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Quantitative sustainability assessment of freeports: Hybrid model evidence from the UK

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ABSTRACT

Freeports and their equivalents are designed to boost national economic prosperity, yet their associated sustainability concerns are often overlooked. Existing research on freeport performance evaluation is largely fragmented, with a predominant focus on economic metrics specific to individual cases. Moreover, the existing methods for sustainability assessments face inherent limitations in addressing uncertainty and integrating indicators within both hierarchical and interconnected network structures. To address these research gaps, this study introduces a novel methodology for holistically assessing freeport sustainability using a hybrid Bayesian Network and Evidential Reasoning (BNER) model. This model can process both qualitative and quantitative performance data, and integrate different Key Performance Indicators (KPIs) to generate a comprehensive index. The new contributions of this paper include: (1) It proposes a novel framework for evaluating freeport sustainability across economic, environmental, and social dimensions and synthesising them into a singular index. (2) It prioritises all relevant KPIs from multiple stakeholder perspectives. The findings indicate that information technology and customs clearance efficiency are the most significant among the 42 identified KPIs. (3) A new BNER model is introduced to address data uncertainty and interdependent factors in performance assessment. (4) The applicability of the developed model is demonstrated through a real-world case study of a UK freeport, providing valuable practical insights.

1. Introduction

Freeports are special economic zones that operate under distinct customs regulations to boost regional trade, employment, and investments (Rowbotham, 2022). They play a crucial role in economic development, functioning as dynamic centres for productive work, importing raw materials, and exporting finished products. Although showing appealing economic benefits, freeports face certain issues and challenges in their implementation. The risks associated with freeports have been extensively documented, encompassing concerns such as the trade in counterfeit goods, drug trafficking, gunrunning, human trafficking, smuggling of untaxed goods (e.g., cigarettes, alcohol, and luxury goods), trade-based money laundering, and tax evasion (RUSI, 2020; Boffey, 2020; Davidson, 2008). Moreover, lax application processes and regulations, poor enforcement, and opaque customs processes can lead to significant environmental degradation (Wildlife and Countryside Link, 2020). Furthermore, the technological developments stemming from Industry 4.0 have profoundly transformed operational concepts and services across all industries, including the freeport sector. This revolution could lead to increased investment costs and elevated cyber risks during the transition.

Given the myriad of concerns and emerging challenges, it becomes clear that assessing the performance of freeports exclusively from an economic standpoint is inadequate. It is imperative to also take into

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account the environmental and social dimensions. However, the crucial task of monitoring and evaluating the sustainable development of freeports in coping with environmental and social challenges has been largely overlooked in existing studies. Therefore, it is necessary to develop a new methodology for evaluating the freeport performance, which integrates sustainability into their overarching development objectives and policies. In recent decades, sustainability has attracted much attention from both academia and industry. The most adopted definition of sustainability is as follows (WCED): "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Despite the increasing number of studies on maritime and port sustainability development over recent years (Shin et al., 2018), current state-of-the-art studies fail to employ advanced methods for sustainability assessment, that can integrate diverse KPIs within a unified framework, address data uncertainty and interdependent KPIs, and engage diverse stakeholders at the early stage. In conclusion, current studies reveal a notable research gap to be addressed from both methodological and empirical perspectives.

To address the research gap, this study aims to develop an innovative methodology for assessing the sustainability of freeports. To achieve this aim, it initiates its research process with a systematic and comprehensive literature review. It spans the domain of freeports, ports, and port cities, recognising their interconnected pivotal roles. By reviewing the existing sustainability frameworks and decision-support methodologies, this study creates an innovative approach to identifying Key Performance Indicators (KPIs) influencing the sustainability of freeports. Secondly, it engages a diverse range of stakeholders in evaluating the significance of KPIs through a global survey. Thirdly, this study employs a hybrid Bayesian Network and Evidential Reasoning (BNER) approach to synthesise the overall sustainability performance of a freeport based on the integrated information across multiple criteria, particularly addressing the challenge of the KPIs interconnected in a network structure through BN's learning and inference ability. Lastly, this study demonstrates the applicability of the developed model through a case study of a UK freeport, subjected to a consistency test through sensitivity analysis. Accordingly, the novelties of this paper are highlighted as follows.

(1) This study creates a three-tier hierarchical KPI index for freeports. This index is designed following the framework of the Global Reporting Initiative (GRI), which encompasses three sustainability dimensions. Furthermore, this study integrates top-down and bottom-up methods to select KPIs from an extensive literature review and case studies.
(2) The significance of all KPIs is assessed through a global survey that engages multiple stakeholders, including researchers, policymakers, practitioners, service users, and public residents. Moreover, this diverse engagement draws upon the collective knowledge and experience of respondents across 10 countries.
(3) It develops a groundbreaking hybrid BNER methodology that, for the first time, allows for the inclusion of KPIs in both network and hierarchical structures within the same framework. This makes it possible to comprehensively evaluate the sustainability of freeports. This methodology also helps merge assessments with uncertainties, resulting in more accurate outcomes that are closer to reality when compared to other techniques.
(4) A real case study is carried out to illustrate the practical applicability of the proposed model and provide valuable managerial insights towards freeport sustainability. Wherein, a sensitivity analysis is performed to examine the consistency regarding the impact of minor input changes on the outputs.

The rest of the paper is structured as follows. Section 2 presents a literature review on freeport evaluation themes and sustainability assessment frameworks and methods, followed by an analysis of the research gaps. Section 3 introduces the designed framework and corresponding steps, including KPI identification and purification, evaluation of KPI importance, performance assessment and aggregation, and model validation. The practical application of these steps is illustrated in Section 4. The implications of this research are discussed in Section 5. Section 6 is the conclusion of this paper.

2. Literature review

The literature review in this study is organised into four subsections. Section 2.1 reviews the existing research on freeport evaluation. Section 2.2 focuses on sustainability assessment frameworks and indices, while Section 2.3 examines decision-support methods for sustainability assessments in the context of ports and port cities and introduces a novel BNER approach. Section 2.4 discusses the identified research gaps.

2.1. Freeport evaluation

Existing studies on freeport evaluation can be categorised into macro-level evaluations (urban or regional performance evaluations) and micro-level evaluations (enterprise performance evaluations). Many papers have examined the impact of freeports or their equivalents using indices at the urban or regional level. For instance, Liu and Feng (2024) explored how Pilot Free Trade Zones (PFTZs) influenced the innovation performance of economically connected neighbouring cities, as well as the overall innovation level of the region. Xia et al. (2024) demonstrated that PFTZs significantly improved urban land use efficiency, with the policy effects being particularly notable in central cities, inland cities, and those with higher urbanisation rates. Two studies (Chen et al., 2022; Li and Choi, 2022) used provincial-level panel data to analyse the impact of Free Trade Zones (FTZs) on the transformation and upgradation of trade patterns, and economic benefits and ecological environment Impact of export trade, respectively. A study by Teixeira (2020) confirmed that the establishment of the Manaus FTZ contributed to improved labour and social efficiency in the region compared to other major industrial municipalities in Brazil, using residuals and stochastic frontier techniques to estimate performance. Other used indexes include Green Total Factor Productivity (GTFP) (Guan et al., 2024; Ma et al., 2021), the efficiency of urban green technology innovation (Liu et al., 2024), high-quality economic development (Chang and Wang, 2024), and green dual-circulation development (Lai and Chang, 2023).

Many other papers have examined the impact of freeports or their equivalents at the enterprise level. The applied performance indexes include the economic performance development of port-listed companies (Li et al., 2021), enterprise digital transformation (Wang et al., 2024), firms' Environmental, Social and Governance (ESG) performance (Zeng et al., 2024b), innovation performance of firms (Su and Wang, 2024), green innovation efficiency (Wang et al., 2023a), production efficiency of environmental protection enterprises (Song et al., 2018), environmental performance (Li et al., 2023b), and sustainability performance of companies (Cheng and Ma, 2023). Jiang and Zhang (2023) found that in civil cases involving Chinese FTZ enterprises as plaintiffs, judicial justice was not compromised for economic efficiency, such as attracting foreign investment.

Several papers have explored the impact of freeports or their equivalents on specific industries. For instance, Fan et al. (2024) found that FTZ policies significantly promoted the high-quality development of the pharmaceutical manufacturing industry. In terms of spatial effects, these zones also created a spillover effect that enhanced the industry's development in neighbouring regions. Zeng et al. (2024a) revealed that establishing FTZs with partner countries had boosted China's agricultural trade.

Unlike most studies that assess freeport performance through regional, urban, or enterprise-level indices, often focusing on a single aspect, only a limited number of papers have integrated multiple performance indexes for evaluating the overall impact of freeports or their equivalents. Huang et al. (2020) evaluated the service quality of the Free Trade Port Zone (FTPZ) based on 16 customer requirements and 16 service provider requirements, identified through a literature review and expert interviews. Deng et al. (2017) investigated the determinants of investment in Free Trade Port Areas (FTPAs) in China from an enterprise perspective, using 13 indicators across four categories. Chen et al. (2018) developed a multi-dimensional evaluation system with 23 indicators across five categories to assess the development performance of China's FTPZs, using quantitative data from statistics and qualitative data from expert scoring. Although providing valuable insights, these studies primarily focused on economic indicators and overlooked sustainability. Moreover, they did not adequately address uncertainty and incomplete data in expert judgment. For example, experts may rate unfamiliar indicators based on limited or incorrect understanding, introducing biases, as they cannot express uncertainty. This limitation can reduce data quality and undermine the reliability of the research outcomes.

Additionally, most existing studies develop the assessment index applicable to a single country, offering limited insights from a global perspective. Only a few studies have demonstrated the use of the developed framework as a benchmark for comparing cross-country freeport practice. For instance, Arbolino et al. (2023) evaluated the economic effects of 51 European incentive zones using a propensity score matching method. The developed policy assessment framework included 14 indicators across six macro areas but relied solely on quantitative indicators. Wang and Zeng (2022) introduced the PMC index model and constructed a national park policy evaluation index system to analyse 14 representative national park policies in the Hainan rainforest, Hong Kong, and Singapore, employing only qualitative indicators.

In summary, while the literature underscores the multifaceted role of freeports in fostering economic and technological progress, a notable gap remains in aligning these impacts with broader sustainability objectives. Existing studies on freeport impact evaluation are largely fragmented, focusing primarily on isolated indicators while overlooking their overall sustainability effects. Moreover, current methodologies exhibit limitations, such as insufficient integration of quantitative and qualitative indicators, as well as inadequate handling of uncertainty and incomplete data in expert judgment. Geographically, most studies have predominantly focused on freeports in China, highlighting the need for broader evidence from other economies to provide a more holistic understanding.

2.2. Sustainability assessment frameworks and indices

Given the notable absence of freeport sustainability assessments in the current literature, this study extends the scope of the review to encompass sustainability evaluations within the broader context of ports and port cities to gain a comprehensive understanding of the potential KPIs influencing freeport sustainability from multiple dimensions, as well as the commonly used decision-support methods. This approach recognises the interconnected roles of freeports, ports, and port cities in supporting international trade, optimising logistics operations, and promoting economic development.

In the past decade, there has been a noticeable increase in research dedicated to sustainability evaluation within the context of ports and port cities, leading to the establishment of various frameworks and standards. Most studies have focused on the environmental dimension of sustainability, emphasising the crucial role of economic development in line with environmental protection. Some global environmental standards already exist. For instance, there are three certifications for improving environmental performance in ports: ISO 14001, Green Ports, and Ecoports (Asgari et al., 2015). ISO 14001 provides general management standards to reduce pollution across systems. Green Ports focuses on balancing environmental protection with economic benefits, while Ecoports integrates environmental and port management, mainly in Europe. By adhering to these certifications, ports can improve their environmental performance by monitoring issues such as air and water pollution, noise pollution, energy consumption, efficient resource utilisation, waste management, and the adoption of clean technologies. In addition, two universities (Yale/New Haven and Columbia/New York) undertook a research project known as the Environmental Performance Index (EPI) aiming at establishing an international composite environment index, which has been commissioned by the World Economic Forum/Davos. The latest edition of the EPI contains a total of 58 indicators distributed across 11 environmental issue categories and structured around three key policy objectives: climate change, ecosystem vitality, and environmental health (EPI, 2024).

The distinction between sustainability and the concept of "green" is notable. Sustainability encompasses a broader spectrum of concerns, including economic, environmental, and social aspects, whereas the concept of "green" focuses solely on the exploitation of the environment (Lu et al., 2016). In other words, the "green" does not encompass the prosperity or well-being of a society (Zervas, 2012). However, compared to studies focusing on environmental sustainability, fewer studies have evaluated the balance among economic, environmental, and social aspects of sustainability. Among those studies that did consider additional sustainability aspects beyond the economic and environmental aspects in ports and port cities, the hierarchical framework in the GRI has been mostly used (Cavallo et al., 2015; Liu et al., 2021a; MacNeil et al., 2021; Majidi et al., 2021; Oh et al., 2018; Roh et al., 2021; Schipper et al., 2017; Shiau and Chuang, 2015; Stanković et al., 2021). 78% of the world's top 250 companies – known as the G250 companies have adopted the GRI Standards for sustainability reporting (GRI, 2022). The GRI uses a Triple Bottom Line method to build an index system from social, economic, and environmental dimensions. The Triple Bottom Line approach evaluates the business performance by taking into account not only the traditional bottom line of financial performance, such as net income, but also two additional bottom lines. These additional bottom lines are evaluated based on the impact of a company's social responsibility and its environmental stewardship efforts (Roh et al., 2021). There are also other sustainability frameworks, such as the Driving Force-State-Response and Pressure-State-Response frameworks (Dai et al., 2013), the Global Synthetic Index (Laxe et al., 2017), Capital frameworks, the System of Integrated Environmental and Economic Accounting framework, and Systems Analytical framework, whereas they expose various practical limitations comparing with the GRI framework concluded by Lam and Yap (2019). The GRI hierarchical framework enables the comparison of the three sustainability dimensions on their importance. It takes advantage of flexible indicator sets and clear indicator categories, which helps prevent ambiguity and overlap among different indicator categories. Consequently, the study utilises the GRI hierarchical framework to identify specific KPIs for freeport assessment.

It is a challenging task to identify indicators aligned with sustainability goals, and this complexity increases when assessments must consider multiple dimensions and be aggregated into a single value (Kuik and Verbruggen, 2012). The criteria used for selecting indicators encompass aspects such as significance, policy relevance, measurability, and representativeness (Shiau and Chuang, 2015). Chamaret et al. (2007) outlined two primary indicator selection approaches: the top-down and bottom-up methods. In the top-down approach, indicators are initially identified through a literature review, including publications, reports, and standards. These are then refined to establish a mutually agreed-upon set of indicators. Conversely, the bottom-up approach entails compiling the final set of indicators by gathering proposals from sector stakeholders, considering their perceptions of issues and their significance. However, this study cannot rely solely on a single method due to specific considerations. In the top-down approach, the existing literature on the performance evaluation of freeports predominantly focuses on the economic dimension, offering little reference for environmental and social dimensions. Conversely, the bottom-up approach, as observed in practices in the UK and China, primarily utilises quantitative indicators that can be assessed through objective numerical data. Therefore, this study integrates both approaches to develop a comprehensive and balanced KPI framework for assessing freeport sustainability.

2.3. Decision-support methods for sustainability assessment

2.3.1. Methods employed in ports and port cities' sustainability assessment

Several decision-making techniques have been applied in previous studies concerning sustainability evaluation in the context of ports and port cities. Fig. 1 illustrates the distribution of papers using different methods. The most popular methods are the Analytic Hierarchy Process (AHP), Data Envelopment Analysis (DEA), Importance-Performance Analysis (IPA), PROMETHEE, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Other established methods include the Slack-Based Measure (SBM), Decision Making Trial and Evaluation Laboratory (DEMATEL), Structural Equation Modelling (SEM), Social Construction of Technology (SCOT), and Gray Relational Analysis (GRA). The strengths and weaknesses of the commonly used methods are summarised, and the relevant references in port and port city sustainability evaluation are given in Table 1.

Although the literature offers valuable insights into KPI selection for sustainability evaluation, the methods used in these studies have inherent limitations, particularly concerning index weighting, data collection, and the integration of indices in various forms.

(1) Index weighting. Methods like PROMETHEE and TOPSIS often struggle with assigning appropriate weights (Stanković et al., 2021; Majidi et al., 2021), leading to oversimplified or biased evaluations.
(2) Data quality and collection. Methods such as AHP, DEA, SBM, and DEMATEL rely on precise, complete, and consistent data, making them impractical for cases with incomplete or uncertain data. Additionally, methods like AHP or DEMATEL become cumbersome as the number of KPIs increases (Hsu et al., 2023; Kong and Liu, 2021).
(3) Integration of multiple indices. Simpler methods like IPA fail to handle multiple criteria effectively, and methods such as TOPSIS and PROMETHEE are often restricted to aggregating indices of similar types or formats, making it difficult to integrate quantitative and qualitative data (Pandey et al., 2023; Wu et al., 2020).

Given these constraints, this study will contribute by developing an innovative method for evaluating sustainability performance that effectively overcomes these limitations. From the applied research perspective, it also stands as one of the pioneering efforts in assessing freeport sustainability.

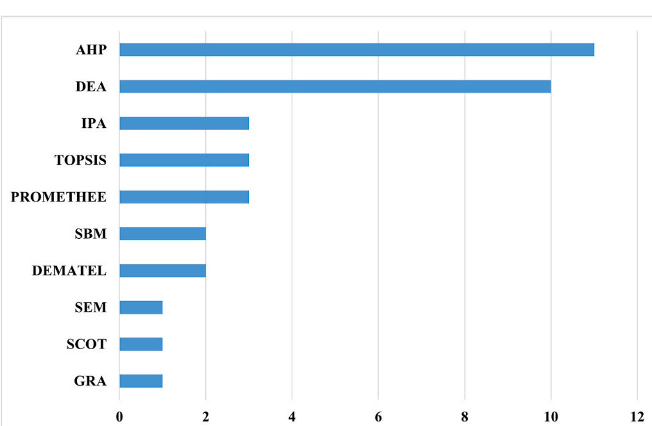

Fig. 1. Methods for sustainability performance analysis.

Table 1
Strengths and weaknesses of the commonly used methods.

Methods	Strengths	Weaknesses	References
AHP	Priorities multiple criteria.	Sensitive to inconsistent data; time-consuming and complex to collect data.	Asgari et al. (2015); Cavallo et al. (2015); Chiu et al. (2014); Dai et al. (2013); Garg et al. (2022); Hsu et al. (2023); Jeevan et al. (2022); Kovačič Lukman et al. (2022); Lirn et al. (2013); Pourebrahim and Mokhtar (2016); Roh et al. (2021)
DEA	Considers multiple inputs and outputs.	Requires complete and accurate data.	Castellano et al. (2020); Cheon et al. (2017); Dong et al. (2019); Jiang et al. (2020); Kong and Liu (2021); Li et al. (2018b); Lin et al. (2019); Liu et al. (2021a); Puig et al. (2017); Quintano et al. (2021)
IPA	Easy to understand and implement.	Not capable of analysing multiple criteria.	Hua et al. (2020); Lirn et al. (2013); Oh et al. (2018)
PROMETHEE	Does not require the assumption that criteria are proportionate.	Difficult to weigh; difficult to aggregate indices of different types.	Argyriou et al. (2022); Cerreta et al. (2020); Stanković et al. (2021)
TOPSIS	Easy to understand and implement.	Difficult to weigh; difficult to aggregate indices of different types.	Li et al. (2018a); Majidi et al. (2021); Pourebrahim and Mokhtar (2016)
SBM	Incorporates desirable and undesirable outputs.	Requires precise and reliable data; sensitive to outliers and extreme values.	Dong et al. (2019); Kong and Liu (2021)
DEMATEL	Reflects causal structure among multiple criteria.	Time-consuming and complex to collect data.	Hsu et al. (2023); Liu et al. (2021a)

2.3.2. Review of the application of BN and ER

The ER approach is developed based on the Dempster-Shafer theory of evidence (D-S theory), which was initially generated by (Dempster, 1967) and further developed by (Shafer, 1976). It offers a novel method for aggregating multiple criteria using the distributed assessment framework and the evidence combination rule of the D-S theory (Yang, 2001). Unlike most conventional multiple-criteria decision-making techniques, it utilises a belief degree structure to assess an attribute based on a set of mutually exclusive assessment grades (Pathak et al., 2021). The belief function enables the measurement of an attribute with uncertainties such as ignorance, fuzziness, and incomplete information. Moreover, the ER approach can effectively model both precise data and subjective judgments with uncertainties under the unified framework.

Due to its numerous advantages, the ER approach has been successfully applied in security and risk assessment in marine engineering (Liu et al., 2008; Ren et al., 2008; Sii et al., 2004), port and maritime supply chains (Ha et al., 2017; Jiang et al., 2023; Poo et al., 2021; Wan et al., 2018; Yang et al., 2009). Although there have been a few attempts to incorporate the ER approach in sustainability performance assessment, such as in engine production lines (Zhou et al., 2017), maritime tourism (Gao, 2019), freight transportation systems (Fulzele and Shankar, 2023; Pathak et al., 2021), assurance services for sustainability reporting (Srivastava et al., 2013), and supply chains (Wan et al., 2021), only one was in alignment with the GRI (Srivastava et al., 2013). Additionally, the advantages of the ER algorithm have not been thoroughly substantiated in empirical studies. To date, only Wan et al. (2021) employed both qualitative and quantitative indicators within a unified framework. Therefore, this study stands as one of the pioneering works in sustainability assessment, showcasing a comprehensive application of the ER approach by integrating objective and subjective data with uncertainties.

While the advantages mentioned above are notable, the ER approach falls short in assessing KPIs influenced by factors that exist beyond the confines of an independent hierarchical structure and operate within an interconnected network framework. This limitation could compromise the comprehensiveness of the selected KPIs from a sustainability perspective, thereby diminishing the benchmark value of the sustainability assessment results. To overcome this limitation, this study proposes a novel solution to handling KPIs influenced by network-based factors by incorporating BN into ER.

BN theory was introduced by Pearl (1988). It utilises a probabilistic graphical model to analyse the significance of variables and their interrelationships, allowing for system uncertainty (Jones et al., 2010; Yang et al., 2021). Of all the risk assessment methods, BN has generated growing attention due to its enhanced capabilities in learning and inferencing, particularly in data tolerance and bi-directional risk diagnosis and predictive analysis (Fan et al., 2022; Li et al., 2023a). These characteristics position BN as a fitting solution to addressing the limitation of ER in dealing with interdependent variables. Existing studies that integrate both BN and ER are limited, focusing primarily on the field of risk analysis (Chang et al., 2021; Wang et al., 2023b; Yang et al., 2019; Zhou et al., 2023), requiring more empirical evidence from a wider range of applications across different sectors. Moreover, these studies fail to demonstrate the significance of BN in overcoming the limitations of ER in combining results from interdependent attributes.

2.4. Research gaps

Several key research gaps are identified based on the detailed literature review, summarised as follows.

(1) Lack of comprehensive freeport sustainability assessment.

Existing studies on freeport impacts at macro or micro levels primarily focus on individual indicators, neglecting their combined sustainability effects. This gap underscores the need for a comprehensive, multi-dimensional sustainability assessment framework for freeports.

(2) Geographical limitations.

Most studies are geographically restricted, with limited exploration of freeports across diverse global regions. Broader research could help develop an adaptable framework for benchmarking freeport practices internationally.

(3) Integration of quantitative and qualitative KPIs and data uncertainty management.

Few studies effectively integrate quantitative and qualitative KPIs into a unified assessment framework. Current approaches often fail to address the challenges of synthesising diverse data types or managing issues such as uncertainty and incomplete data in KPI performance assessments.

(4) Integration of independent and interdependent variables.

While the ER method has been proposed as an innovative approach, its benefits remain underexplored in empirical studies on sustainability assessment. Moreover, insufficient research has been conducted on integrating complementary methodologies to address ER's limitations, particularly in handling interdependent variables.

To address these gaps, this study extends the application of the ER approach by incorporating quantitative and qualitative indicators into a unified framework, particularly guided by the GRI. To overcome a key limitation of ER in managing interdependencies among variables, BN is employed as an enhancement. Unlike prior research, which has primarily focused on risk analysis, this study leverages BN to enhance ER in multi-dimensional sustainability assessment. This hybrid model is applied to assess sustainability in the context of a freeport, illustrated through a case study in the UK.

3. Methodology

3.1. The proposed framework

Fig. 2 illustrates the proposed framework in this study, highlighting its novel aspects. This study develops a three-tier KPI index in alignment with the GRI sustainability framework and identifies specific KPIs influencing freeport sustainability by combining literature review and real case analysis. In addition, the identified KPIs are purified through expert interviews in terms of their relevance and comprehensiveness in evaluating freeport sustainability. The importance of KPIs is evaluated using a global online survey involving multiple freeport stakeholders, providing relative weightings for the KPIs. Using a BNER model, the performance data of a freeport for KPIs with hierarchical or network characteristics are appropriately obtained and assessed according to their respective assessment grades. Furthermore, the performance results of top-level KPIs are derived by aggregating the assessments of bottom-level KPIs. Finally, the developed model is validated through

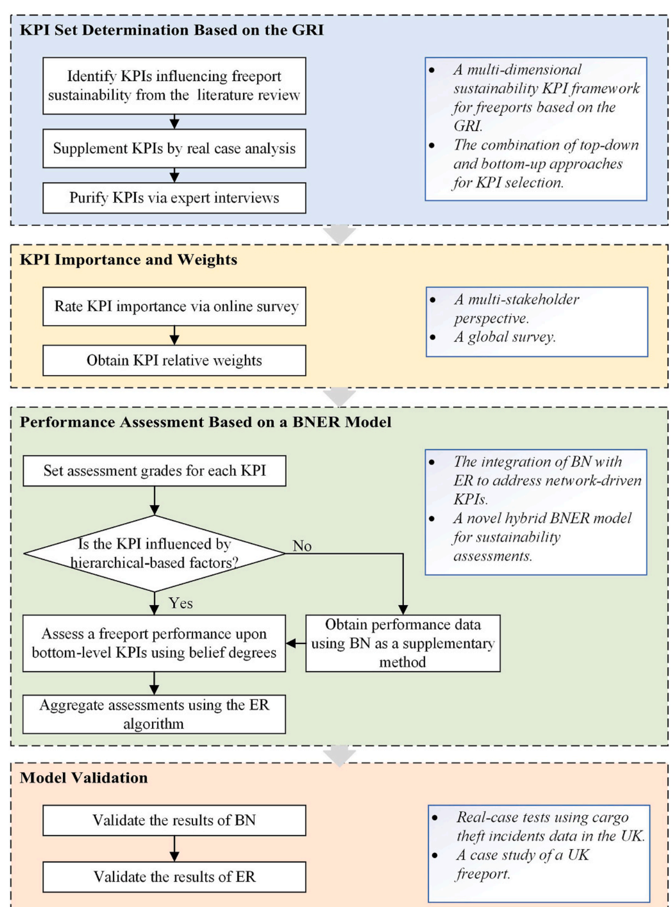

Fig. 2. The proposed framework.

various methods using real-case data, ensuring its reliability and applicability.

3.2. KPI identification and purification

As mentioned in the literature review section, this study integrates both top-down and bottom-up approaches to establish a holistic framework combining quantitative and qualitative KPIs from multiple dimensions for evaluating freeport sustainability. In other words, it utilises both literature and case studies to gather a more comprehensive array of indicators. Additionally, the identified KPIs from the aforementioned procedure undergo a refinement process guided by expert knowledge.

Given the absence of freeport sustainability assessments in the current literature, the literature review has been broadened to include sustainability assessments in the context of ports and port cities, as they share similar roles with freeports. The procedure for literature selection includes three steps as shown in Fig. 3.

Step 1. Online search. This study specifically selects peer-reviewed articles published in academic journals, as in other related review-type literature (Lim et al., 2019; Yang et al., 2020). The database Web of Science (WoS) Core Collection is used, with the key terms displayed in Fig. 3 used for the search. Additionally, the inclusion and exclusion criteria shown in Table 2 are employed for the initial online search, resulting in 713 articles.

Step 2. Given that not all results automatically retrieved in Step 1 are pertinent to the key terms used, the 713 papers are further filtered through a manual screening of titles and abstracts based on the relevance of the research topic, resulting in 78 papers with significant relevance. These 78 papers contain valuable information for this study, including state-of-the-art research on port and port city sustainability, empirical studies on the sustainability performance of worldwide ports and port cities, and decision-support methods of sustainability assessment.

Step 3. Sample reduction based on the research depth. A thorough full-text review of the 78 papers is undertaken to identify papers that establish comprehensive and practical sustainability KPI frameworks. As a result, 30 papers are excluded from further analysis due to a lack of references to the significance of KPIs and/or their applicability. Thus, 48 papers are ultimately used for a comprehensive review of established frameworks, applied decision-making methods, and KPIs for sustainability assessment. This reduction rate of 93% is comparable to findings in other systematic review papers, showcasing that significant reduction rates are common in systematic reviews on similar topics. For example, Lim et al. (2019) selected 21 papers from 704 (a 97% reduction rate) for a systematic review of port sustainability and performance. Zheng et al. (2020) reviewed 61 out of 514 articles (an 88% reduction rate) to analyse research trends on the sustainability of port cities.

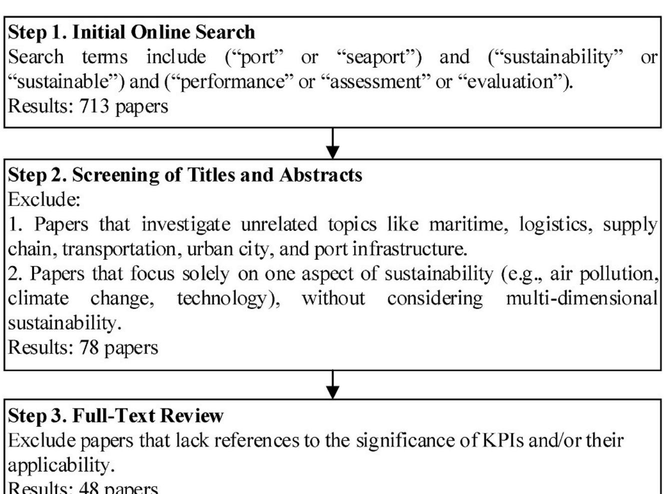

Fig. 3. The procedure for literature selection.

Table 2
Inclusion and exclusion criteria for the online search.

	Inclusion criteria	Exclusion criteria
WoS Index	SCI, SSCI	Other Indices
Language	English	Non-English
Doc type	Journal article, review article, early access	Proceedings paper, data paper, book chapters

3.3. KPI importance and weights from multiple stakeholder perspectives

Following the refinement of the KPI framework, the importance of KPIs is evaluated by experts using the Linkert Scale method through a global survey. Compared to other commonly used methods in criteria evaluation, as mentioned in section 2.3.1 (e.g., AHP, DEMATEL, and PROMETHEE), the Linkert scale shows its competitive advantage as it is easy to understand and implement, particularly valuable in scenarios involving numerous KPIs and limited availability of professionals. Researchers often use 5, 7, or 10-point scales to obtain importance ratings, ranging from "not important at all" to "extremely important" or "very important" (Fontenot et al., 2007). This study uses a 7-point scale (1 means "not important at all", 7 indicates"extremely important"). Subsequently, the relative weights of the KPIs are determined by normalising the importance ratings.

The sustainability assessment requires effective approaches to enhance its legitimacy and relevance. It should engage early with assessment users, incorporating public perspectives while providing active leadership (Sala et al., 2015). Stakeholders' engagement is a specific requirement of sustainability assessment. However, previous studies on sustainability assessment within the context of ports, port cities, and freeports show limitations in analysing multiple stakeholders' perspectives, especially in terms of the engagement of service users and public residents. Participants of this survey involve multiple freeport stakeholders, including researchers (who have related studies on freeports), policymakers, practitioners (who are experts directly involved in the day-to-day operations and management of freeports), service users (who make use of the infrastructure, incentives, and trade facilitation services offered by freeports, e.g., businesses, traders, importers, exporters, and manufacturers), and public residents.

3.4. Performance assessment upon bottom-level KPIs

3.4.1. Assessment of KPIs with independent influential factors

This study uses five exclusive assessment grades uniformly for the assessment of all KPIs across all levels. This approach eliminates the necessity for establishing complex transformation rules and fosters improved communication between academia and industry by providing a clear and transparent aggregation process (Poo et al., 2021).

According to the methodology framework depicted in Fig. 2, prior to evaluating the performance of a freeport using individual bottom-level KPIs, it is imperative to determine the structure of influential factors relevant to each respective KPI. If the influential factors of a specific KPI are independent in a hierarchical structure, direct assessment of this KPI becomes feasible using the ER algorithm. In this case, the freeport performance data could be obtained from direct statistics for quantitative KPIs, and expert judgements for qualitative KPIs. Conversely, if the influential factors of a particular KPI are interdependent within a network structure, supplementary methods such as BN must be employed to acquire the essential performance data for this KPI in freeports.

3.4.2. Assessment of KPIs with interdependent influential factors

In this study, a data-driven BN method is employed for handling KPIs influenced by interdependent factors in a network structure. This study develops a BN model through the steps including BN structure learning, Conditional Probability Tables (CPTs) learning, and model validation. The structure of the BN can be developed through either subjective methods, objective methods, or a combination of both. In this research, we adopt an objective approach to design the BN structure, leveraging the Tree Augmented Naive Bayes (TAN) algorithm. TAN amends the naive Bayes' independence assumption but maintains its straightforward computation and stability (Friedman et al., 1997). By considering the interrelationships among multiple influential factors, it effectively overcomes the limitation of ER in handling network-driven factors. For more detailed technical descriptions, one can refer to Fan et al. (2022), Li et al. (2024b), and Yang et al. (2018).

3.5. Performance aggregation using the ER algorithm

After obtaining assessments of all bottom-level KPIs, the ER algorithm is employed to aggregate assessments of multiple KPIs. The current widely used ER algorithm for evidence aggregation is presented by Yang and Xu (2002) and applied in many studies (Akhoundi and Nazif, 2018; Poo et al., 2021; Zhang et al., 2020). This study employs it in the freeport context for the first time. The ER approach can be implemented for the sustainability assessment of freeports as follows, for instance, to aggregate all assessments related to a level-2 KPI 'service quality'.

$$R = \{R_k, k = 1, \dots, L\} \tag{1}$$

Equation (1) represents a set of level-3 KPIs influencing the assessment of service quality, then $L = 4$ in this case.

$$G = \{G_j, j = 1, \dots, N\} \tag{2}$$

The set of assessment grades for each KPI can be represented as Equation (2), where G_j is the jth assessment grade, $j+1$ is preferred to j, and $N = 5$ in this study.

$$\beta_{j,k} \geq 0 \text{ and } \sum_{j=1}^{N} \beta_{j,k} \ll 1 \tag{3}$$

$$\theta_k \geq 0 \text{ and } \sum_{k=1}^{L} \theta_k = 1 \tag{4}$$

In Equations (3) and (4), $\beta_{j,k}$ represents the belief degree for the jth assessment grade of R_k, and θ_k is the normalised weight of R_k.

$$m_{j,k} = \theta_k \beta_{j,k} \tag{5}$$

$$M_k = \overline{M}_k + \widetilde{M}_k \tag{6}$$

$$\overline{M}_k = 1 - \theta_k \tag{7}$$

$$\widetilde{M}_k = \theta_k \left(1 - \sum_{j=1}^{N} \beta_{j,k} \right) \tag{8}$$

The belief degree is transformed into basic probability masses as outlined in Equations (5)–(8). $m_{j,k}$ signifies the probability mass associated with R_k when evaluated at grade G_j. The residual probability mass, M_k, unallocated to any individual grade, is divided into $\overline{M}_k$ and $\widetilde{M}_k$. Here $\overline{M}_k$ represents the extent to which other KPIs may influence the assessment, and $\widetilde{M}_k$ arises from the incompleteness of the belief degree assessment.

$$\{G_j\} m_{j,I(k+1)} = K_{I(k+1)} \left[m_{j,I(k)} m_{j,k+1} + m_{j,k+1} M_{I(k)} + m_{j,I(k)} M_{k+1} \right], \ k = 1, \dots, L-1 \tag{9}$$

$$\{G\} : M_{I(k+1)} = \overline{M}_{I(k+1)} + \widetilde{M}_{I(k+1)} \tag{10}$$

$$\{G\} : \overline{M}_{I(k+1)} = K_{I(k+1)} \left[\overline{M}_{I(k)} \overline{M}_{k+1} \right] \tag{11}$$

$$\{G\} : \widetilde{M}_{I(k+1)} = K_{I(k+1)} \left[\widetilde{M}_{I(k)} \widetilde{M}_{k+1} + \widetilde{M}_{I(k)} \overline{M}_{k+1} + \overline{M}_{I(k)} \widetilde{M}_{k+1} \right] \tag{12}$$

$$K_{I(k+1)} = \left[1 - \sum_{j=1}^{N} \sum_{t=1 \neq j}^{N} m_{j,I(k)} m_{t,k+1} \right]^{-1}, \ k = 1, \dots, L-1 \tag{13}$$

Next, it is ready to aggregate assessments of the four level-3 KPIs. Equation (9) represents the combined probability masses by aggregating the output from R_k and R_{k+1}. Equations (10)–(12) represent the combined remaining belief degree unassigned to any individual grade. Note that $m_{j,I(1)} = m_{j,1}$, $\widetilde{M}_{I(1)} = \widetilde{M}_1$, $\overline{M}_{I(1)} = \overline{M}_1$, and $M_{I(1)} = M_1$.

After aggregating the four assessments, the cumulative belief degree is calculated as follows. β_j represents the aggregated belief degree allocated to the jth assessment grade of service quality, while β_H stands for the residual belief degree unallocated to any individual grade of service quality.

$$\{G_j\} : \beta_j = \frac{m_{j,I(L)}}{1 - \overline{M}_{I(L)}}, \ j = 1, \dots, N \tag{14}$$

$$\{G\} : \beta_H = \frac{\widetilde{M}_{I(L)}}{1 - \overline{M}_{I(L)}} \tag{15}$$

The overall sustainability performance of a freeport can be obtained by repeating the above ER algorithm to aggregate assessments of other KPIs in the proposed index system from the bottom level to the top level. The aggregation process is conducted through the Intelligent Decision System, an ER-based software, developed by Xu and Yang (2005).

Furthermore, the theory of expected utility (Yang, 2001) is used to obtain a numerical performance score in a crisp value for each KPI, which makes it easy to compare results in different scenarios.

3.6. Validation methods

The validation of the hybrid model comprises two distinct phases. First, real cases are used to evaluate the constructed BN model by comparing predicted outcomes with the actual results observed in these cases, and the model's consistency is verified using the kappa statistic (Cohen, 1960). Subsequently, to validate the consistency of the results of ER, a sensitivity analysis is performed to examine the impact of minor input changes on the corresponding outputs. For the methodology to be deemed robust with logical inference reasoning, the sensitivity analysis should meet at least the following two axioms (Li et al., 2024a; Yang et al., 2009).

- Axiom 1. A minor increase or decrease in the belief degrees related to the linguistic variables of the bottom-level KPIs will inevitably lead to a corresponding rise or fall in the belief degree of the linguistic variables and the values of the freeport sustainability indexes.
- Axiom 2. For the same change in belief degree distributions of the bottom-level KPIs, the impact on the values of freeport sustainability indexes will remain consistent with their weight distributions.

4. Case studies and analysis

4.1. KPIs for the sustainability assessment of freeports

This study identified KPIs for assessing freeport sustainability based on a combination of top-down and bottom-up approaches. First, 40 KPIs were chosen from the literature review based on the top-down approach, while eight additional KPIs were selected from the real case of UK freeports based on the bottom-up approach. This created an index with 48 level-3 KPIs, 13 level-2 KPIs, and three top-level KPIs. Next, three experts were interviewed independently to verify the relevance and comprehensiveness of the KPIs selected from the first round. The three interviewees comprise a UK Freeport director boasting three decades of industry expertise in both strategy and execution in the UK and Morocco, along with two distinguished professors who have authored extensively cited articles in top-tier journals pertinent to the subject matter focusing on freeports in the UK and China, respectively. As a result, three new KPIs were created based on expert opinions, as depicted in Table 3. Nine level-3 KPIs were considered to have no direct influence on freeport development goals nor are they impacted by the freeport construction. Thus, they were assigned zero weight in this case analysis and are not included in Table 3. These nine KPIs include four economic KPIs (port infrastructure capacity, labour productivity, electricity cost, and fuel cost), three environmental KPIs (electricity consumption, fuel consumption, and contingency plans for pollution accidents), and two social KPIs (employment of collective bargaining agreements, and employee retention rates). A level-2 KPI (productivity and cost efficiency) was eliminated along with its three sub-KPIs (labour productivity, electricity cost, and fuel cost).

These KPIs were excluded mainly due to their lack of relevance to the freeport context. For instance, while port infrastructure capacity is a critical factor in traditional port operations, it is not directly applicable to assessing freeport sustainability. Freeports encompass a broader scope that extends beyond port operations alone. KPIs related to labour productivity, electricity consumption, fuel consumption, and their associated costs are influenced by national or regional energy policies and market conditions, beyond the control of any individual freeport. Conversely, KPIs such as employment of collective bargaining agreements and employee retention rates were excluded as they pertain to individual businesses within the freeport rather than the freeport as a whole. Furthermore, such data is unlikely to be disclosed due to its commercial sensitivity. Eventually, the purified index consists of 42 level-3 KPIs, 12 level-2 KPIs, and three level-1 KPIs, as presented in Table 3. The 42 level-3 KPIs include 22 quantitative ones and 20 qualitative ones, while all level-1 and level-2 KPIs are qualitative. Please see Appendix A for descriptions of these KPIs.

4.2. KPI importance and weights from multiple stakeholder perspectives

4.2.1. Survey

Subjective data was collected for rating the importance of KPIs using the Jisc online survey platform. The survey of this research consisted of two main parts. The first part aimed to gather information about the experience and background of participants. The second part aimed to evaluate the relative importance of KPIs using the 7-point Linkert scale.

Recognising the scarcity of professionals within the freeport industry, deliberate efforts were made to engage a diverse array of stakeholders from around the world. The survey was distributed from July to November 2022 both individually (via phone calls, emails, LinkedIn, etc.) and publicly, such as at the Mersey Maritime face-to-face networking session (LBN, 2022). Ultimately, 21 completed responses were received, of which, four were unsuitable due to the respondents' knowledge primarily focusing on other sectors within the maritime industry, such as naval architecture and maritime transportation rather than freeport. The collective experience and knowledge of the remaining 17 participants contributed to a comprehensive global perspective, encompassing 10 countries: the UK, China, Morocco, Germany, Russia, Dubai, Ghana, Canada, Brazil, and Iran (see Appendix B). Among them, three freeport researchers are professors recognised by their publications on freeports, indexed in the WoS Core Collection, with expertise representing freeports in Russia, Taiwan, and Brazil. Additionally, each of the policymakers and practitioners has 10 to 30 years of experience in this field. The three service users represent key stakeholders from a port, a shipping company, and a forwarding company, respectively.

4.2.2. KPI importance

Given the importance ratings (1–7) assigned to each level-3 KPI by all 17 respondents, the Arithmetic Mean (AM) and Standard Deviation (SD) values were calculated. Subsequently, the importance score of an upper-level KPI was obtained by the average of its child KPIs, as presented in Table 4. The results of Table 4 reveal the most significant KPIs on each level of the framework. This procedure was then replicated using data from each of the five stakeholder types, allowing for the comparison of different scenarios when determining KPI weights using different stakeholder perspectives.

Among level-3 KPIs, the most significant ones are information technology and efficiency of customs clearance, both scoring 6.12. There are 13 KPIs ranked top 10, of which 12 are under the economic dimension, one belongs to the environmental dimension (environmental protection policy), and none falls within the social dimension. Under the social dimension, the most important KPIs are the number of new jobs due to the freeport development, employment in high-tech and knowledge-oriented sectors, and the number of skill training, all ranking at 17th place. At the 2nd level of the framework, service quality is the most important KPI with a score of 5.74, followed by freeport size (5.66) and freeport infrastructure (5.60). Among the three level-1 dimensions, the economic dimension has the highest importance score at 5.45, followed by the environmental dimension (5.08) and the social dimension (5.02).

4.2.3. KPI weights from multiple stakeholders' perspectives

Based on the importance ratings in Table 4 of section 4.2.2, KPI weights at each level were obtained through normalisation. This was performed from different stakeholder perspectives. Their global weights illustrate their influence on the overall framework and are presented in the following. For instance, Fig. 4 illustrates the global weight distribution of the 12 level-2 KPIs based on the combined stakeholder perspective. Each KPI's weight was calculated by dividing its rating by the total sum of the 12 ratings. Within the framework, service quality has the greatest weight (9.21%), followed by freeport size (9.09%) and freeport infrastructure (8.99%). Table 5 provides the outcomes corresponding to each stakeholder viewpoint.

Fig. 5 shows the weight distribution among three sustainability dimensions from each respective stakeholder perspective and the combined one. The results show that policymakers and practitioners have similar preferences, both prioritising the economic dimension, followed by the social and environmental dimensions. Whereas researchers and public residents prefer the environmental dimension first, followed by the economic and social dimensions. Service users uniquely exhibit the highest focus on the social dimension. In the combined scenario, the economic dimension has a higher weight than the environmental and social dimensions.

4.3. Performance assessment upon bottom-level KPIs: A UK freeport

4.3.1. Assessment of KPIs with independent influential factors

As explained in section 3.4, this study used five exclusive assessment grades uniformly for all KPIs across all levels. To be specific, five numerical grades (1 indicates "the worst", 5 is "the best") were used for all qualitative KPIs, and five assessment grades for quantitative KPIs were determined based on literature review and freeport inputs. For example, five assessment grades were assigned to KPI No. 10 (number of tax sites), with values {0, 1, 2, 3, 4}.

Out of the 42 bottom-level KPIs within the constructed framework, 41 are hierarchical-driven KPIs, including 21 quantitative KPIs and 20 qualitative ones. The remaining single KPI with a network structure is explained in Section 4.3.2. In the subsequent steps of this case study, a freeport in the UK was used anonymously. The freeport performance

Table 3
The KPI framework.

Level 1	Level 2	No.	Level 3	QT/ QL	References
Economic	Freeport size	1	Development area of freeport	QT	Chen et al. (2018); Huang et al. (2020); Liu et al. (2021a)
		2	Port cargo tonnage	QT	Li et al. (2018a); Liu et al. (2021b); Molavi et al. (2020); Pourebrahim and Mokhtar (2016)
		3	Port container throughput	QT	Li et al. (2018a); Liu et al. (2021b); Molavi et al. (2020); Papaefthimiou et al. (2017)
		4	Movement of rail freight in/out of the freeport	QT	Case study
		5	Movement of road freight in/out of the freeport	QT	Case study
	Freeport infrastructure	6	Number of new infrastructure projects	QT	Case study
		7	Information technology	QL	Chen et al. (2018); Garg et al. (2022); Hsu et al. (2023); Liu et al. (2021b)
		8	Facility availability	QL	Huang et al. (2020); Majidi et al. (2021)
		9	Number of customs sites	QT	Case study
		10	Number of tax sites	QT	Case study
		11	Tax policy	QL	Chen et al. (2018); Huang et al. (2020)
	Service quality	12	Cargo traffic congestion	QL	Expert interview
		13	The efficiency of customs clearance	QL	Chen et al. (2018); Hsu et al. (2023); Huang et al. (2020)
		14	Diversity of logistics services	QL	Chen et al. (2018); Hsu et al. (2023); Huang et al. (2020)
		15	Operational accuracy	QL	Expert interview
	Economic aggregate	16	GDP change rate	QT	Jugović et al. (2022); Liu et al. (2021a); Pourebrahim and Mokhtar (2016)
		17	GDP per capita	QT	Jugović et al. (2022); Liu et al. (2021a); Pourebrahim and Mokhtar (2016)
		18	Total import and export of foreign trade change rate	QT	Cerreta et al. (2020); Liu et al. (2021a)
		19	Foreign direct investment	QT	Kovačič Lukman et al. (2022); Shiau and Chuang (2015)
		20	Number of businesses operating at freeport development sites	QT	Case study
Environmental	Environmental pollution	21	Air pollution	QL	Burskyte et al. (2011); Garg et al. (2022); Jeevan et al. (2022); MacNeil et al. (2021); Papaefthimiou et al. (2017)
		22	Water pollution	QL	Garg et al. (2022); Jeevan et al. (2022); Jugović et al. (2022); Leal Junior et al. (2022)
		23	Noise pollution	QL	Castellano et al. (2020); Jeevan et al. (2022); Leal Junior et al. (2022); Peris-Mora et al. (2005)
		24	Soil pollution	QL	Jugović et al. (2022); Leal Junior et al. (2022); MacNeil et al. (2021); Peris-Mora et al. (2005)
	Waste management	25	Hazardous waste handling	QL	Chiu et al. (2014); Hua et al. (2020); Molavi et al. (2020)
		26	General waste management	QL	Castellano et al. (2020); Chiu et al. (2014); Garg et al. (2022); Jeevan et al. (2022); Kovačič Lukman et al. (2022)
		27	Centralised sewage treatment percentage	QT	Jeevan et al. (2022); Li et al. (2018a); Liu et al. (2021a)
	Energy and resource usage	28	Water consumption management	QL	Chiu et al. (2014); Leal Junior et al. (2022); Molavi et al. (2020)
		29	Clean energy sources	QL	Jeevan et al. (2022); Lirn et al. (2013); Shiau and Chuang (2015)
	Environmental protection	30	Environmental training	QL	Laxe et al. (2017); Lirn et al. (2013)
		31	Ecosystem and habitat protection	QL	Burskyte et al. (2011); Castellano et al. (2020); Dai et al. (2013); Lirn et al. (2013); Peris-Mora et al. (2005)
		32	Climate change adaptation and mitigation	QL	Burskyte et al. (2011); MacNeil et al. (2021)
		33	Environmental protection policy	QL	Expert interview
Social	Job generation	34	Number of new jobs due to the freeport development	QT	Jugović et al. (2022); Kovačič Lukman et al. (2022); Majidi et al. (2021)
		35	Employment in high-tech and knowledge-oriented sectors	QT	Cerreta et al. (2020); Pourebrahim and Mokhtar (2016); Stanković et al. (2021)
	Workforce development and diversity	36	Gender equality	QL	Laxe et al. (2017); Leal Junior et al. (2022); Stanković et al. (2021)
		37	Number and level of skills training	QT	Laxe et al. (2017); Roh et al. (2021)
		38	Participation in skills training	QT	Pourebrahim and Mokhtar (2016); Stanković et al. (2021)
	Safety and security	39	Fatal injuries	QT	Hua et al. (2020); Jugović et al. (2022); Leal Junior et al. (2022); Roh et al. (2021)
		40	Non-fatal injuries	QT	Hua et al. (2020); Jugović et al. (2022); Leal Junior et al. (2022); Roh et al. (2021)
		41	Cargo theft incidents	QT	Case study
	Innovation and collaboration	42	The number of projects between firms and research innovation organisations within the Freeport area	QT	Case study

*QL = qualitative, QT = quantitative.

Table 4
KPIs' importance ratings and rank.

Level 1	Level 2	No.	Level 3	AM (1–7)	SD	Rank
Economic dimension (5.45)	Freeport size (5.66)	1	Development area of freeport	5.59	1.66	10
		2	Port cargo tonnage	5.65	1.41	9
		3	Port container throughput	5.71	1.31	6
		4	Movement of rail freight in/out of the freeport	5.59	1.66	10
		5	Movement of road freight in/out of the freeport	5.76	1.68	5
	Freeport infrastructure (5.60)	6	Number of new infrastructure projects	5.59	1.06	10
		7	**Information technology**	**6.12**	1.36	**1**
		8	Facility availability	5.94	1.48	3
		9	Number of customs sites	5.12	1.83	25
		10	Number of tax sites	5.00	1.87	31
		11	Tax policy	5.82	1.74	4
	Service quality **(5.74)**	12	Cargo traffic congestion	5.71	1.53	6
		13	**The efficiency of customs clearance**	**6.12**	**1.32**	**1**
		14	Diversity of logistics services	5.71	1.49	6
		15	Operational accuracy	5.41	1.42	15
	Economic aggregate (4.84)	16	GDP change rate	4.18	1.70	42
		17	GDP per capita	4.41	1.87	40
		18	Total import and export of foreign trade change rate	5.12	1.65	25
		19	Foreign direct investment	5.00	1.70	31
		20	Number of businesses operating at freeport development sites	5.47	1.37	14
Environmental dimension (5.08)	Environmental pollution (5.10)	21	Air pollution	5.24	1.86	17
		22	Water pollution	5.24	1.86	17
		23	Noise pollution	4.82	1.91	37
		24	Soil pollution	5.12	1.80	25
	Waste management (5.20)	25	Hazardous waste handling	5.29	1.61	16
		26	General waste management	5.24	1.60	17
		27	Centralised sewage treatment	5.06	1.64	29
	Energy and resource usage (5.00)	28	Water consumption management	5.00	1.97	31
		29	Clean energy sources	5.00	1.90	31
	Environmental protection (5.01)	30	Environmental training	4.59	1.66	39
		31	Ecosystem and habitat protection	5.18	1.94	23
		32	Climate change adaptation and mitigation	4.71	2.17	38
		33	Environmental protection policy	5.59	1.33	10
Social dimension (5.02)	Job generation (5.24)	34	Number of new jobs due to the freeport development	5.24	1.82	17
		35	Employment in high-tech and knowledge-oriented sectors	5.24	1.30	17
	Workforce development and diversity (4.88)	36	Gender equality	4.29	1.96	41
		37	Number and level of skills training	5.24	1.35	17
		38	Participation in skills training	5.12	1.45	25
	Safety and security (5.04)	39	Fatal injuries	5.18	1.98	23
		40	Non-fatal injuries	5.06	2.08	29
		41	Cargo theft incidents	4.88	1.96	36
	Innovation and collaboration (4.94)	42	The number of projects between firms and research innovation organisations within the freeport area	4.94	1.82	35

data for individual quantitative KPIs was obtained from online statistics and freeport inputs, and the performance was assessed directly. For example, belief degrees {0%, 0%, 0%, 100%, 0%} were assigned to grades {0, 1, 2, 3, 4} if a freeport has three tax sites. To assess the freeport performance against individual qualitative KPIs, four senior managers at the investigated freeport were interviewed independently, each lasting about 30 minutes. During these interviews, each interviewee was asked to select one or multiple grades for each of the 20 qualitative KPIs based on the performance of the investigated freeport. As a result, the belief degree of each grade was obtained by the percentage of experts selecting that grade.

The interviewees were not required to select a grade if they felt uncertain about a specific KPI. This flexibility is due to the ER algorithm's capacity to incorporate belief degrees, even when uncertainties are present, to accurately reflect the real-world situation. For instance, belief degrees for KPI No. 30 (environmental training) were assigned as {0%, 0%, 50%, 25%, 0%}, with the remaining 25% representing the unknown category. In this study, the KPIs were identified from a wide range of references covering comprehensive aspects. As a result, some KPIs may be relatively new to domain experts.

4.3.2. *Assessment of KPIs with interdependent influential factors*

Within the constructed framework, one network-driven KPI associated with cargo theft incidents cannot be directly evaluated like the other KPIs. This is because online statistics and reports only contained detected and reported incidents, failing to capture all actual occurrences. Furthermore, this KPI is influenced by multiple interdependent factors within a network structure. Therefore, evaluating this KPI requires additional data collection for each influential factor and an analysis of their relationships. To address this challenge, we used a data-driven BN model to forecast the probability of cargo theft incidents in the investigated freeport region.

To be specific, this study used a collection of 9,316 historical incidents (including 8,386 for model construction and 930 for model validation) provided by the Transported Asset Protection Association (TAPA) to identify Risk Influencing Factors (RIFs) contributing to cargo

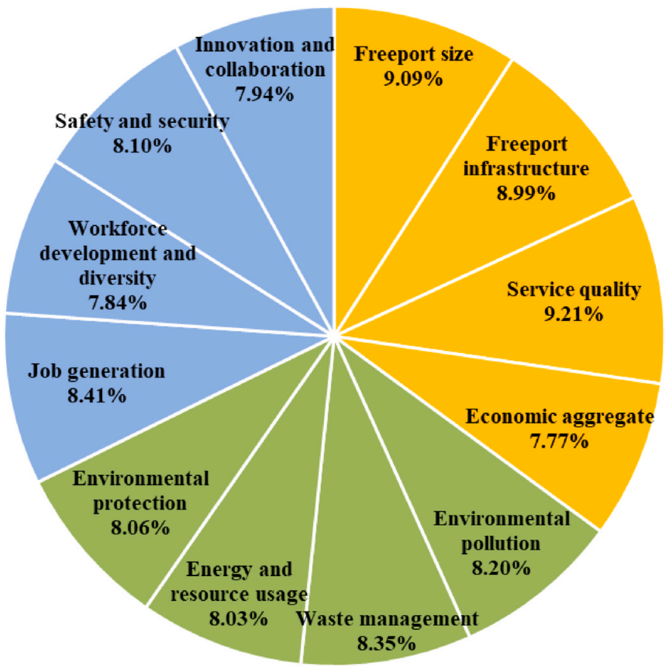

Fig. 4. Global weight distribution on Level-2 KPIs by combined stakeholders.

theft occurrences and to construct the BN structure. The identified RIFs from incident reports include "major incident", "attempt", "Modus Operandi (MO)", "location type", "product category", "weekday", "region", "month", and "year". Fig. 6 depicts the learned BN structure, containing 10 nodes, including the target node "incident type" and nine RIFs. This structure, including the CPT for each node, was generated using the TAN learning process (Chow and Liu, 1968) and implemented through the Netica software. Fig. 7 shows the prediction results of TAN. The details are documented in Liang et al. (2022).

Using this structure, the marginal probabilities of the relevant nodes were derived, enabling the prediction of cargo theft likelihood across various regions and transforming it into a vital input metric for ER. For instance, in Fig. 7, the probability value for the selected region was converted into belief degrees (0%, 0%, 54%, 46%, and 0%) across the five defined grades (0%, 5%, 10%, 15%, and 20%), resulting in a numerical performance score of 0.3850.

4.3.3. Presentation of assessment results

Due to commercial sensitivity, this case study presents a partial view of the bottom-level KPIs, omitting the display of their assessment results against the five respective grades. Following the assessment against each respective KPI, as detailed in Sections 4.3.1 and 4.3.2, a numerical performance score (ranging from 0 to 1) was obtained using the expected utility theory. The results of the investigated case are shown in Table 6.

KPI local weights indicate the relative importance of each KPI within its corresponding upper-level category. For example, KPIs Nos. 1–5 at level 3 are all the sub-level indicators under their parent level-2 KPI category of freeport size, with KPI No. 5 accounting for a weight of 20.37% among these five KPIs.

4.4. Performance aggregation using the ER algorithm: A UK Freeport

Finally, the performance aggregation was conducted using Equations (1)–(15) and implemented via the Intelligent Decision System software, based on six different weighting scenarios that assign weights by researchers, policymakers, practitioners, service users, public residents, and all combined, respectively. Table 7 presents the results of aggregated assessments for level-2 KPIs in the combined scenario (Scenario

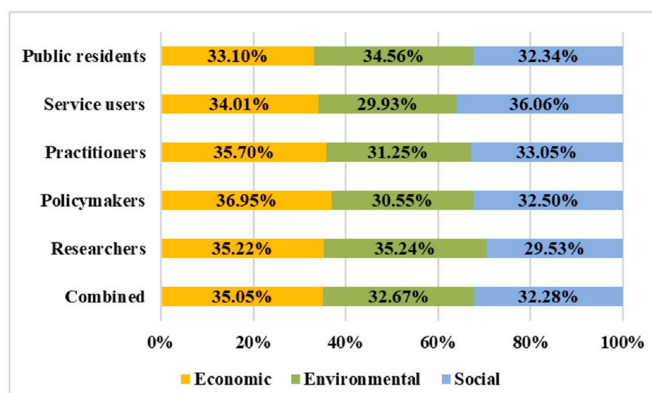

Fig. 5. Weight distribution on level-1 KPIs.

Table 5
Global weight distribution on Level-2 KPIs by different stakeholders.

	Researchers	Policymakers	Practitioners	Service users	Public residents
Freeport size	10.05%	9.23%	10.15%	6.83%	8.70%
Freeport infrastructure	8.47%	9.68%	8.11%	10.88%	8.36%
Service quality	10.14%	9.43%	9.20%	9.88%	7.93%
Economic aggregate	6.92%	8.73%	8.29%	6.35%	7.96%
Environmental pollution	9.33%	7.19%	7.72%	7.19%	9.13%
Waste management	9.55%	7.28%	8.32%	7.98%	8.48%
Energy and resource usage	7.84%	7.69%	8.46%	7.49%	8.30%
Environmental protection	8.24%	8.44%	7.09%	7.49%	8.39%
Job generation	7.84%	9.68%	9.52%	8.38%	7.93%
Workforce development and diversity	6.67%	7.94%	8.60%	8.58%	7.62%
Safety and security	7.93%	7.77%	7.33%	9.98%	8.36%
Innovation and collaboration	7.03%	6.95%	7.19%	8.98%	8.85%

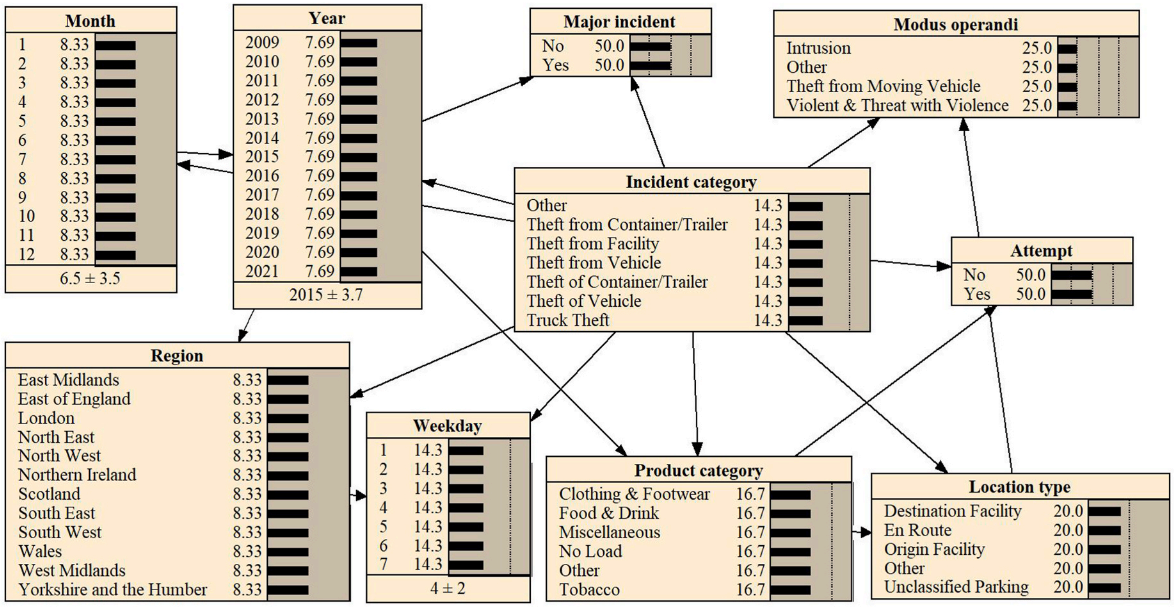

Fig. 6. The structure of BN learned through TAN.

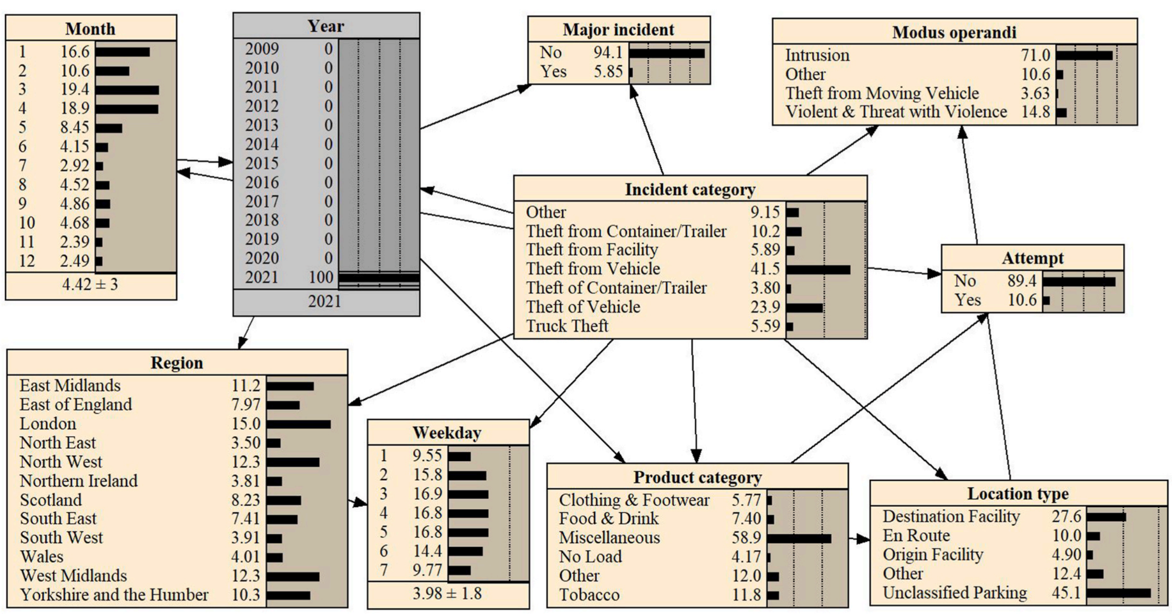

Fig. 7. Prediction results of TAN.

6). It indicates that the freeport attained the highest performance score in waste management (0.9677) and the lowest score in safety and security (0.2579). Table 8 presents the results for level-1 KPIs and overall freeport sustainability in the six scenarios. Across Scenarios 1, 2, 3, 5, and 6, the highest performance score was observed in the environmental dimension, while the economic dimension, as the most significant dimension, recorded the lowest performance score. Overall sustainability performance scores of the six scenarios are 0.7259, 0.7270, 0.7228, 0.7350, 0.7252, and 0.7318, respectively. Fig. 8 provides a visual representation of overall freeport sustainability in Scenario 1 as an example.

4.5. Validation results

930 real accidents were employed to validate the BN model, yielding an accuracy of 89.14%. Additionally, the computed Kappa coefficient stands at 0.7896. Compared to previous studies, these results indicate that the model is robust in terms of accuracy (Song et al., 2020) and consistency (Altman, 1990).

The two axioms in sensitivity analysis outlined in Section 3.6 were achieved by the following procedure. Firstly, a belief degree of 10% was reallocated in each bottom-level KPI from the least preferred grade to the most preferred grade (+10%), or conversely (−10%) if the belief degree assigned to the most preferred grade is 1. The change in the overall index was calculated, as shown in Table 9. It was observed that the new index value increased or decreased with the increase or decrease in the input of each bottom-level KPI. Thus, Axiom 1 was achieved.

Second, using the same belief degree variations for the bottom-level KPIs as detailed in Table 9, the change in the new index was compared between two weighting scenarios, Scenario 6 and Scenario 4. The 21 most important bottom-level KPIs were selected to unveil outcomes (see

Table 6
Weights and performance on bottom-level KPIs.

No.	Level-3 KPI	Global weight	Local weight	Performance score (0–1)	Data source
1	Development area of freeport	2.54%	19.75%	0.5175	Freeport website
2	Port cargo tonnage	2.56%	19.96%	0.5525	GOV.UK
3	Port container throughput	2.59%	20.17%	0.3000	GOV.UK
4	Movement of rail freight in/out of the freeport	2.54%	19.75%	0.0000	Freeport input
5	Movement of road freight in/out of the freeport	2.62%	20.37%	1.0000	Freeport input
6	Number of new infrastructure projects	2.54%	16.64%	1.0000	Freeport input
7	Information technology	2.78%	18.21%	0.6875	Expert judgement
8	Facility availability	2.70%	17.69%	0.6875	Expert judgement
9	Number of customs sites	2.32%	15.24%	1.0000	Freeport website
10	Number of tax sites	2.27%	14.89%	0.7500	Freeport website
11	Tax policy	2.64%	17.34%	0.8750	Expert judgement
12	Cargo traffic congestion	2.59%	24.87%	0.6250	Expert judgement
13	The efficiency of customs clearance	2.78%	26.67%	0.8750	Expert judgement
14	Diversity of logistics services	2.59%	24.87%	0.9063	Expert judgement
15	Operational accuracy	2.46%	23.59%	0.8750	Expert judgement
16	GDP change rate	1.90%	17.27%	0.3450	UK Parliament
17	GDP per capita	2.00%	18.25%	0.6075	Council website
18	Total import and export of foreign trade change rate	2.32%	21.17%	0.0000	OEC World
19	Foreign direct investment	2.27%	20.68%	0.2000	Freeport website
20	Number of businesses operating at freeport development sites	2.48%	22.63%	0.2500	Freeport input
21	Air pollution	2.38%	25.65%	0.7500	Expert judgement
22	Water pollution	2.38%	25.65%	0.7500	Expert judgement
23	Noise pollution	2.19%	23.63%	0.6250	Expert judgement
24	Soil pollution	2.32%	25.07%	0.7500	Expert judgement
25	Hazardous waste handling	2.40%	33.96%	0.9375	Expert judgement
26	General waste management	2.38%	33.58%	0.9375	Expert judgement
27	Centralised sewage treatment	2.30%	32.45%	1.0000	GOV.UK
28	Water consumption management	2.27%	50.00%	0.6875	Expert judgement
29	Clean energy sources	2.27%	50.00%	0.8125	Expert judgement
30	Environmental training	2.08%	22.87%	0.5625	Expert judgement
31	Ecosystem and habitat protection	2.35%	25.81%	0.8125	Expert judgement
32	Climate change adaptation and mitigation	2.14%	23.46%	0.8125	Expert judgement
33	Environmental protection policy	2.54%	27.86%	0.9375	Expert judgement
34	Number of new jobs due to the freeport development	2.38%	50.00%	0.7000	Freeport website
35	Employment in high-tech and knowledge-oriented sectors	2.38%	50.00%	1.0000	Freeport input
36	Gender equality	1.95%	29.32%	0.5625	Expert judgement
37	Number and level of skill training	2.38%	35.74%	1.0000	Freeport input
38	Participation in skill training	2.32%	34.94%	0.9000	Freeport input
39	Fatal injuries	2.35%	34.24%	0.1800	Freeport input
40	Non-fatal injuries	2.30%	33.46%	0.2275	Freeport input
41	Cargo theft incidents	2.22%	32.30%	0.3850	The BN model
42	The number of projects between firms and research innovation organisations within the freeport area	2.24%	100.00%	0.7500	Freeport input

Table 10). These outcomes align with Axiom 2. For instance, the influence of KPIs Nos. 1-5 on the index value in Scenario 6 surpasses that in Scenario 4, as these KPIs carry greater weights in the former scenario than in the latter.

5. Implications

The findings from this research offer substantial insights into the sustainability assessment of freeports, shedding light on significant KPIs and aggregate performance indexes. In general, it reveals the predominant influence of the economic dimension among the three sustainability dimensions in enhancing the attractiveness of freeports based on the overall perspective of multiple stakeholders in the freeport sector. However, perceptions vary among different stakeholders concerning the value of each sustainability dimension. For instance, researchers and public residents have a higher preference for the environmental dimension compared to policymakers, practitioners, and particularly service users.

This disparity makes the examined freeport's overall performance reveal mild fluctuations across diverse weighting scenarios. These variations, which ranged from scores of 0.7228 (assessed by practitioners) to 0.7350 (evaluated by service users), underline the importance of understanding stakeholders' unique viewpoints. Such variations in scores, especially in distinct sustainability dimensions, can guide more personalised and effective engagement strategies with stakeholders, ensuring their expectations are met and addressed.

A solution to this disparity involves fostering improved communication among stakeholders and promoting collaborations. Additionally, policy measures that incentivise and inform service users to opt for eco-friendly choices are essential. By fostering collaboration among stakeholders and aligning policy measures with sustainable practices, freeports can deliver long-term benefits to local communities, promoting

Table 7
Performance on level-2 KPIs based on weights given by combined stakeholders.

Level-2 KPI	Belief degrees G1	G2	G3	G4	G5	Unknown	Score
Freeport size	18.65%	15.31%	41.32%	5.43%	19.38%	0.00%	0.4787
Freeport infrastructure	0.00%	3.98%	7.68%	26.88%	57.90%	3.56%	0.8467
Service quality	0.00%	5.14%	5.14%	41.06%	48.66%	0.00%	0.8331
Economic aggregate	23.71%	54.14%	15.35%	6.80%	0.00%	0.00%	0.2631
Environmental pollution	0.00%	0.00%	32.38%	25.00%	32.00%	10.63%	0.7225
Waste management	0.00%	0.00%	0.00%	12.91%	87.09%	0.00%	0.9677
Energy and resource usage	0.00%	0.00%	10.00%	55.00%	25.00%	10.00%	0.7625
Environmental protection	0.00%	0.00%	15.46%	24.92%	49.77%	9.85%	0.8112
Job generation	0.00%	0.00%	10.00%	40.00%	50.00%	0.00%	0.8500
Workforce development and diversity	0.00%	5.77%	11.54%	11.95%	70.73%	0.00%	0.8691
Safety and security	10.41%	76.03%	13.56%	0.00%	0.00%	0.00%	0.2579
Innovation and collaboration	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.7500

Table 8
Performance on level-1 KPIs and the overall freeport sustainability based on weights given by different stakeholders.

Level-1 KPI	Belief degrees G1	G2	G3	G4	G5	Unknown	Score
Researchers (scenario 1)							
Economic	9.39%	17.52%	16.66%	20.89%	34.97%	0.58%	0.6363
Environmental	0.00%	0.00%	13.40%	27.43%	52.79%	6.38%	0.8325
Social	2.33%	21.79%	11.15%	41.18%	23.55%	0.00%	0.6546
Overall sustainability	**3.64%**	**11.62%**	**13.21%**	**29.42%**	**39.92%**	**2.18%**	**0.7259**
Policymakers (scenario 2)							
Economic	8.79%	18.60%	17.48%	20.50%	33.74%	0.89%	0.6295
Environmental	0.00%	0.00%	12.42%	29.22%	52.22%	6.15%	0.8341
Social	2.36%	18.95%	9.90%	35.33%	33.45%	0.00%	0.6964
Overall sustainability	**3.73%**	**12.37%**	**12.74%**	**27.97%**	**41.33%**	**1.85%**	**0.7270**
Practitioners (Scenario 3)							
Economic	12.03%	18.21%	17.71%	18.28%	32.86%	0.92%	0.6043
Environmental	0.00%	0.00%	13.00%	29.05%	51.61%	6.34%	0.8307
Social	2.42%	17.47%	9.19%	37.31%	33.62%	0.00%	0.7056
Overall sustainability	**4.70%**	**11.61%**	**12.68%**	**27.98%**	**41.08%**	**1.96%**	**0.7228**
Service users (Scenario 4)							
Economic	6.24%	14.63%	14.26%	24.62%	39.33%	0.92%	0.6904
Environmental	0.00%	0.00%	12.18%	26.75%	54.71%	6.36%	0.8404
Social	2.58%	21.78%	9.61%	42.25%	23.78%	0.00%	0.6572
Overall sustainability	**2.77%**	**12.21%**	**11.12%**	**32.41%**	**39.67%**	**1.83%**	**0.7350**
Public residents (Scenario 5)							
Economic	9.86%	17.83%	18.37%	20.19%	32.90%	0.84%	0.6211
Environmental	0.00%	0.00%	13.65%	29.18%	51.04%	6.13%	0.8281
Social	2.14%	19.62%	9.38%	43.11%	25.76%	0.00%	0.6769
Overall sustainability	**3.54%**	**11.34%**	**13.08%**	**31.31%**	**38.60%**	**2.12%**	**0.7252**
Combined (Scenario 6)							
Economic	9.44%	17.56%	17.10%	20.61%	34.44%	0.84%	0.6326
Environmental	0.00%	0.00%	12.95%	28.45%	52.38%	6.23%	0.8330
Social	2.40%	19.16%	8.44%	39.41%	30.58%	0.00%	0.6915
Overall sustainability	**3.73%**	**11.53%**	**12.17%**	**29.45%**	**41.12%**	**2.00%**	**0.7318**

shared prosperity. Beyond enhancing trade efficiency, freeports also minimise environmental impacts, aligning with public expectations for sustainability.

This study aligns with prior research in terms of the prioritisation of KPIs. Historically, KPIs like freeport development areas, information technology capabilities, tax policies, customs clearance efficiency, and logistics have been pivotal in gauging freeport performance. The results of this study highlight the significance of these indicators in freeport sustainability evaluation, as they are consistently ranked among the top 10 KPIs. It indicates that the overall freeport sustainability can be improved by allocating more funds to develop intelligent e-commerce and digital trade, advanced information technology, effective tax policies, efficient customs systems, and convenient logistics services. By focusing on these aspects, freeports can achieve sustainable success in a rapidly evolving global trade landscape. Furthermore, the results of this study highlight that information technology and the efficiency of customs clearance are the most pivotal KPIs out of the 42 bottom-level KPIs in evaluating freeport sustainability. This observation echoes Huang et al. (2020), who emphasised the role of technology applications in shaping the service quality of free trade zones. In a parallel sentiment, Gerber (2021) asserted that information technology is a key driver for international trade as it promotes cross-border value chains and further integrates manufacturing systems.

To fully capitalise on technological advancements and customs

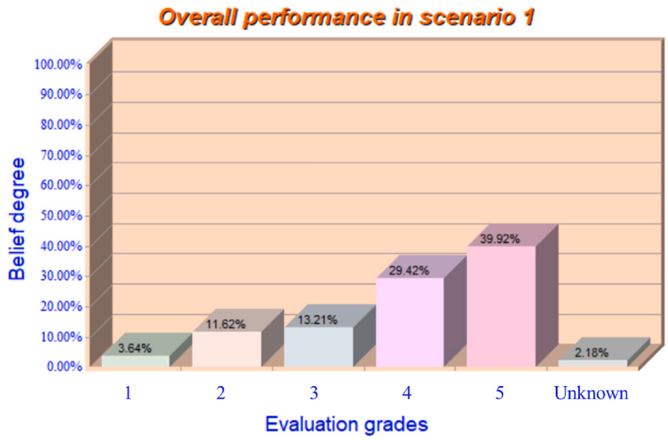

Fig. 8. Overall performance (weights given by researchers).

efficiencies, freeports must overcome several key challenges. First, infrastructure must be capable of supporting advanced technologies, as outdated systems can impede the integration of new solutions. Additionally, freeports need to cultivate a skilled workforce that is proficient in emerging technologies, which may require substantial investment in training and development programs.

Moreover, freeports must navigate complex and often inconsistent regulations that vary significantly between regions and countries. These regulatory discrepancies can complicate operations and slow progress. Another critical concern is the ongoing maintenance and security of technological systems. Heavy reliance on advanced technologies increases vulnerability to cyber threats and system failures, which can disrupt operations and compromise data integrity.

Lastly, enhancing customs efficiency while maintaining a high level of security presents a delicate balancing act. Streamlined customs processes must ensure thorough inspections to prevent illicit activities, as rapid clearance may sometimes compromise security. Developing comprehensive risk management strategies is vital for distinguishing between low-risk and high-risk shipments, enabling efficient operations without sacrificing safety and security.

A novel framework for sustainability assessment of freeport performance is introduced in this study. This multi-dimensional framework presents a holistic picture of freeport performance, identifying strengths and areas of improvement. As demonstrated in our case study, the investigated freeport exposes specific areas for improvement, including the freeport size (KPIs Nos. 1–5), economic aggregate (KPIs Nos. 16–20), and safety and security (KPIs Nos. 39–41). By adopting this novel framework, stakeholders can gain deeper insights into freeport operations, enabling targeted enhancements and fostering overall progress.

The synthesised performance index serves as a benchmark for tracking the evolution of a freeport's overall performance, identifying potential areas of concern, and ensuring continuous monitoring and improvement of sustainability efforts. Auditing and monitoring of implemented measures can be efficiently conducted at the KPI level, with best practices from leading freeports providing benchmarks to accelerate sustainability across other freeports.

6. Conclusion

This paper presents a novel hybrid methodology for assessing the sustainability of freeports, offering significant contributions both methodologically and practically. First, this study conducted a systematic literature review to present well-established sustainability frameworks and methods, thereby establishing a primary database for identifying KPIs. Subsequently, it employed a combination of top-down and bottom-up approaches to select KPIs within the freeport-specific context and engaged diverse stakeholders from around the globe to

Table 9
Sensitivity by belief degrees.

No.	Level-3 KPI	Belief degrees variation	New sustainability index	Index change
1	Development area of freeport	+10%	0.7333	0.0015
2	Port cargo tonnage	+10%	0.7333	0.0015
3	Port container throughput	+10%	0.7338	0.0020
4	Movement of rail freight in/out of the freeport	+10%	0.734	0.0022
5	Movement of road freight in/out of the freeport	−10%	0.7295	−0.0023
6	Number of new infrastructure projects	−10%	0.7302	−0.0016
7	Information technology	+10%	0.7333	0.0015
8	Facility availability	+10%	0.7329	0.0011
9	Number of customs sites	−10%	0.7303	−0.0015
10	Number of tax sites	+10%	0.7324	0.0006
11	Tax policy	+10%	0.7333	0.0015
12	Cargo traffic congestion	+10%	0.7339	0.0021
13	The efficiency of customs clearance	+10%	0.733	0.0012
14	Diversity of logistics services	+10%	0.7329	0.0011
15	Operational accuracy	+10%	0.7328	0.001
16	GDP change rate	+10%	0.7329	0.0011
17	GDP per capita	+10%	0.7326	0.0008
18	Total import and export of foreign trade change rate	+10%	0.7334	0.0016
19	Foreign direct investment	+10%	0.7335	0.0017
20	Number of businesses operating at freeport development sites	+10%	0.7333	0.0015
21	Air pollution	+10%	0.7333	0.0015
22	Water pollution	+10%	0.7332	0.0014
23	Noise pollution	+10%	0.7332	0.0014
24	Soil pollution	+10%	0.7331	0.0013
25	Hazardous waste handling	+10%	0.7326	0.0008
26	General waste management	+10%	0.7326	0.0008
27	Centralised sewage treatment	−10%	0.7298	−0.002
28	Water consumption management	+10%	0.734	0.0022
29	Clean energy sources	+10%	0.7336	0.0018
30	Environmental training	+10%	0.733	0.0012
31	Ecosystem and habitat protection	+10%	0.7327	0.0009
32	Climate change adaptation and mitigation	+10%	0.7331	0.0013
33	Environmental protection policy	+10%	0.7328	0.001
34	Number of new jobs due to the freeport development	+10%	0.7352	0.0034
35	Employment in high-tech and knowledge-oriented sectors	−10%	0.7273	−0.0045
36	Gender equality	+10%	0.7337	0.0019
37	Number and level of skill training	−10%	0.7291	−0.0027
38	Participation in skill training	+10%	0.7328	0.001
39	Fatal injuries	+10%	0.7342	0.0024
40	Non-fatal injuries	+10%	0.7341	0.0023
41	Cargo theft incidents	+10%	0.7337	0.0019
42	The number of projects between firms and research innovation organisations within the freeport area	+10%	0.7352	0.0034

Table 10
Sensitivity by weights.

No.	Level-3 KPI	Belief degrees variation	Global weights		Index change	
			Scenario 6	Scenario 4	Scenario 6	Scenario 4
1	Development area of freeport	+10%	2.54%	2.23%	0.0015	0.0012
2	Port cargo tonnage	+10%	2.56%	2.05%	0.0015	0.0011
3	Port container throughput	+10%	2.59%	2.05%	0.0020	0.0014
4	Movement of rail freight in/out of the freeport	+10%	2.54%	1.37%	0.0022	0.0009
5	Movement of road freight in/out of the freeport	−10%	2.62%	2.05%	−0.0023	−0.0015
6	Number of new infrastructure projects	−10%	2.54%	2.91%	−0.0016	−0.0018
7	Information technology	+10%	2.78%	3.25%	0.0015	0.0018
8	Facility availability	+10%	2.70%	3.25%	0.0011	0.0013
11	Tax policy	+10%	2.64%	2.74%	0.0015	0.0011
12	Cargo traffic congestion	+10%	2.59%	2.74%	0.0021	0.0021
13	The efficiency of customs clearance	+10%	2.78%	3.25%	0.0012	0.0014
14	Diversity of logistics services	+10%	2.59%	2.40%	0.0011	0.0010
15	Operational accuracy	+10%	2.46%	2.91%	0.0010	0.0012
20	Number of businesses operating at freeport development sites	+10%	2.48%	2.57%	0.0015	0.0015
21	Air pollution	+10%	2.38%	2.05%	0.0015	0.0012
22	Water pollution	+10%	2.38%	2.05%	0.0014	0.0011
25	Hazardous waste handling	+10%	2.40%	2.23%	0.0008	0.0007
26	General waste management	+10%	2.38%	2.23%	0.0008	0.0007
33	Environmental protection policy	+10%	2.54%	2.91%	0.0010	0.0011
34	Number of new jobs due to the freeport development	+10%	2.38%	2.74%	0.0034	0.0043
35	Employment in high-tech and knowledge-oriented sectors	−10%	2.38%	2.05%	−0.0045	−0.0032
37	Number and level of skills training	−10%	2.38%	2.23%	−0.0027	−0.0024

evaluate the importance of these KPIs. Utilising the BNER model, it conducted a comprehensive assessment of overall freeport sustainability, effectively handling uncertain and network-based KPIs. Lastly, the model was successfully applied in a UK freeport, with sensitivity analysis results confirming its consistency. The developed framework is comprehensive and highly adaptable, as it encompasses KPIs from multiple dimensions in both quantitative and qualitative forms within hierarchical and network structures and accommodates data uncertainties. Therefore, it allows the incorporation of new KPIs without modifying the existing structure as relevant data becomes available.

The findings of this study provide important implications for the development of sustainable freeports. 1) This study provides a comprehensive KPI framework consisting of 42 bottom-level KPIs for the sustainability assessment of freeports, where the most significant KPIs are identified as the information technology, efficiency of customs clearance, facility availability, tax policy, and road freight in/out of freeport. 2) Different stakeholders' perceptions regarding the preferences on the economic, environmental, and social dimensions of freeport sustainability are varying. Accordingly, several measures are recommended to bridge the gap and foster sustainable development, such as building more partnerships and subsidising sustainable service options. 3) By adopting the developed model, stakeholders can gain a comprehensive understanding of a freeport performance in terms of strengths and weaknesses. The integrated index framework can serve as a benchmark for evaluating the sustainability of freeports over time and enabling underperforming freeports to learn from the best practices of top performers.

In addition, this research has identified certain limitations within the KPI framework and case study. To address them, future research could refine the KPI framework by verifying the importance and interdependences of the selected KPIs. Besides, expanding the case study to more freeports would enable a comparative analysis of results among different performers.

CRediT authorship contribution statement

Xinrui Liang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shiqi Fan:** Writing – review & editing, Supervision, Methodology. **John Lucy:** Supervision, Resources, Conceptualization. **Jihong Chen:** Supervision, Methodology, Conceptualization. **Jonathan Coleman:** Resources, Investigation. **Yan Li:** Resources, Investigation. **Zhuohua Qu:** Supervision, Resources, Investigation. **Huanhuan Li:** Writing – review & editing, Supervision, Methodology. **Zaili Yang:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. KPI descriptions

No.	Level-3 KPIs	Descriptions
1	Development area of freeport (Hectare)	Land within the freeport area that has been earmarked for development.
2	Port cargo tonnage (tons)	Total volume by commodity type of freight loaded and unloaded at the port. If the freeport has more than one seaport or airport, use the total of all.
3	Port container throughput (TEUs)	It refers to containers. If the freeport has more than one seaport or airport, use the total of all.

(continued on next page)

(*continued*)

No.	Level-3 KPIs	Descriptions
4	Movement of rail freight in/out of the freeport (tons or TEUs)	The number of units of rail freight entering and leaving the freeport zone. Rail movements can be collected using advance plans.
5	Movement of road freight in/out of the freeport (tons or TEUs)	The number of units of road freight entering and leaving the freeport zone. Road movements can be collected through the use of traffic counters at entrances/exits.
6	Number of new infrastructure projects	Number/type of new infrastructure projects directly related to the Freeport (set up within the tax site, customs site, port area, and freeport boundary)
7	Information technology	It reflects the development of freeports in intelligent E-commerce, digital trade, and information resource sharing.
8	Facility availability	It refers to the availability of cargo handling facilities with freeport development and increasing cargo volume.
9	Number of customs sites	
10	Number of tax sites	
11	Tax policy	It refers to the coverage of relevant policy areas such as: 1)Stamp Duty Land Tax (SDLT) Relief 2)Enhanced Structures and Buildings Allowance 3)Enhanced Capital Allowances 4)Employer National Insurance Contributions Relief 5)Business rates
12	Cargo traffic congestion	It measures the timeliness of freeport services when cargoes enter the freeport zone.
13	The efficiency of customs clearance	It refers to the timeliness and simpleness of customs procedures.
14	Diversity of logistics services	It refers to the diversity of services such as intermodal transportation, storage, and on-time delivery to meet customer requirements in a timely, cost-effective manner.
15	Operational accuracy	It refers to the accuracy of business operations in the freeport.
16	GDP (change rate)	Data is to be collected within the direct area where the freeport is to have an impact. Otherwise, use the UK regional (where the freeport is located) data instead.
17	GDP per capita (thousand pounds)	Data is to be collected within the direct area where the freeport is to have an impact. Otherwise, use the UK regional (where the freeport is located) data instead.
18	Total import and export of foreign trade (change rate)	Data is to be collected within the direct area where the freeport is to have an impact. Otherwise, use the UK regional (where the freeport is located) data instead.
19	Foreign direct investment (pounds)	Foreign direct investment that is directly related to the freeports program.
20	Number of businesses and jobs operating at freeport development sites	
21	Air pollution	It refers to the air quality degradation caused by main air pollutants from freeport activities (e.g., CO2, SO2, NOx, PM2.5, and PM10).
22	Water pollution	It refers to the water environmental degradation caused by spills or leaks from oil products and bulk liquids, and discharges of chemical pollutants in freeport waters.
23	Noise pollution	It refers to the disturbance (e.g., noise and vibration) to the community during cargo handling, infrastructure construction and demolishment.
24	Soil pollution	It refers to spills or leaks of dangerous liquids (HC, paints, solvents, oils) from land traffic, construction, vessel repair, and leached material from storage of stock.
25	Hazardous waste handling	It includes separating hazardous goods and poisons during construction and operation, employing licensed contractors to handle hazardous waste, sterilising and burning cargo coming from the epidemic area, etc.
26	General waste management	It includes garbage classification in the freeport area, a dedicated storage area for recycling, reducing packaging use and office waste.
27	Centralized sewage treatment	It refers to the percentage of productions and operations in freeports using the centralized sewerage service.
28	Water consumption management	It includes reducing waste of drinking water and irrigation, monitoring water leakage, on-site water treatment and reuse.
29	Clean energy sources	It refers to the ratio of freeport operation machinery, ships, and vehicles using electricity, Liquefied natural gas (LNG) and other clean energy sources.
30	Environmental training	It refers to the popularization of training sessions for workers to improve their environmental awareness.
31	Ecosystem and habitat protection	It refers to the strategies for reducing the degradation of natural habitats, halting the loss of biodiversity, and protecting threatened species.
32	Climate change adaptation and mitigation	It refers to the adaptive capacity of freeports in dealing with climate change through policy planning and operational changes.
33	Environmental protection policy	By consideration of the following principles (Wildlife and Countryside Link, July 2020): Freeport proposals must align with the UK's net-zero carbon emissions commitment, excluding airports from the scope; All environmental and animal welfare standards must take precedence over trade policy regulations; Freeports must maintain strict customs procedures to prevent facilitating illegal trade in wildlife.
34	Number of new jobs due to the freeport development	The number of new jobs to be created due to the freeport development.
35	Employment in high-tech and knowledge-oriented sectors	It refers to the percentage of employment in high-tech and knowledge-intensive sectors.
36	Gender equality	It refers to the balance between female and male employees.
37	Number and level of skills training	The number of skills programs and information on the type of program (i.e. length of the course, level of expertise) set up to meet identified Freeport workforce needs.
38	Participation in skills training	The number of people enrolled in skills programs set up to meet identified freeport workforce needs.
39	Fatal injuries	Rate of fatal injuries per 100,000 workers (the data of the UK regions is to be collected if the data within freeports is not available).
40	Non-fatal injuries	Rate of non-fatal injuries per 100,000 workers (the data of the UK regions is to be collected if the data within freeports is not available).

(*continued on next page*)

(*continued*)

No.	Level-3 KPIs	Descriptions
41	Cargo theft incidents	The occurrence probability of cargo theft incidents within the UK regions where the freeports are located.
42	The number of projects run jointly between firms and research innovation organisations within the freeport area	The number of projects featuring the collaboration between firms and research innovation organisations as a direct result of the freeport. Research innovation organisations include universities, catapult centres, research infrastructure and Public Sector Research Establishments (PSREs).

Appendix B. Valid respondents' list

Participant No.	Role	Experienced countries
1	Researcher (Professor)	Russia
2	Researcher (Professor)	China
3	Researcher (Professor)	Brazil
4	Policymaker (Director)	The UK, Morocco
5	Policymaker (Director)	China
6	Policymaker (Investment Officer)	China
7	Practitioner (Customs Officer)	China
8	Practitioner (Administrative Officer)	China
9	Practitioner (Freeport Consultant and Adviser)	The UK, Dubai, Ghana, Canada
10	Practitioner (Infrastructure Management)	The UK
11	Freeport service user (Shipping Center Construction Office/Port)	China
12	Freeport service user (Forwarder)	China
13	Freeport service user (Shipping Company)	Germany
14	Public resident	The UK
15	Public resident	The UK
16	Public resident	China, the UK
17	Public resident	The UK, Iran

Data availability

The data that has been used is confidential.

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