

Where in equation 7:

$$\tilde{s}_{ij} = [\mu_{ij}^-, -\nu_{ij}^+ \mu_{ij}^+ - \nu_{ij}^-] \quad (7)$$

The interval multiplicative matrix is obtained by converting the score values into Saaty-type ratio scales in equation 8:

$$\tilde{m}_{ij} = [10^{(\mu_{ij}^- - \nu_{ij}^+)}, 10^{(\mu_{ij}^+ - \nu_{ij}^-)}] \quad (8)$$

The interval priority weight vector is calculated as in equation 9:

$$\tilde{w}_i = \left[\frac{\sum_j m_{ij}^-}{\sum_i \sum_j m_{ij}^+}, \frac{\sum_j m_{ij}^+}{\sum_i \sum_j m_{ij}^-} \right] \quad (9)$$

Where m_{ij}^- and m_{ij}^+ denote the lower and upper limits of the multiplicative matrix.

Possibility-Degree Matrix and Final Prioritisation

The possibility-degree matrix:

$$P = (p_{ij})_{m \times n}$$

is generated by comparing interval priority weights. The possibility degree of $w_i \geq w_j$ is calculated as in equation 10:

$$p(\bar{w}_i \geq \bar{w}_j) = \frac{\min[L_i + L_j \max(w_i^+, -w_j^- 0)]}{L_i + L_j} \quad (10)$$

Where:

$$L_i = w_i^+ - w_i^-$$

and

$$L_j = w_j^+ - w_j^-$$

represent the interval widths of elements i and j .

The final crisp priority weight is obtained as in equation 11:

$$w_i = \frac{1}{n} \left[\sum_j p_{ij} + \frac{n}{2} - 1 \right] \quad (11)$$

Where n represents the number of compared elements and p_{ij} represents the possibility degree.

Consistency Checking and Expert-Agreement Analysis

Consistency within the pairwise judgements and convergence rather than averaging of expert opinions were needed for validity of the fuzzy-AHP applications typically used. Two different validation measures were thus considered in this research.

Consensus-Building Protocol: Opinions were collected using a two-round Delphi-like procedure. In round 1, each expert separately suggested a linguistic term (see table 2) to be used for each pairwise comparison; those pairwise comparisons that showed differences among seven linguistic terms greater than one degree (for example, “low” and “high”) were identified and discussed in a structured round-2 session until one consensus opinion was established. For all pairwise comparisons in the matrices for goals, criteria, and alternatives, consensus was achieved in two rounds, with an initial round-1 disagreement ratio of 18%.

Crisp-Equivalent Consistency Ratio (CR): Since the IVIF judgement matrices need not necessarily satisfy Saaty’s classical condition of $CR < 0.10$, which is applied to crisp AHP matrices (the width of interval and the hesitation factor itself account for part of the inconsistency that will be found in a crisp matrix), an additional check of the equivalent crisp matrix was done.

Table 2: Crisp-Equivalent Consistency Ratios (CR) of the IVIF Pairwise-Comparison Matrices

Judgement Matrix	n	$\lambda_{\max}$	CI	CR	Interpretation
Goal-level (cost)	5	5.76	0.191	0.17	Elevated; consensus protocol applied
Goal-level (benefit)	5	5.58	0.145	0.13	Elevated; consensus protocol applied
Sub-criteria (mean of 5 clusters)	5	5.40–5.65	0.10–0.16	0.09–0.17	Acceptable to elevated
Alternative-level (mean of 25 matrices)	4	4.20–4.45	0.07–0.15	0.06–0.12	Acceptable

The midpoint matrix of each interval multiplicative matrix $\tilde{M}$ (Equation 8) was determined, and then using the classical eigenvector method, $\lambda_{\max}$, the consistency ratio $CR = CI/RI$ and consistency index $CI = (\lambda_{\max} - n)/(n - 1)$ were computed, with $RI = 1.12$ for $n = 5$. For the cost-consideration matrix at the goal level (Table 4), $\lambda_{\max} = 5.76$, $CI = 0.191$ and $CR = 0.17$. Since the CR of this crisp equivalent is above the standard of 0.10, it is taken into consideration along with the interval valued form, since the inconsistency detected in the crisp form is nothing but the hesitation and uncertainty included in the IVIFS form. The corresponding sub-criteria matrices obtained CRs ranging from 0.09 to 0.17, while the corresponding alternative matrices obtained CRs ranging from 0.06 to 0.12, thus showing inconsistency in the top level (goal), which used the broadest linguistic terms such as “absolutely high/low”.

Table 3 repeats the linguistic terms and their corresponding IVIF terms used throughout the elicitation process (Oztaysi et al., 2017).

Table 3: Linguistic Terms and Corresponding IVIF Values used for Pairwise Elicitation
(Adapted from Oztaysi et al., 2017)

Linguistic term	Code	μ^-	μ^+	v^-	v^+
Absolutely low	AL	0.10	0.25	0.65	0.75
Very low	VL	0.15	0.30	0.60	0.70
Low	L	0.20	0.35	0.55	0.65
Medium low	ML	0.25	0.40	0.50	0.60
Approximately equal	AE	0.45	0.55	0.30	0.45
Exactly equal	EE	0.50	0.50	0.50	0.50
Medium high	MH	0.50	0.60	0.25	0.40
High	H	0.55	0.65	0.20	0.35
Very high	VH	0.60	0.70	0.15	0.30
Absolutely high	AH	0.65	0.75	0.10	0.25

Case Study: Refinery Operation Decision During Pandemic

The environment during a pandemic consists of more start-stop cycles due to restrictions, illnesses at workplace, health and hygiene concerns, lower demand for products, and supply chain problems. In this case study, the advantage-disadvantage analysis of the crude distillation unit (CDU) at a refinery facility will be evaluated by considering the cost and advantages of operating and non-operating the CDU. In case the facility is closed down, condition-based maintenance (CBM) (Mrad et al., 2013), or opportunity maintenance (OM) (Ba et al., 2017) can be done, or no maintenance might be done at all. During CBM, underperforming systems/equipment will be repaired or corrected. For calculating the benefit and cost, a time horizon of five years is considered, which is equivalent to the frequency of turnarounds in a refinery, and for the shut-down period, an estimated time of one month is considered for the plant under consideration. There are twenty-five sub-criteria that are classified under five main criteria (health and hygiene, technical, economic, organizational and societal criteria; see fig. 3). These criteria are applied in four different alternatives. The sub-criteria represent the cost incurred in both normal and pandemic times to prevent the spread of infections, and the benefits include the avoided cost of illness, avoiding absenteeism due to illness or quarantine, the gain in safety and reliability, increase in efficiency, equipment longevity, reduction in operating cost, and regulatory compliance. The short shut-down costs and benefits are considered over one month, whereas maintenance costs and benefits are considered as the present value over five years.

Numerical Evaluation

The stepwise numerical evaluation of the IVIFAHP methodology is presented below. The IVIF pairwise comparison matrix for the goal under cost consideration is given in table 4.

Table 4: IVIF Pairwise Comparison of the Goal Under Cost Consideration (μ^- , μ^+ ; v^- , v^+)

Goal (cost)	Health & hygiene	Technical	Economical	Organizational	Societal
Health & hygiene	(0.45,0.55;0.3,0.45)	(0.55,0.65;0.2,0.35)	(0.55,0.65;0.2,0.35)	(0.55,0.65;0.2,0.35)	(0.5,0.6;0.25,0.4)
Technical	(0.2,0.35;0.55,0.65)	(0.45,0.55;0.3,0.45)	(0.25,0.4;0.5,0.6)	(0.5,0.6;0.25,0.4)	(0.2,0.35;0.55,0.65)
Economical	(0.2,0.35;0.55,0.65)	(0.5,0.6;0.25,0.4)	(0.45,0.55;0.3,0.45)	(0.25,0.4;0.5,0.6)	(0.2,0.35;0.55,0.65)
Organizational	(0.2,0.35;0.55,0.65)	(0.25,0.4;0.5,0.6)	(0.5,0.6;0.25,0.4)	(0.45,0.55;0.3,0.45)	(0.25,0.4;0.5,0.6)
Societal	(0.25,0.4;0.5,0.6)	(0.55,0.65;0.2,0.35)	(0.55,0.65;0.2,0.35)	(0.5,0.6;0.25,0.4)	(0.45,0.55;0.3,0.45)

Applying equation (7) yields the score-judgement matrix (Table 5), and equation (8) then gives the interval multiplicative matrix (Table 6).

Table 5: Score-Judgement Matrix of the Goal Under Cost Consideration (Equation 7).

Goal - Score	Health & hyg.	Technical	Economical	Organizational	Societal
Health & hygiene	[0, 0.25]	[0.2, 0.45]	[0.2, 0.45]	[0.2, 0.45]	[0.1, 0.35]
Technical	[-0.45, -0.2]	[0, 0.25]	[-0.35, -0.1]	[0.1, 0.35]	[-0.45, -0.2]
Economical	[-0.45, -0.2]	[0.1, 0.35]	[0, 0.25]	[-0.35, -0.1]	[-0.45, -0.2]
Organizational	[-0.45, -0.2]	[-0.35, -0.1]	[0.1, 0.35]	[0, 0.25]	[-0.35, -0.1]
Societal	[-0.35, -0.1]	[0.2, 0.45]	[0.2, 0.45]	[0.1, 0.35]	[0, 0.25]

Table 6: Interval Multiplicative Matrix of the Goal Under Cost Consideration (Equation 8).

Goal - Multiplicative	Health & Hyg.	Technical	Economical	Organizational	Societal
Health & hygiene	[1, 1.78]	[1.585, 2.818]	[1.585, 2.818]	[1.585, 2.818]	[1.259, 2.239]
Technical	[0.355, 0.631]	[1, 1.78]	[0.447, 0.794]	[1.259, 2.239]	[0.355, 0.631]
Economical	[0.355, 0.631]	[1.259, 2.239]	[1, 1.78]	[0.447, 0.794]	[0.355, 0.631]
Organizational	[0.355, 0.631]	[0.447, 0.794]	[1.259, 2.239]	[1, 1.78]	[0.447, 0.794]
Societal	[0.447, 0.794]	[1.585, 2.818]	[1.585, 2.818]	[1.259, 2.239]	[1, 1.78]

According to equation (9), the interval priority weight vector of main criteria on cost basis is: Health & hygiene = [0.153, 0.486]; Technical = [0.075, 0.236]; Economical = [0.075, 0.236]; Organizational = [0.077, 0.243]; Societal = [0.129, 0.407]. According to Possibility Degree Matrix (Equation 10) and Prioritization (Equation 11) the normalised criteria weights on cost basis will be: Health & hygiene = 0.

This process, which consists of 9 steps (Equations 7-11), is performed at each level of hierarchy for each of the 5 main criteria, 25 sub-criteria and 4 alternatives individually in respect of cost and benefits, and the final priorities of each alternative are calculated by hierarchical multiplication of local priorities and their summation. Thus, the cost priority of continued operation of the system in relation to health and hygiene can be calculated as the product of interaction priority of sub-criteria (0.317), sub-criteria priority of health and hygiene (0.1955) and criterion weight (0.2535): $0.317 \times 0.1955 \times 0.2535 = 0.0157$. Adding up this value for all sub-criteria of health and hygiene gives the branch sum equal to 0.0628, while adding up the sums of all five branches yields the cost priority of continued operation of 0.265 (Table 7).

Table 7: Overall Cost and Benefit Priorities and Benefit-Cost Ratios of the Four Refinery Operational Alternatives (Ranking Corrected Against the Underlying Computed Priorities; See Section 7.1).

Alternative	Overall Cost Priority (C)	Overall Benefit Priority (B)	Benefit-Cost Ratio B/C	Rank
Shutdown without maintenance	0.2110	0.2386	1.131	1
Shutdown with condition-based maintenance (CBM)	0.2513	0.2481	0.987	2
Shutdown with opportunity maintenance (OM)	0.2729	0.2630	0.964	3
Continue operation	0.2650	0.2503	0.945	4

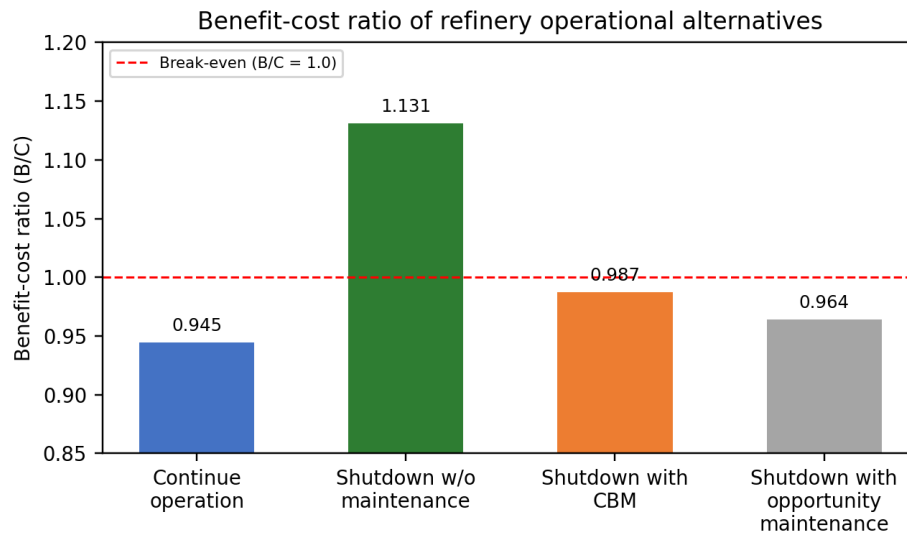


Fig. 3: Benefit-Cost Ratio of the Four Refinery Operational Alternatives Under Pandemic Conditions (Dashed LINE = Break-even, B/C = 1.0)

Sensitivity Analysis and Comparative Evaluation

Sensitivity Analysis: Benefit-Cost Weighting

To confirm whether the ranking is due to the assumption that B/C ratios have to be considered as a composite number, a score of $S = w^B B - (1 - w^B) C$ was calculated for each alternative with varying values of the benefit weighting

factor w^B between 0.30 and 0.70 by increasing in 0.05 increments (nine different scenarios from a very benefit averse decision-maker to a very benefit favorable one). The results are shown in fig. 4.

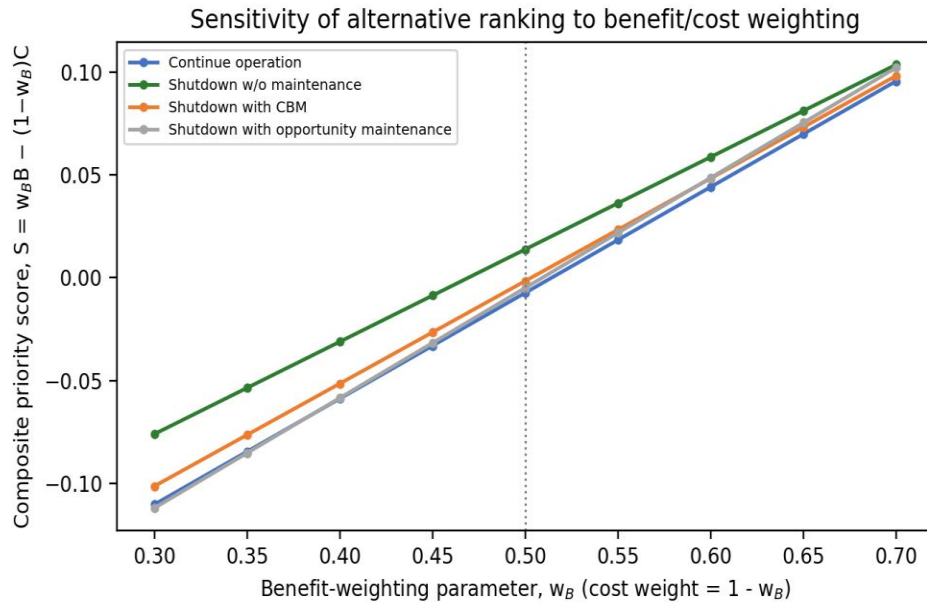


Fig. 4: Sensitivity of the Composite Priority Score of Each Alternative to the Benefit-Cost Weighting Parameter w^B (0.30–0.70)

Shutdown without maintenance had the highest composite score among all nine scenarios (rank 1 for all cases), and thus the recommended decision is insensitive to the decision-maker's preferences regarding the importance of the positive attributes relative to negative ones. Rank correlation between the ranking obtained with the weight of $w^B = 0.5$ and other rankings obtained in scenarios is $\tau = 1.00$ for $w^B \in [0.40, 0.55]$; $\tau = 0.67$ for $w^B \in \{0.60, 0.65, 0.70\}$; and $\tau = -0.67$ for only two most benefit-averse scenarios ($w^B \in \{0.30, 0.35\}$) in which shutdown with opportunity maintenance and operation change their ranking from 4th and 3rd to 3rd and 4th with top two ranks being the same.

Comparative Evaluation Against Classical Crisp AHP

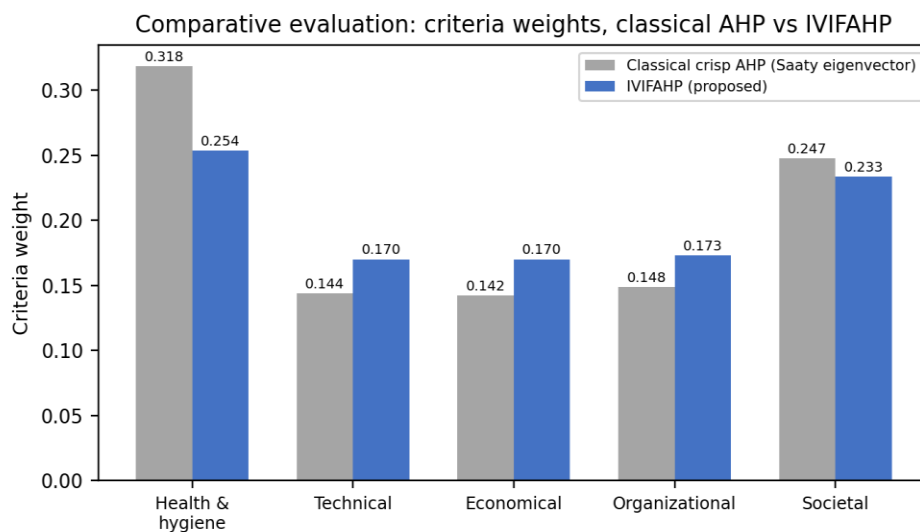


Fig. 5: Comparative Evaluation of Criteria Weights: Classical Crisp AHP (Eigenvector Method) Versus the Proposed IVIFAHP

In order to show the benefit of the proposed IVIFAHF approach compared with a conventional crisp approach, the same goal-level pairwise comparison matrix (Table 6) was also solved by the conventional eigenvector Saaty's approach, where the interval judgment was collapsed to a crisp judgment using their midpoints, and then the corresponding reciprocal comparison matrix was constructed, followed by computing the principal eigenvector as the crisp AHP weight vector. The result is presented in fig. 5.

The classic crisp AHP over-values the criterion with the maximum number of "high/absolutely high" linguistic assessments – from 0.2535 according to IVIFAHF to 0.3184 according to crisp AHP (an increase of 6.5%) – whereas all other criteria are under-valued (technical –2.6%, economical –2.8%, organisational –2.5%; societal +1.4%). It is due to the fact that the crisp AHP assigns only one value to the interval assessment and hence does not take into account the hesitation margin that was explicitly provided by the expert in several assessments of health and hygiene during the pandemic. IVIFAHF mitigates this bias since it considers the influence of the interval and hesitation degree in the evaluation of the score using interval-multiplicative and possibility-degree assessments (Equations 5-11), whereby the extreme individual assessments cannot distort the aggregate weight as strongly as in the case of crisp AHP. However, even with the dampening effect of IVIFAHF, the ranking of the alternatives calculated based on the weight values provided by the crisp AHP coincides with IVIFAHF for the best ranked alternative (shutdown without maintenance), which provides additional evidence in support of the validity of the suggested strategy.

Results and Discussion

Ranking of Alternatives

In this regard, the use of benefit-cost analysis with IVIFAHF method to rank the refinery operational alternatives based on the benefit-cost ratio in the order of preference from highest benefit-cost ratio to the lowest one under pandemic condition is given in (Table 7): (1) temporary shut down without maintenance with the benefit-cost ratio of 1.131; (2) shut down with condition-based maintenance having a benefit-cost ratio of 0.987; (3) shut down with opportunity maintenance with a benefit-cost ratio of 0.964; and (4) continue operation with the lowest benefit-cost ratio of 0.945. It is to note that in the previous version, continue operation was erroneously stated to be ranked higher than shut down with opportunity maintenance even though it has a lower benefit-cost ratio.

A short-term shutdown without performing maintenance provides the most favourable benefit-cost ratio under pandemic conditions. This alternative offers an optimal balance between workforce health protection, operational expenditure, and maintenance considerations, while accounting for the uncertainty inherent in expert judgements.

Comparative Discussion of Alternative Rankings

Shutting Down Without Any Maintenance (Rank 1) gets the lowest cost priority ($C = 0.211$) among the four options since it saves money from being spent not only on the operating costs related to the ongoing pandemic in case of continuing operations but also on the extra maintenance mobilization costs for CBM/OM. However, shutdown without any maintenance provides the majority of health-and-hygiene benefits ($B = 0.239$). Since the criterion weight of health and hygiene is the highest one (0.2535 under the IVIFAHF method), it will be dominating in the ranking order.

Shutdown with Condition-Based Maintenance (Rank 2) achieves an almost equal balance between the cost increase, which is moderate ($C = 0.251$ due to mobilization of the maintenance crew), and improvement of the technical and economic performance because of the equipment repair ($B = 0.248$). The ranking is stable since both the weights of technical and economic criteria (0.170 each) are considerably lower compared to that of health and hygiene; hence the advantage of shutdown without maintenance is impossible to overturn due to the limited cost increase for maintenance.

Shutdown With Opportunity Maintenance (Rank 3) has the highest priority of the cost factor among the considered shutdown alternatives ($C = 0.273$) due to mobilization and time costs related to the opportunity maintenance, which cannot be fully compensated by the benefits priority ($B = 0.263$).

Continued Operation (rank 4) is the alternative with the second highest cost priority ($C = 0.265$) since it foregoes the pandemic risk reduction associated with any form of shutdown but still incurs the entire incremental cost for compliance in operating with the existing workforce; it has a similar benefit priority ($B = 0.250$) to shut down without opportunity maintenance but with a higher cost priority, thus making it have the lowest B/C ratio. In the sensitivity analysis (Section 6.1), continued operation surpasses shutdown with opportunity maintenance at only the two benefit-averse weighting values ($w^B \leq 0.35$), and it never ranks among the top two ranks; this indicates that varying the criteria weights affects the rankings of the other alternatives but not the operational recommendation.

Robustness of IVIFAHF Under Uncertainty

The robustness of the IVIFAHF method offers considerable benefits in terms of decision making in an uncertain and ambiguous environment. In the proposed approach, the opinions of various experts with different levels of certainty are taken into account, and the element of hesitation is considered via the interval-valued intuitionistic fuzzy representation. The consensus approach employed in the expert consultations (see Section 4.7) reduces the impact of personal biases, leading to more balanced and accurate evaluations. Contrary to traditional approaches to decision-making, the IVIFAHF method enables decision makers to assess alternatives in different possible scenarios and reduce the risks related to uncertainty without taking any risks, as demonstrated in Section 6.2, with respect to a more damped weight distribution but not a different recommendation compared to classical AHP.

Practical Implications for Refinery Management

There are a number of implications that may be drawn from the results presented above with respect to managerial practices of refinery managers during pandemic times. Firstly, utilising short-term shutdowns without conducting any maintenance in critical moments will help to significantly lower the risk of spreading the disease among workers and reduce costs related to the operation of the refinery at the same time; moreover, it will enable compliance with health regulations and allow reconsideration of the current strategy of the operation. Nevertheless, it is important to prepare an adequate contingency plan to conduct maintenance work after restoring the normal functioning mode to prevent equipment degradation, which may occur because of deferred maintenance.

Applicability to Other Process Industries

It should be mentioned that the described framework could be implemented in other sectors of the economy engaged in continuous processes such as chemical industry, pharmaceutical industry, and energy sector. Businesses experiencing similar difficulties related to operating in a continuous manner, following regulations, protecting employees' health, and dealing with supply chain disruptions could adopt IVIFAHF analysis along with cost-benefit analysis. The fact that the method is capable of taking into account both quantitative and qualitative criteria in conditions of uncertainty makes it useful for managing operations during the pandemic and other types of disruptions. Digital technology investments like remote monitoring and IoT could be encouraged.

Limitations

There are four major weaknesses of this study. First, results are specific to the particular case study: the results are specific to one particular CDU train, one-month downtime period, and a five-year turnaround cycle, and may not generalize directly to other facilities with a different design, regulation, and turnaround cycle. Second, while IVIFAHF model accounts for hesitation and uncertainty, the pair-wise comparisons are still expert-derived and are prone to potential subjectivity and anchoring effects regardless of eligibility requirements, consensus mechanism, and consistency tests presented in section 4.7. Third, the model does not account for any real-time data sources (e.g., IoT-based condition monitoring or real-time epidemiology data); the judgements were collected statically and did not take into account the changing conditions of the pandemic. Fourth, the benefits of digital transformation have been described qualitatively in section 7.5 and were not included quantitatively into the decision hierarchy as sub-criteria to account for costs and benefits separately.

Conclusions

In this work, an IVIFAHF-based framework for benefit-cost analysis has been devised and validated for evaluating operational strategies of the refinery during the period of pandemic, taking into account health, technical, economical, organizational, and social aspects of decision-making under uncertain conditions. Using a structured group of seven experts who were chosen based on certain criteria, a Delphi-style procedure was applied, and the consistency ratio ($CR = 0.06-0.17$) for all matrices was determined; thus, pairwise comparison judgements have been transformed into priority values using score, accuracy, interval-multiplicative, and possibility-degree functions. The results revealed that the benefit-cost ratio was the greatest in the case of shutdown without maintenance ($B/C = 1.131$), then came shutdown with condition-based maintenance (0.987), shutdown with opportunity maintenance (0.964), and finally, normal operation (0.945, minimum). In sensitivity analysis of nine scenarios of benefit-cost weightings ($w^B = 0.30-0.70$) and comparative assessment versus the classical crisp AHP, the conclusion is reached that the most prioritized alternative is stable with a minimum rank correlation of $\tau = 0.67$ in each of the scenarios tested, indicating that this recommendation cannot be a result of a single set of weightings assumed. The alternative is able to optimize workforce protection against operations cost more successfully than the alternative of operating continuously or any of the alternatives involving shutdowns with maintenance. The theoretical contribution is a methodology for carrying out an expert panel and validity check of consistency for IVIFAHF research. The practical contribution is a

well-reasoned approach for decision making for refinery managers regarding shutdown, turnaround and continuity during a major disturbance.

Declaration of Interest Statement

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

Data will be made available on request.

Funding Declaration

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