

DISSERTATION

DEVELOPMENT OF GREEN PORT INDEX

A TOOL FOR ASSESSING PORTS BASED ON IMPLEMENTATION OF GHG EMISSION REDUCTION MEASURES

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of the requirements for the award of the degree of Master of Science in
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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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Abstract

Title of Dissertation: **Development of Green Port Index: A tool for assessing ports based on implementation of GHG emission reduction measures.**

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As the global attention shift towards climate change due its devastating impact on our environment, all sectors including ports should implement mitigation and adaptation strategies to combat it. This is why green port development and operation has become increasingly important to reduce the environmental impact of port operations. Despite the growing number of research in green ports, quantitative assessment of ports based on implementation of measures to mitigate their environmental impacts is rarely addressed. Therefore, this study seeks to develop a green port index (GPI) which is a comprehensive mechanism for evaluating ports based on implementation of key measures to reduce GHG emissions. This assessment tool produces a 0 – 100% composite score taking into account 12 key performance indicators (KPIs) identified through literature review. These KPIs include energy efficiency, electrification, green fuel utilization, port greenery, renewable energy usage, smart/microgrid coverage, onshore power supply (OPS) usage, just in time arrival, alternative fuel bunkering, green hinterland transportation of cargo, employee commuting and truck congestion reduction. The KPIs are classified based on the greenhouse gas (GHG) emission scope impacted. Additionally, this research proposes a methodology to quantify each of the 12 KPIs.

Fuzzy Analytical Hierarchy Process (FAHP) and Adaptive Neuro-Fuzzy Inference System (ANFIS) hybrid methodology was used to develop the GPI. Questionnaires were sent to heterogeneous group of experts to determine relative importance of the KPIs. FAHP technique was used to determine the weights of the KPIs. The scores and weights of the KPIs are used to develop a mathematical model which provide training data for the ANFIS model. ANFIS is then used to develop GPI which undergoes rigorous testing to determine its sensitivity to changes in KPI scores.

The study revealed that renewable energy (RE) usage is the most important measure to reduce port GHG emission and green employee commuting is the least important. Additionally, the findings reveal that electrification, RE and OPS usage are the most important KPIs for scope 1, scope 2 and scope 3 port GHG emission reduction respectively. This study also demonstrated how policy makers and other relevant stakeholders can use the propose methodology to evaluate their GPI score.

KEYWORDS: Green Port Index, Key performance indicators, GHG Emissions, Fuzzy AHP, Adaptive Neuro-Fuzzy Inference System.

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List of Abbreviation

AFB	Alternative fuel bunkering
AHP	Analytical Hierarchy Process
ANFIS	Adaptive Neuro-Fuzzy Inference system
ANN	Artificial Neural network
CHE	Cargo handling equipment
DEA	Data Envelopment Analysis
DM	Decision makers
EC	Employee commuting
ECLAC	Economic Commission for Latin America and the Caribbean
EE	Energy efficiency
ES	Emission scope
ESPO	European Sea Ports Organisation
ETS	Emission trading system
EU	European Union
FAHP	Fuzzy Analytical Hierarchy Process
FIS	Fuzzy Inference System
GEF	Global Environment Facility
GFU	Green fuel utilisation
GHG	Green House Gas
GHT	Green hinterland transportation
GPI	Green Port Index
GWh	Gigawatt hour
IAPH	International Association of Port and Harbors
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JIT	Just in time
KPI	Key performance indicator
KWh	Kilowatt hour

LDE	litres of diesel equivalent
MCDM	Multi-Criteria decision making
MF	Membership function
NCTV	Noatum Container Terminal Valencia
NO _x	Nitrogen Oxides
OPS	Onshore power supply
PA	Port Authority
PCA	Principal Component Analysis
PCM	Pairwise comparison matrix
PEM	Port Equipment and Machinery
PG	Port greenery
PM	Particulate matter
POLA	Ports of Los Angeles
POLB	Ports of Long Beach
RE	Renewable energy
SMART	Simple Multi Attribute Rating Technique
SMG	Smart and Microgrid
SO _x	Sulphur Oxides
TAS	Truck appointment system
TC	Truck congestion
TEU	Twenty-foot equivalent unit
TFN	Triangular fuzzy numbers
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UN	United Nation
WBCSD	World Business Council for Sustainable Development
WRI	World Research Institute

Chapter 1 Introduction

1.1 Background

Recently the global impact of climate change is worsening with more extreme weather events characterised by flooding, hurricanes, heatwaves, etc. The global surface temperature reached 1.1 °C above the pre – industrial level between 2011 – 2020 and the temperature projections showed that under current scenario global warming will exceed 1.5°C by 2030 - 2035 (IPCC, 2023). To ensure effective mitigation and possible reversal of the current trends, a well coordinated global effort with high level of commitment is required and all sectors including Ports need to play an important role. This therefore necessitates the greenification of ports to complement the targets set by the IMO GHG strategy and Paris agreement. The initial GHG strategy introduced by the IMO in 2018 outlined the short term, medium term and long term measures to reduce GHG emission from international shipping (IMO, 2018). Subsequently, this was followed by the revised GHG strategy with higher levels of ambition aiming to achieve net-zero GHG emission from international shipping by or around 2050 (IMO, 2023). This cannot be achieved without ports providing the enabling infrastructure and more to support the maritime decarbonisation efforts. This is why Sustainable port development has become increasingly important with the primary focus on reducing environmental hazards from port operations while ensuring port operational efficiency (Doan & Huynh, 2024).

Besides, green shipping corridors (GSC) are emerging as potential solutions to facilitate maritime decarbonisation through the use of low or zero carbon transportation along major shipping routes. They are perceived as prerequisite for achieving the IMO net-zero targets (Ismail et al., 2024). To ensure effective functioning of GSC, ports need to provide alternative fuel bunkering infrastructure. Therefore, a GSC requires involvement of a network of green ports (Ismail et al., 2024). This clearly underscores the significant role of ports in mitigation of GHG emission from shipping.

However, ports should also look inwards and focus on measures to reduce their own carbon footprint. Unfortunately there is no global regulations to drive this. IMO do not have mandate to regulate ports. Its primary focus has been on international shipping, in line with its core mandate as defined by the IMO convention. This is why there has been lot of globally recognised standards, regulations and guidelines to address marine pollution from shipping. By contrast, ports are not governed by these standards and regulations although in some cases initiatives are taken at national or regional level to enhance environmental stewardship of ports. For instance, port of Antwerp is involved in the "power-to-methanol" project which aimed at reducing CO₂ emissions by at least 8000 tons (DEMİR et al., 2022). Regional organisation such as European Seaport organisation (ESPO) plays a significant role in promoting sustainable port operation within the European Union. It awards Ecoport certificate to eligible ports meeting the environmental sustainability requirements (ESPO, 2024).

Renewable energy (RE) integration in port energy mix is foundamental in port GHG emission reduction. Therefore, ports should be at the forefront leading the green energy transition. According to IEA, (2024), RE provided 30% of global electricity supply in 2023, while fossil fuels dropped to 60% which is its lowest share in 50 years. The share of solar photovoltaics and wind in electricity generation is projected to exceed 40% globally by 2035 in the stated policy scenario, and by 2050 it will increase to nearly 60%” (IEA, 2024). Generally, the global trend indicates a gradual increase of RE use in the total energy generation, which implies reduction in GHG emissions.

1.2 Problem statement

Ports are crucial for effective functioning of the global supply chain to enhance global trade and economic growth. However, there are environmental hazards associated with port development and operation, contributing to GHG emissions and exposing the residents near the ports to health risks. Since most ports are located in cities, it becomes highly important to adopt green port initiatives to

ensure environmental stewardship of ports. This will complement global efforts in mitigating climate change through maritime decarbonisation. Currently, to the author's knowledge, there is no comprehensive and standardised green port index (GPI) to quantitatively assess ports based on implementation of harmonised green port measures. One of the main reasons for this is the variation in the definition of green port concept as revealed in section 2.1 of this dissertation.

Besides, the main motivation of this dissertation is to develop a comprehensive and adaptable GPI that can be used to evaluate ports based on the effective implementation of GHG reduction measures and serves as a benchmarking tool. Therefore, the developed GPI will serve as an effective instrument for port authorities, policy makers and relevant stakeholders to assess port environmental performance with respect to GHG emissions mitigation, identify priority areas requiring improvement and adopt data – driven green port strategies.

1.3 Aims and objectives

1.3.1 Aim

This dissertation aims at providing a comprehensive mechanism for evaluating ports based on implementation of key measures to reduce GHG emissions using an index namely GPI.

1.3.2 Objectives

To achieve the aim, this research seeks to achieve the following objectives:

1. Identify the key performance indicators relevant to green port GHG-reduction assessment.
2. Determine the relative importance of the KPIs.
3. Provide a mechanism to quantify the green port KPIs.
4. Develop a method and index to calculate environmental performance of ports.

5. Demonstrate how policy makers and relevant stakeholders can evaluate GPI using the proposed methodology.

1.4 Research Questions

To achieve the objectives the following questions should be answered:

1. What are the relevant green port GHG-reduction KPIs?
2. Which KPIs are more important?
3. How can these green port KPIs be quantified?
4. What method can be used to aggregate all the KPIs to produce a composite GPI score?
5. How can policy makers and relevant stakeholders benefit from the proposed GPI?

1.5 Research scope

This dissertation focussed on GHG emission reduction measures as a yardstick to assess the performance of ports and determine how environmentally friendly they are. The author recognises other related dimensions such as economic and social perspective to ensure successful implementation of green port strategies and overall sustainability of port operation. However, these dimensions can be used to explain the GPI score of a specific port. For example, if a port has a very high GPI score it indicates significant investment in green technologies and capacity building of its staff. Therefore, the economic and social sustainability components can be viewed as inputs to achieve reduction in GHG emission.

The boundary of this research is defined by the port limits both on the sea side and hinterland. The KPIs are designed such that the variation of these limits from one port to another will not affect the results. The KPIs are derived from the green port measures to mitigate GHG emissions from the ship-port interface, hinterland transportation and ports own activities. These measures are grouped based on

which emission scope they impact in line with GHG protocol. The accounting of port GHG emission is not within the scope of this dissertation.

1.6 Key assumption and potential limitation

1. This research is not focussing on other emission categories such as NO_x, Sox, and PM. However, all the selected green port KPIs except port greenery can also be applied to assess reduction of these emission categories.
2. The weights of the KPIs depends on the opinion of the experts who responded to the questionnaire survey. Therefore, conducting this research with a different group of experts may yield a different result.
3. In this research, a “Port” is considered to be a collective entity comprising of the port authority and relevant stakeholders involved in its operations. Therefore, the evaluation of the environmental performance of ports using GPI will also account for the GHG reduction measures implemented by the various stakeholders such as terminal operators.

1.7 Ethical issues

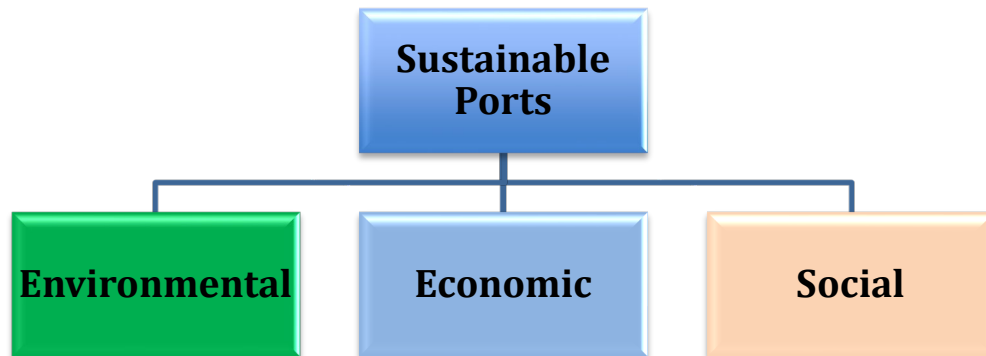
This dissertation involves human participation in responding to the questionnaires. Therefore, approval was sought from the research and ethics committee (REC) before proceeding with the data collection in line with the university’s policy. Besides, the data obtained is saved securely and utilised for the purpose of this research only. The expert questionnaire survey was designed in accordance with WMU REC policy. Similarly, the dissertation is written in accordance with the university’s guidelines provided in the reference guide taking into consideration all ethical issues.

Chapter 2 Literature review

2.1 Green Ports Definition

The concept of green port development and operation will bring about positive transformation in line with UN Sustainable development goals. It was introduced in 1997 by several ports as part of their comprehensive program to mitigate the environmental impact of ports (Mahmud et al., 2023). The definition of green port has evolved since then and scholars have defined it differently. While attempting to define green ports some scholars have treated green ports as sustainable ports. The variations of these definitions are critically explored in this review. Besides, while conceptualizing Chang and Wang (2012) as cited by Mahmud et al. (2023) defined green ports as tool for harmonisation of the principles of sustainability, economic prosperity, environmental preservation and social participation. Similarly, Lam and Li (2019) consider green ports as fulfilment of economic, social, and environmental objectives guiding ports towards sustainability. These definitions are synonymous to Muangpan and Suthiwartnarueput (2019) definition of sustainable ports which posits that Sustainable ports seeks to enhance cost efficiency, environmental and social sustainability in ports. This implies that the green port definition of Chang and Wang (2012) as well as Lam and Li (2019) could be viewed as sustainable port according to Muangpan and Suthiwartnarueput (2019) . In addition, Lim et al. (2019) highlighted that the primary “objective of a sustainable port is to achieve a socially acceptable and safe port that is energy-efficient and environmentally friendly, while at the same time maximizes economic profit”. Thus, consolidating the view of Muangpan and Suthiwartnarueput (2019). Figure 1 summarizes the dimensions of a sustainable port.

Figure 1 Dimensions of sustainable port



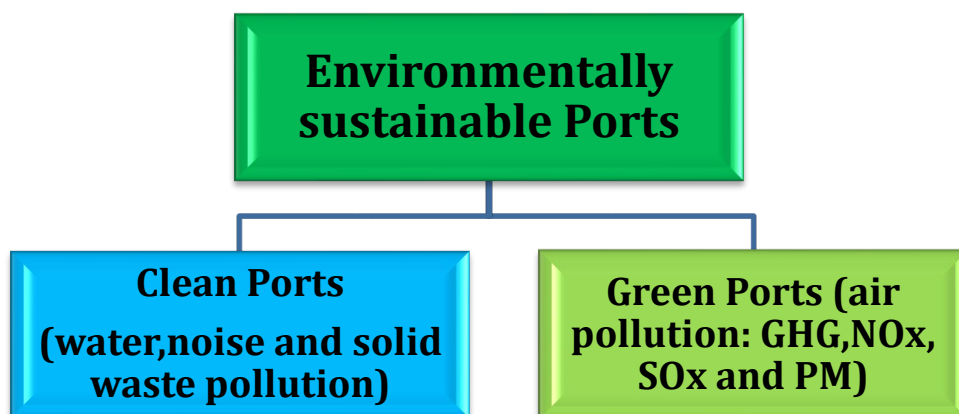
Source: (Muangpan & Suthiwartnarueput, 2019)

The call for greener shipping accelerated after the implementation of IMO MARPOL Annex VI convention in 2003 and there is desire to propagate its effect on greener port development and operation (Arof et al., 2021). This implies that becoming green means being environmentally sustainable. The green port concept was formally proposed at the UN Climate Change Conference in 2009 (Wan et al., 2018). Therefore, green ports refer to eco-friendly ports with efficient resource utilisation and low energy consumption (Di Vaio et al., 2018; Wan et al., 2018). Thus, suggesting that the core idea of green port concept evolved around environmental sustainability. This is supported by the scientific investigations of 1051 green port literatures by Lin et al. (2022) which discovered that the focus was on the following issues: “impact”, “management”, “pollution”, “emissions”, and “model”. However, FAHDI et al. (2019) as cited by Mahmud et al. (2023) considered green ports as ports having minimal adverse effects on the society and environment by managing waste, noise, air and water quality. This definition generally focusses on environmental sustainability. Although the definition of FAHDI et al. (2019) mentioned the various aspects of environmental pollution reduction by ports, it is similar to the definition of Di Vaio et al. (2018) and Wan et al. (2018). The only difference is FAHDI et al. (2019) definition considered the society. In addition, time dimension was introduced by Pavlic et al. (2014). Their studies defined green port as the result of a long-term plan to build eco-friendly port infrastructures. The weakness of this definition is that the amount of time involved depends on the resources available and may vary from one country to

another. According to Chen et al. (2019) “Green ports” seeks to achieve a balance between environmental impact and economic gains with the primary objective of mitigating emissions of harmful gases from ports and ships.

However, the studies conducted by Vakili (2023) clearly distinguished the green and clean concepts with respect to shipyards. According to his studies, the clean concept deals with reduction of environmental impacts such as water, land and noise pollution while the green concept deals with the reduction of air emissions. The combination of the two concepts ensures environmental sustainability. Similarly, green fuels are defined as carbon-free or carbon-neutral fuels, produced from renewable feedstocks using renewable electricity (Institute of sustainability Studies, 2024). Therefore, the green shipyard concept taxonomy of Vakili (2023) is consistent with the green fuels concept. Additionally, Wan et al. (2018) referred to green port as low-carbon ports which is in agreement with Vakili (2023) green concept. Therefore, Vakili (2023) green concept can also be applied to ports to maintain homogeneity of taxonomy in the literature as summarized in Figure 2. Hence, in this dissertation, green ports are assessed based on implementation of measures to reduce GHG emissions. These measures which are discussed in the subsequent sections also contribute in reducing NO_x, SO_x and PM.

Figure 2 Clean Port Vs Green port concept



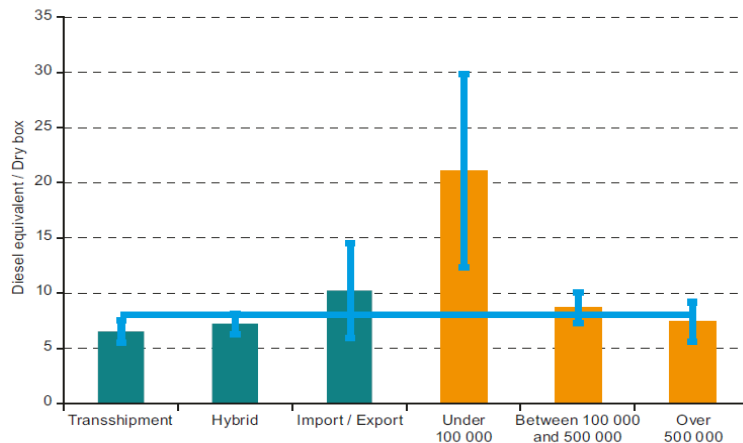
Source: (Vakili, 2023)

2.2 Energy Consumption in Ports

Energy consumption of ports is central in the broader discourse of green ports. This is because ports are significant consumers of energy and therefore contribute to GHG emissions. As the global attention has shifted towards climate change and its mitigation, ports are required to improve their energy efficiency to reduce energy cost and meet sustainability goals (Wilmsmeier & Spengler, 2016). There is no unified or standard tool to measure energy efficiency of ports. However, the ECLAC energy consumption survey technical report authored by Wilmsmeier and Spengler (2016) involving 41 container terminals in 17 countries with a combine throughput of over 37 million TEUs examined the energy consumption of container terminals. The report revealed that the median energy consumption of handling one dry container in Latin America and Caribbean region was 8 litres of diesel equivalent (LDE) in 2015. This represented a slight reduction in energy consumption compared to their previous survey findings in 2013 which showed that the median energy consumption for handling one dry container was 8.6 LDE (Wilmsmeier & Spengler, 2015). According to Spengler & Wilmsmeier (2019) as cited by Alamoush et al. (2020) “Overall, each dry container across the globe consumes around 10.4” LDE. However, energy efficiency of ports is influenced by number of factors including port size and type, type of cargo handled (Wilmsmeier & Spengler, 2016) and degree of automation (Xin et al., 2014). Different type of ports has different energy profile due to variation in CHE required. Therefore, energy consumption of container terminal ports cannot be compared to cruise or bulk terminal ports. Additionally, the type of cargo also influences the energy consumption in many ways. For example, liquid bulk terminals have different equipment and energy requirements compared to dry bulk terminal. Similarly, container terminals handling more reefer containers will consume more energy compared to those handling less reefers. This makes energy consumption benchmarking of ports complicated and difficult. However, Wilmsmeier and Spengler (2016) attempted to address some of these aspects in their energy consumption

benchmarking studies. Figure 3 shows their results based on port type and volume of container handled,

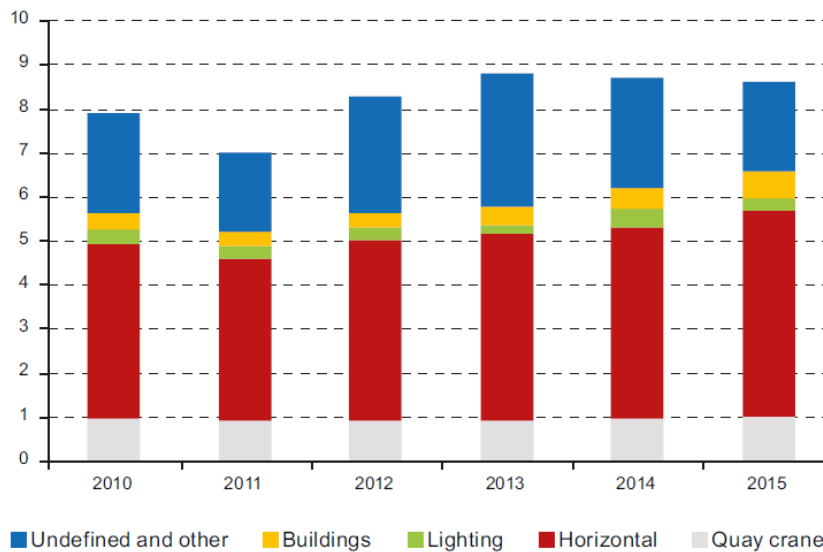
Figure 3 Container Terminal Energy consumption by type and size



Source: (Wilmsmeier & Spengler, 2016)

From the above results presented by Wilmsmeier and Spengler (2016), bigger container terminal ports handling over 500 000 containers recorded the lowest median energy consumption per dry container. This may be due to economic of scale allowing them to invest in modern energy efficient technologies at a reduced cost. Similarly, transshipment ports registered the lowest energy consumption per dry container handled. This is because there is limited horizontal movement in transshipment ports compared to hybrid or import/export ports. Their results shown in Figure 4 also clearly indicates that horizontal movements in container terminals accounts for the highest share of energy consumption.

Figure 4 Container Terminal Energy consumption by Energy activity cluster



Source: (Wilmsmeier & Spengler, 2016)

The energy consumption of port operation can be categorized into two namely, necessary and wasted energy; therefore, energy efficiency measures reduce wasted energy (Alamouh et al., 2020). In the 2024 ESPO environmental priorities report, energy efficiency was ranked second after climate change (ESPO, 2024). “57% of European ports developed energy efficiency programs, and 20% adopted measures to utilise” RE (Alamouh et al., 2020).

Ports can improve their operational and energy efficiency through digitalization and automation. This can be achieved by utilizing digital solutions to identify, monitor and aggregate operational data (Alamouh et al., 2020) which can be used to make well informed data driven decisions such as energy efficient scheduling. Furthermore, digitalization and automation of container terminals help in optimization of terminal equipment, hence reducing unnecessary container lifts, shuffles, travel distances and minimizes weight imbalances (Lee et al., 2015; Xin et al., 2014). This will result in reduction of energy consumption.

2.3 Port GHG accounting

The GHG protocol provides a mechanism for organisations including seaports to account for their GHG emissions. It categorises GHG emission into scope 1, scope 2 and scope 3. Direct GHG emissions from the port activities such as cargo handling and pilotage operation fall under scope 1 emission. The GHG emissions associated with the electricity consumption for lighting, heating, ventilation and air conditioning systems are categorised under scope 2 emissions. (WRI & WBCSD, 2004). However, if the port is involved in power generation through the implementation of microgrid in an island mode, then the emissions resulting from electricity consumption will fall under scope 1. The other indirect GHG emissions related to port activities such as emissions from trucks, employee commuting and ships are categorized under scope 3 emission (WRI & WBCSD, 2004). Similarly, the ISO 14064-1:2018 also provides guidelines for quantification, reporting and verification of GHG emissions and removal. Both the GHG protocol and ISO 14064-1:2018 have the same goal despite some differences in the way GHG emissions are quantified and reported (Freitas & Gervásio, 2024). None of the two standards provide a detailed standardised mechanism to quantify or benchmark port GHG emission. This is because seaports are complex in nature due to the different activities and variation of supply chain and physical boundaries. However, some scholars and ports have attempted to benchmark port emission based on the principles of the above standards. The research conducted by Azarkamand, Wooldridge and Darbra (2020) showed that number of ports have developed methodologies for calculating their carbon footprint. Besides, Freitas and Gervásio (2024) conducted a benchmarking study to compare GHG emissions in EU ports based on the reported port sustainability data. Their results showed that carbon footprint of ports in EU ranged from 0.017 kg CO₂ eq./tonne to 1.27 kg CO₂ eq./tonne, considering scope 1 and 2 GHG emissions. After factoring scope 3 emissions, it varied from 2.0 to 5.4 kg CO₂ eq./tonne. Scope 3 emissions is therefore dominant, representing about 97% of GHG emissions from the ports (Freitas & Gervásio, 2024). Similarly, Azarkamand, Ferré and Darbra (2020) conducted a study on carbon footprints of ports using a standard tool. However, in assessing the scope 3 emission,

they considered only employee commuting which is a limitation of their study. Most recently, Tombak et al. (2025) also conducted comparative studies on “methods for calculating GHG emissions in Baltic Sea ports” using EVISA (Energiaviisas satama) open-source tool. Their results also revealed that scope 3 is the dominant contributor to the port GHG emission. It is therefore, important for ports to implement green port strategies to mitigate these GHG emissions.

Despite the above attempts to quantify and benchmark seaport GHG emission, there are many limitations and challenges yet to be addressed. The study conducted by Tombak et al. (2025) revealed data reporting gaps and application of wrong emission factors by some ports. Significant variation was also discovered in the data collection methodologies, calculations principles and the emission scopes considered. This makes it difficult to compare ports in terms of GHG emission. Additionally, the key limitations to carbon footprint benchmarking identified by Freitas and Gervásio, (2024) was selection of functional units since ports are multifunctional. For instance, selection of functional unit will not be straightforward for a port operating a container and passenger terminals. Additionally, variation in boundary definition significantly hampers GHG accounting and benchmarking efforts. For example, port of Rotterdam considers ship emissions up to 60 km from the coastline while POLA considers emissions within 40-nautical mile and port of Oslo considers GHG emission inventories in the sea area within the boundaries of the city (Freitas & Gervásio, 2024). Similar challenges were echoed in the port emission assessment tool kit published by the IMO and IAPH. It provides mechanisms for ports to account for their emission and compare the results yearly but it points out the fact that such emissions cannot be used to benchmark or compare ports due to numerous factors that could influence port GHG emissions (GEF et al., 2018a).

However, considering all the challenges and complexities associated with port GHG emission quantification and benchmarking, there is the need to develop a standardised and simplified assessment tool that can be used to compare ports. An assessment tool

based on successful implementation of Port GHG reduction measures may address this challenge.

2.4 Existing Port Environmental assessments and certification frameworks

There are number of initiatives and frameworks to assess the environmental performance of ports. These include the Green Marine Environmental Program (GMEP), Green Port Award system (GPAS) and Ecoport certification programs which aim at continuously improving the environmental performance of ports seeking to achieve such certificate (Fei et al., 2025). All the above certification programs are process based, to ensure ports meet their environmental standards and continuously improve on it. This is similar to the ISO 14001 standard in principle. Therefore, these frameworks do not provide a mechanism for quantitative assessment of port environmental performance. To fill this gap Rodrigues et al., (2021) conducted a study with the aim of harmonising assessment of port environmental sustainability using three KPIs namely: GHG emissions, water and energy consumption. The eight Ports under study were ranked based on their performance under each KPI category. Similarly, Milošević et al. (2023) developed a port environmental index (PEI) based on Internet of Things (IoT), relying on real-time data from sensors. Their study utilised a quantitative approach enabling comparison of similar port terminals based on their environmental performance. However, using this IoT-based methodology to evaluate PEI requires an advance and well-established ICT infrastructure.

2.5 Key Performance Indicators of Green Ports

The literatures on sustainable and green ports revealed variations in KPIs although there are points of convergence in some cases. Chiu et al. (2014) identified five important criteria for green ports which are Environmental quality, Use of energy and resource, Habitat quality and port greenery, waste handling and social participation. These KPIs also tend to reflect sustainable ports. Similarly, Muangpan and Suthiwartnarueput (2019) broadly categorized sustainable port KPIs into four main groups, environmental, social, economic, and port organisational management. The

variation in the definition of green ports led to variations in KPIs, making it difficult to use a standardized Indicators for assessing the “greenness” of a Port. Therefore, a key question arises, which measures serve as pre-requisite criteria for certifying or labelling a port as a green port (Lawer et al., 2019)?.

The KPI selection in this dissertation is based on implementation of port GHG emission reduction measures. These KPIs can be categorised based on which emission scope they impact. Port energy efficiency which is discussed in section 2.2 can be categorised under scope one because it is related to emission reduction achieved due to reduction of energy consumption which is influenced by the port’s own activities (WRI & WBCSD, 2004). This can be achieved through reduction of wasted energy and design improvements of port equipment, machinery and layout. Research showed that cargo handling operation accounts for the highest share of energy consumption and scope one GHG emissions in ports as presented in the Table 1 (Martínez-Moya et al., 2019).

Table 1 *Energy consumption and CO2 emission in NCTV 2011*

	Type of Consumer Centre	2011	
		kWh	CO ₂ Tonnes
Electrical Consumption	STS Cranes	6 510 256	2180.935
	Yard Lightning	2 438 803	816.999
	Offices	1 061 346	355.551
	Container Reefers	9 193 395	3070.787
	TOTAL	19 203 800	6424.272
Diesel Fuel Consumption	2011		
	Type of Consumer Centre	TOEs	CO₂ Tonnes
	RTGs	3266.7	9996.102
	Yard Tractors	1684.6	5154.876
	Reach Stackers	163.9	501.534
	Empty Forklifts	52.8	161.568
	TOTAL	5168.0	15 814.080
TOTAL (electrical + diesel)			22 238.352

Source: (Martínez-Moya et al., 2019)

In many ports most of these CHE are powered by diesel oil, further contributing to emission of GHG, NO_x, SO_x and PM. There is a gradual shift towards electrified port

CHE because it reduces energy consumption and emissions from electricity consumption are much lower compared to using fossil fuels in many cases provided the electricity is coming from cleaner sources (Yang & Chang, 2013). For this reason, an increasing number of new CHE models are electrified or diesel-electric hybrid (Iris & Lam, 2019). However, even, if the electricity is not from renewable sources, electrification of CHE will shift GHG emission from Scope one to scope two. The studies conducted by Yang and Chang (2013) showed that using Electrified Rubber-tired gantry (RTG) resulted in “86.60% reduction in energy costs and 67% reduction in GHG emissions compared to diesel-fuelled conventional RTGs”

Alternatively, utilisation of green fuels such as green hydrogen, e-methanol, ammonia, biogas, biofuels, etc will also reduce the scope one emissions. For example, Port of Rotterdam most important green fuel project is the production of green hydrogen using renewable electricity (DEMİR et al., 2022). Additionally, port greenery is a very important initiative ports can undertake to improve air quality (Chiu et al., 2014). It involves planting of trees, ornamental flowers, mangrove reforestation, etc. These plants help in carbon sequestration, therefore supports decarbonisation through nature-based solution. Energy efficiency, electrification and green fuel utilisation are identified as measures to reduce Port GHG emissions (Alamouch et al., 2020; Chiu et al., 2014)

Port smart grid concept presented by Prousalidis et al. (2014, 2017) reduces GHG emission by utilising the potential of RE and integrating energy storage systems in vehicles and CHE into the grid (Alamouch et al., 2020). This is done through a centralised automated system that manages the bidirectional power flow from the grid to electricity consumers, using sensors and other monitoring devices (Yiğit et al., 2016). The smart grid concept is implemented by Port of Amsterdam (Alamouch et al., 2020). Similarly, the microgrid concept enables ports to move towards achieving energy self-sufficiency by generating, transmitting and distributing electrical power which can be connected or disconnected from main grid, thus operating in grid

connected or island mode (Alamoush et al., 2020; Yiğit et al., 2016). Microgrid also harnesses RE and integrates energy storage and backup generators to control energy demand and supply. RE sources such as wind and solar do not provide steady power flow. Therefore, it is important to have storage system to store excess energy during high wind velocity and peak solar irradiation periods, hence reducing energy waste and improve energy efficiency. As ports are now transforming into energy hub, implementation of Smart and microgrid is paramount to handle growing energy demand from OPS and electrified CHE. Besides, if the national grids cannot handle the growing demand of the port and city, then this will incentivise ports to implement microgrids. An example of a port implementing microgrid is the POLA (Alamoush et al., 2020).

In addition, Ports should play a key role in mitigating scope three GHG emission through effective implementation of vessel arrival system (VAS) and virtual arrival (VA) agreements to help facilitate JIT berthing of ships. VAS are tools used by port authorities to optimise the timing of vessel arrival. “VA is an operational process that involves an agreement to reduce a vessel’s speed on a voyage to meet a required time of arrival when there is a known delay at the discharge port” (INTERTANKO, 2010) as cited by Jia et al. (2017). Furthermore, according to Jia et al., (2017) application of VA policy yielded savings of 138 tonnes of fuel and 655 tonnes CO₂ per voyage. Therefore, JIT arrival reduces scope three port GHG emissions. Besides, OPS usage is another green port KPI that has attracted the attention of researchers. It is a system that provides power supply to the vessels at berths. The studies of OPS by many scholars revealed that it is one of the measures recommended to reduce carbon footprint of shipping in port areas (Cullinane & Cullinane, 2019; Poulsen et al., 2018; Styhre et al., 2017; Yun et al., 2018). Besides, to support the green energy transition of the shipping sector, ports need to provide alternative fuel bunkering facilities since they are responsible for providing bunkering services to vessels (Alamoush et al., 2020; Styhre et al., 2017). This will attract ships utilising such fuels to call the port.

Then it implies that the scope three emissions of the port will also reduce as a result of an increasing number of ships using alternative fuels.

With regards to hinterland transport, ports can use regulations and incentives to mitigate GHG emissions related to cargo transport and employee commuting. For example, mandatory clean truck program has been implemented by POLA, POLB and port of Seattle which is estimated to yield CO₂ reduction of 46% by 2031 (Alamoush et al., 2020). Similarly, ports can adopt policies to encourage green employee commuting to reduce GHG emission. Employee commuting was considered by Azarkamand, Ferré and Darbra (2020) in their assessment of port carbon footprint. Ports can equally reduce their scope three GHG emission by effectively managing truck congestion inside and outside the port through implementation of measures such as truck appointment system (TAS) and smart gates (Alamoush et al., 2020). A TAS is a mechanism where trucks book time in advance before going to the port (Alamoush et al., 2020). The port of Vancouver in Canada is among ports implementing TAS (Li et al., 2018).

Chapter 3. Methodology

3.1 Introduction

The literature review revealed twelve KPIs which are used to assess ports based on implementation of GHG emission reduction measures as summarised in Table 2. The KPIs are categorised based on the emission scope they impact. These KPIs may not have the same weights based on opinions of different experts. Therefore, in order to develop a GPI, it is important to first establish the weights of these KPIs. This can be done through the use of MCDM tools such as entropy method, TOPSIS, AHP, PCA, Delphi method, SMART, etc. There are so many MCDM tools that exist, each with its pros and cons. However, the choice of method to be used depends on its suitability in relation to the research topic. In this research Fuzzy AHP (FAHP) is used to derive the weights of the KPIs and Adaptive Neuro Fuzzy Inference system (ANFIS) is used to develop GPI model.

Table 2 Summary of identified green port KPIs

Scope	Code	KPI	Source
Scope 1	K1	Energy efficiency	(Alamoush et al., 2020; Chiu et al., 2014; Fei et al., 2025; Sdoukopoulos et al., 2019)
	K2	Electrification of port equipment and machinery	(Alamoush et al., 2020; Chiu et al., 2014; GEF et al., 2018b; Sdoukopoulos et al., 2019; Yang & Chang, 2013)
	K3	Green fuel utilization	(Alamoush et al., 2020; Chiu et al., 2014)
	K4	Port Greenery	(Chiu et al., 2014)
Scope 2	K5	Carbon neutral/ Renewable energy Usage	(Alamoush et al., 2020; Chiu et al., 2014; Fei et al., 2025)
	K6	Implementation of smart or microgrid	(Alamoush et al., 2020; Yiğit et al., 2016)
Scope 3	K7	Onshore Power Supply (OPS) usage	(Alamoush et al., 2020; Chiu et al., 2014; GEF et al., 2018b)
	K8	Just in time arrival	(Alamoush et al., 2020; Jia et al., 2017)
	K9	Alternative fuel bunkering (AFB)	(Alamoush et al., 2020; Styhre et al., 2017)
	K10	Green Hinterland transportation	(Alamoush et al., 2020; Chiu et al., 2014)
	K11	Employee commuting	(Azarkamand, Ferré and Darbra 2020; Sdoukopoulos et al., 2019)
	K12	Truck congestion	(Alamoush et al., 2020; Sdoukopoulos et al., 2019)

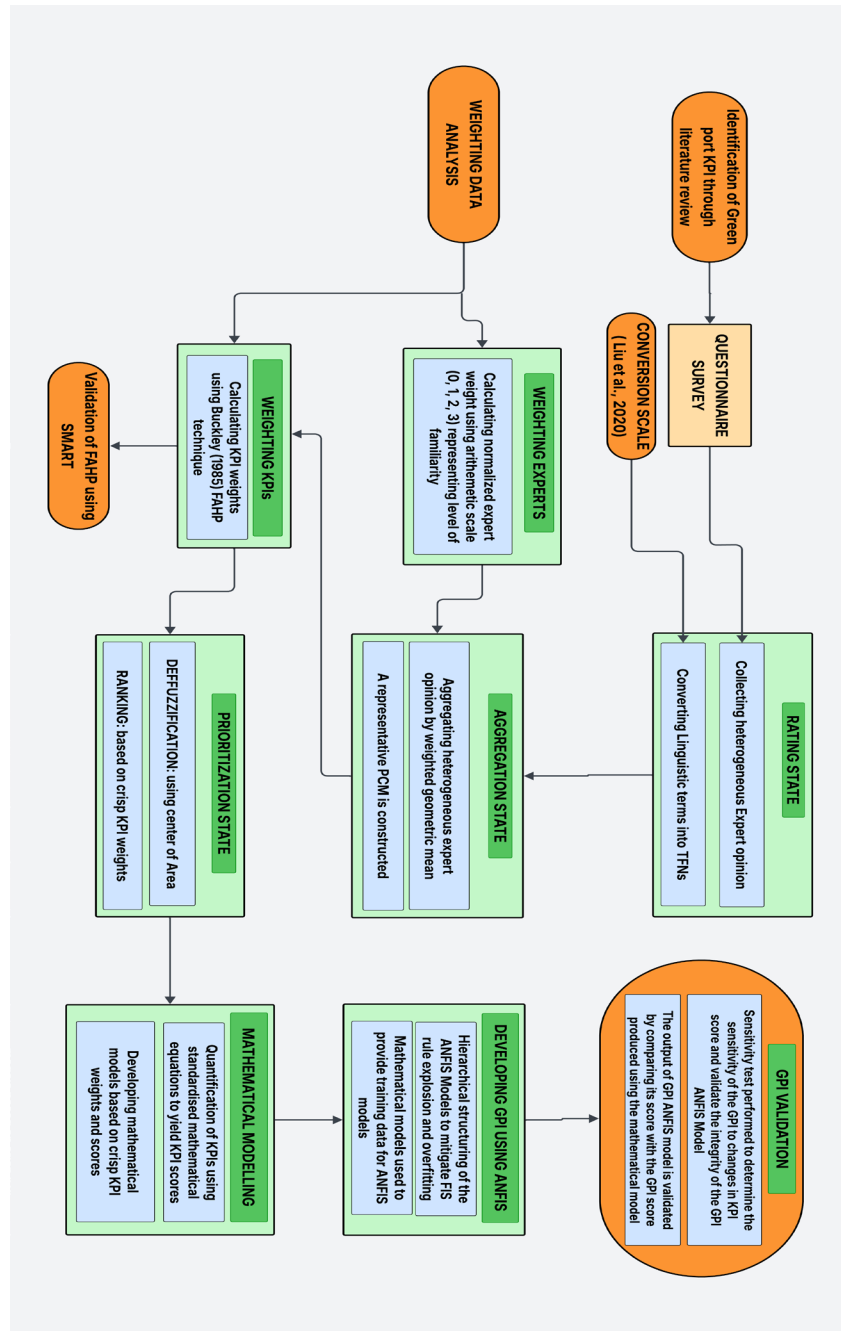
Compiled by Author

3.2 Conceptual framework

The conceptual framework of this dissertation is shown in Figure 5. The first step involved literature review to identify relevant green port KPIs with respect to implementation of GHG emission reduction measures. A questionnaire survey was designed and distributed with the aim of determining the relative importance of the green port KPIs. The questionnaire survey also assessed the homogeneity or heterogeneity of experts with respect to familiarity to green port concept. Weighting of expert opinion is necessitated to reflect the reality that the survey participants are heterogeneous which means they have different level of familiarity to green port concept. Otherwise, if the survey participants were assumed to be homogeneous then their expert opinions will carry equal weight. FAHP methodology is used to determine the weights of the KPIs. These weights and KPI scores are used to develop the

mathematical model which is used to generate training data for the ANFIS-based GPI models. Series of validation test are conducted to determine the robustness and sensitivity of the ANFIS-based GPI model. The justification and detail explanation of the proposed conceptual framework are given in the subsequent sections.

Figure 5 Conceptual framework of the proposed methodology



3.3 Justification of Methodology

Despite the popularity of AHP as a MCDM tool, many have criticised it because of its inadequacy to address the inherent imprecision and uncertainty associated with mapping perception of decision makers (DMs) into crisp numeric values (Deng, 1999). To address this weakness, AHP is combined with Fuzzy set theory proposed by Zadeh (1965) which is a popular methodology for handling imprecision and uncertainty. This hybrid method called Fuzzy-AHP, maintains the advantage of traditional AHP while tolerating vagueness in decision making. Hence, it has become a popular methodology among researchers in the field of environmental studies including port sustainability studies. This methodology is used by Chiu et al. (2014), Doan and Huynh (2024), and Kunambi and Zheng (2024) to assess green ports. Additionally, both the green port and sustainability concepts as a whole are fuzzy in nature. The above considerations justified the use of FAHP in this dissertation to evaluate the weights of the KPIs and GHG emission scopes.

On the other hand, FIS is a powerful tool used to solve complex and non-linear problems where enough data is not available and/or mathematical modeling is difficult which may involve uncertainty and imprecision (Ng & Ölçer, 2012). It allows personal experience and expert knowledge to be transform into linguistic rules which are in the form of IF-Then clauses. FIS has been used by Ng and Ölçer (2012) to model passenger comfort index which measures passenger comfort based on motion sickness index and predicted mean vote. FIS has proven to be a robust methodology in modelling imprecise problems. There are basically two types of FIS, namely: Mamdani (1974) and Sugeno (1985). The review of the two systems by Jun et al. (2009) and Mathworks (2010) as cited by Ng and Ölçer, (2012) revealed the following:

- The main difference between the two techniques is that the output membership function in the Mamdani's inference system is expected to be fuzzy sets while it is either linear or constant in the sugeno inference system
- The computational efficiency and compactness of Sugeno FIS is an additional benefit to real-time systems such as performance evaluation of green ports.

- Additionally, Sugeno type FIS is more ideal for mathematical analysis when compare to Mamdani type FIS.
- Furthermore, Sugeno type FIS performs very well with optimization and adaptive techniques.

Sugeno type FIS is therefore superior to Mamdani FIS. However, the main disadvantage of FIS in general, is that it requires experience to accurately define memberships functions (MFs) and fuzzy rules which is often time consuming (Singh et al., 2012). While searching for an alternative, Artificial Neural network (ANN) has been considered by some researchers as a better solution. It works by establishing the relationship between input and output from training data to determine MF parameters and distribution (Naderloo et al., 2012) as cited by Tan et al. (2017). However, the main disadvantage of ANN is difficulty in establishing the ideal size and optimal structure of the network (Singh et al., 2012). Therefore, the two techniques can be combined to overcome their individual limitations. This hybrid technique is referred to as ANFIS introduced by Jang (1993) as cited by Tan et al. (2017). It combines the strength of FIS in dealing with explicit knowledge (which can be explained and understood) with ANN for dealing with implicit knowledge (acquired by learning) (Singh et al., 2012). It allows the modelling of FIS by extracting knowledge from a training data to compute the parameters of the membership function that effectively allows the associated FIS to track the input and output data (Ng & Ölçer, 2012). ANFIS is therefore, a suitable technique in effectively modeling GPI by using the mathematical models to provide training data.

3.4 Proposed Methodology for Quantification of KPIs

There are many literatures available on green ports. The green port KPI are discussed and evaluated by Chiu et al. (2014) and Kunambi and Zheng (2024). They did not propose a methodology to quantify the KPIs, instead Chiu et al. (2014) conducted a survey asking experts to give direct rating of the KPIs with respect to each of the three Ports under study using a fuzzy scale. However, in this dissertation, each of the 12

KPIs are quantified, normalised and expressed in percentages to enable chronological assessment of green port performance and comparison of performance of different ports irrespective of their sizes and volume of cargo handled. The KPIs are quantified as follows:

K1. Energy Efficiency

It is established in the literature review that the energy profile of a port is largely dependent on its functionality. Besides, it is also important to establish baseline from which energy efficiency can be measured. Hence, the container terminal energy consumption benchmarking survey findings of ECLAC reported by Wilmsmeier and Spengler (2015) is assumed as the baseline. According to the report:

The median energy consumption for handling one dry container = 8.6 LDE

The median energy consumption for handling one reefer container = 24.7 LDE.

Conversion factor = 9.94KWh/LDE

Therefore, assuming a container terminal port handles equal proportion of dry and reefer containers, the energy efficiency baseline (EEF_{ref}) is calculated as follows:

$$EEF_{ref} = \frac{8.6+24.7}{2} = 16.65 \text{ LDE/TEU} = 16.65 \times 9.94 = 165.5 \text{ Kwh/TEU}$$

Otherwise, where the ratio (R) of dry containers to reefer containers is not equal to one, then EEF_{ref} is given by:

$$EEF_{ref} = 165.5 - C_f \quad (1)$$

Where: C_f is the reefer correction factor. A container terminal handling higher proportion of reefer containers will have a higher energy consumption compared to a port handling smaller proportion of reefers. Thus, necessitating the need to introduce a correction factor to accommodate these variations in the energy efficiency calculation. This correction factor can be calculated using equation 2.

$$C_f = 16.65 - \left(\frac{8.6n_{DC} + 24.7n_{RC}}{C_T} \right) \quad (2)$$

The ratio (R) of reefer containers to dry containers is calculated as follows:

$$R = \frac{n_{RC}}{n_{DC}} \quad (3)$$

Where: n_{RC} is the number of reefer containers and n_{DC} is the number of dry containers. An excel model has been created to determine the reefer correction factor for any given R value. The graphical representation is shown in Figures 6 and 7.

In general Energy efficiency of a container terminal (EEF_{CT}) is given by:

$$EEF_{CT} = \frac{E_T}{C_T} \quad (4)$$

Where: E_T is the total annual energy consumption, C_T is the annual cargo throughput

Figure 6 Reefer correction factor curve (a)

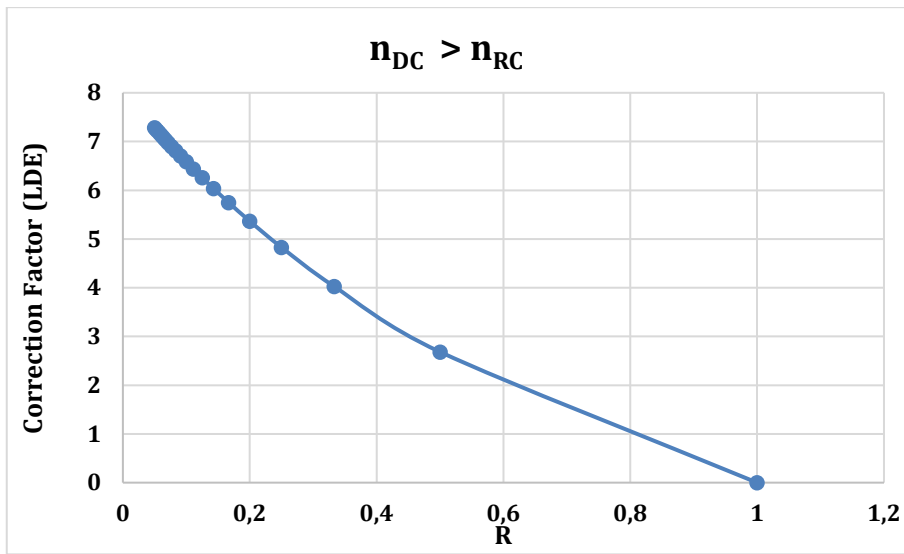
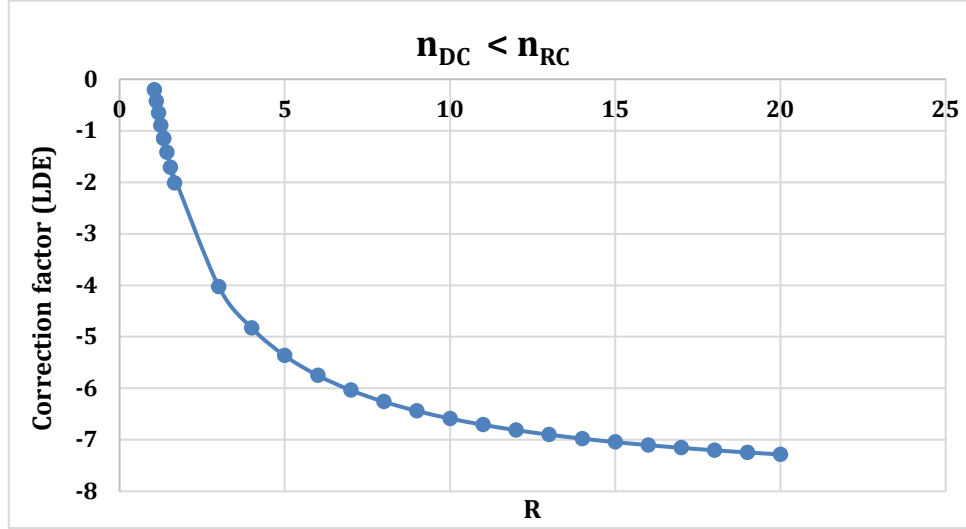


Figure 7 Reefer correction factor curve (b)



Therefore, percentage improvement in energy efficiency can be calculated as,

$$EEF_{Imp} = \frac{EEF_{ref} - EEF_{CT}}{EEF_{ref}} \times 100 \quad (5)$$

K2. Electrification of Port Equipment and Machinery (PEM)

This KPI is evaluated by first assessing the total number of PEM (n_{tpem}) which includes: CHE and machinery, harbour crafts and port vehicles. Then the total number of electrified PEM (n_{epem}) are evaluated. Thus, the percentage of electrified PEM is given by:

$$EL_{PEM} = \frac{n_{epem}}{n_{tpem}} \times 100 \quad (6)$$

K3. Green Fuel Utilization (GFU)

This is quantified by evaluating the total amount of green fuel utilised by the port annually (T_{Gfu}) and expressing it as a percentage of the total amount of fuel consumed in the port annually (T_{Tf}). These green fuels include: hydrogen, biogas, biofuel, ammonia, etc. It is therefore, given by the formula:

$$GFU = \frac{T_{Gfu}}{T_{Tf}} \times 100 \quad (7)$$

K4. Port greenery (PG).

Port greenery is a decarbonisation initiative involving nature-based solutions such as tree planting. Plants improve air quality by removing CO₂ from the atmosphere and releasing oxygen. However, different plant species have varying carbon sequestration rates. Hence, this variation should be factored in quantifying this KPI. Therefore, port greenery KPI is evaluated as follows:

$$PG = \frac{A_{PG}}{A_T} \times C_a \times 100 \quad (8)$$

Where: A_{PG} is the area covered by port greenery, A_T is the total area of the port and C_a is the correction factor reflecting the variation in plant species. This will be assumed to be one in this dissertation. Quantifying this correction factor is a research domain of its own because of inadequate data. More data is needed to compute the carbon sequestration rate of a plant/tree which includes age, biomass above ground and biomass below ground (Forfora et al., 2024; Sohrabi et al., 2016; Tooichi, 2018). Once the carbon sequestration rate is computed for all possible plant species that may be used for port greenery initiatives, then the baseline can be established with respect the species with the lowest carbon sequestration rate. Hence, the correction factor C_a is given by:

$$C_a = \frac{CSR_P}{CSR_b} \quad (9)$$

Where: CSR_P is the carbon sequestration rate of the trees planted and CSR_b is the baseline carbon sequestration rate established from research outside the scope of this dissertation.

K5. Renewable energy usage (REU)

This KPI is evaluated by summing all the RE used annually (E_{REU}) (includes electricity supply and district heating) and expressed as a percentage of the total energy consumption of the port. It is given by the formula:

$$REU = \frac{E_{REU}}{E_T} \times 100 \quad (10)$$

K6. Implementation of Smart and Microgrid (SMG)

This KPI is evaluated by assessing the extend of coverage of the smart and microgrid network within the port. Thus, it can be computed by:

$$SMG = \frac{L_{SMG}}{L_T} \times 100 \quad (11)$$

Where: L_{SMG} is the load of the port covered by the SMG network and L_T is the total electrical load.

K7. OPS usage

OPS usage is quantified by computing the ratio of the number of ships using OPS (n_{ops}) to the total number of ships calling the port annually (n_{ts}) and expressed in percentage as follows:

$$OPS_{usage} = \frac{n_{ops}}{n_{ts}} \times 100 \quad (12)$$

K8. Just in time arrival/berthing (JIT)

Similar to K7, this KPI is computed by calculating the percentage of the ships arriving just in time and berthed (n_{jit}). Thus, it is given by:

$$JIT_{arrival} = \frac{n_{jit}}{n_{ts}} \times 100 \quad (13)$$

K9. Alternative fuel bunkering (AFB)

This KPI is quantified by evaluating the total alternative fuels bunkered ($TAF_{bunkered}$) in a particular port and expressing it as a percentage of the amount of fuel bunkered annually ($TF_{bunkered}$) using equation 14.

$$AF_{bunkering} = \frac{TAF_{bunkered}}{TF_{bunkered}} \times 100 \quad (14)$$

K10. Green hinterland transportation of cargo (GHT)

The emission reduction measures associated with the transportation of cargo is evaluated using this KPI. This can be assessed by computing the annual volume of cargo transported using green energy sources (C_{TG}) such as electric truck, electric rails (electricity from RE) and trucks operating on green fuels. The result is normalised using the annual cargo throughput (C_T) as given by:

$$GHT = \frac{C_{TG}}{C_T} \times 100 \quad (15)$$

K11. Employee commuting (EC)

Similar to K10, green employee commuting with respect to scope 3 GHG emission reduction is evaluated by first determining the total number of staff/port users travelling green (Emp_{TG}) which is expressed as a percentage of the total number of staff/port users (Emp_T). This can be expressed mathematically as:

$$EC = \frac{Emp_{TG}}{Emp_T} \times 100 \quad (16)$$

K12. Truck congestion (TC)

The contribution of truck congestion to scope three emissions is mitigated through the implementation of truck appointment systems (TAS), good road network and improvement of operation efficiency. Therefore, this KPI can be quantified by measuring the adherence to TAS which is a reflection of the congestion level inside and outside the port. This is given by:

$$TC = \frac{TN_{TAS}}{TN_{Trucks}} \times 100 \quad (17)$$

Where: TN_{TAS} is number of truck arrivals at the port gate as scheduled by the TAS per year and N_{Trucks} is the total truck traffic per year

While successful implementation of TAS is linked to operational efficiency, it is important to note that truck congestion due to poor road network design has not been factored in the evaluation of this KPI.

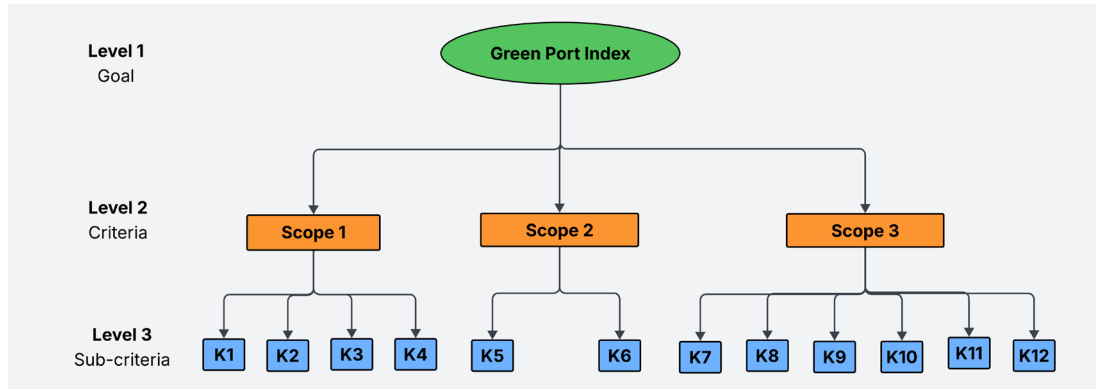
3.5 Fuzzy AHP

Fuzzy AHP follows similar procedure as traditional AHP with the introduction of fuzzy set theory as described earlier. The main processes involve 1) Hierarchical structuring of the problem 2) Data collection through expert questionnaire survey 3) Construction of the pairwise matrix 4) Evaluation of criteria weight 5) Check for consistency and 6) defuzzification. These stages are adapted to evaluate green port KPI weights as follows:

3.5.1 Hierarchical structuring of the FAHP problem

This is done by clearly defining the goal in level 1 which is to determine GPI based on implementation of port GHG reduction measures. In level 2, the weights of criteria (emission scopes) are evaluated with respect to the goal and in level 3 the weight of sub-criteria (KPIs) are evaluated with respect to the emission scopes. The KPIs K1 to K12 are defined in Table 2. The structure of the FAHP problem is shown in Figure 8.

Figure 8 Structure of the FAHP problem



3.5.2 Data Collection

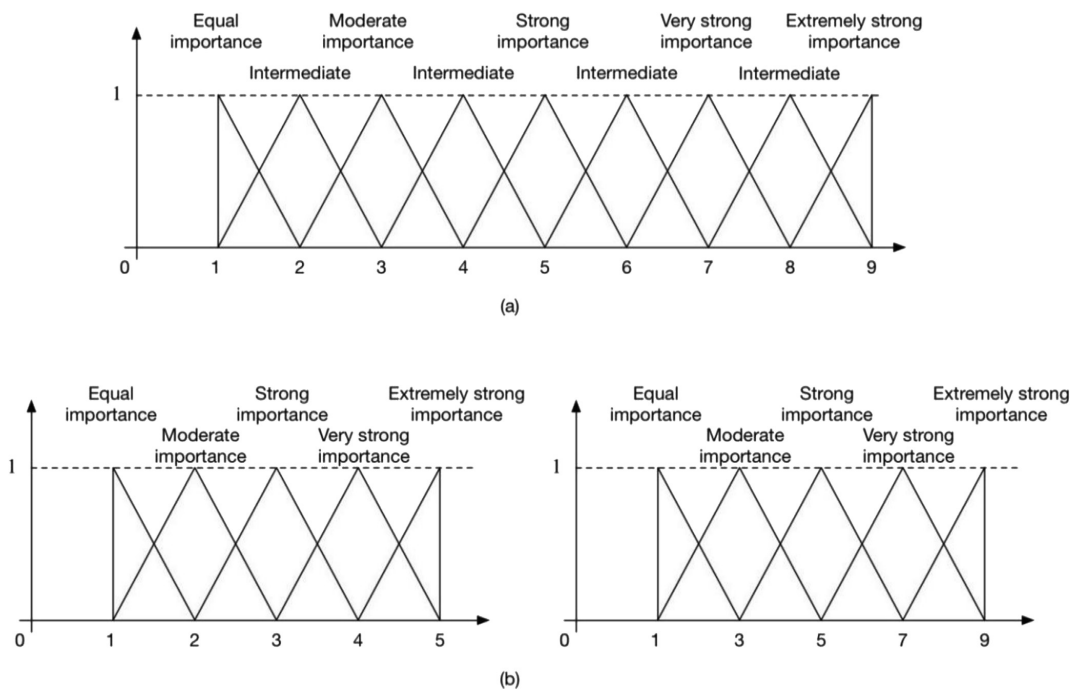
An initial questionnaire survey was design and distributed to ten professionals in the field of maritime energy affairs for validation. Six responses were received indicating that the questionnaire was very complex and difficult to follow the logic. Additionally, the pairwise comparisons of KPIs were inconsistent and cannot be used for calculation of FAHP weights. Thus, necessitating a thorough review and simplification of the questionnaire. This was done and the final questionnaire was sent to experts in port and maritime energy affairs. This method of data collection is chosen over interviews because it eliminates interviewer bias. Multiple experts can be reached by sharing the survey online through email. Besides, the anonymity of the questionnaires reduces pressure and ensures honest assessment. The experts were asked to rate the importance of the KPIs with respect to GHG emission reduction of their respective emission scopes. The importance of the emission scopes was also rated with respect to overall port GHG emission reduction using the scale in Table 3. The questionnaire used for the survey is in Appendix A.

Table 3 Scale of importance

Judgment	Degree of importance	Fuzzy numbers
Not important	1	1, 1, 1
Moderately important	2	1, 2, 3
Strongly important	3	2, 3, 4
Very strongly important	4	3, 4, 5
Extremely strong importance	5	4, 5, 5

The choice of scale depends of the relationship of the alternatives that are been compared. Saaty proposed a 9-level fundamental scale from 1 – 9 which is a numerical approximation of how many times is one alternative more important than the other (Vargas & Saaty, 2022). For closely related alternatives, the scale can further be refined to 5 level scale from 1.1 – 1.9 (saaty, 1990) as cited by El Hefnawy and Mohammed (2014). Researcher have used different refined scale to fit their analysis. For example, Cebeci (2009) and Zyoud et al. (2016) used 5 level scale from 1 – 9, Kilincci and Onal (2011) used 5 level scale from 1 – 4.5, Calabrese et al. (2019) used 5 level scale from 1 – 3.5. Figure 9 shows the 9 level and 5 level scale.

Figure 9 FAHP scale



Source: (Liu et al., 2020)

3.5.3 Construction of pairwise comparison matrix (PCM)

In AHP a DM is ask to make a pairwise comparison of two alternatives or give ratings of alternatives with respect to the criteria (Harker & Vargas, 1987; Stam & Duarte Silva, 2003; Taira et al., 1996; Vargas & Saaty, 2022). The same is done for the criteria with respect to the overall goal. The following equations govern the construction and conditions for consistency of the PCM:

- Comparing an alternative with itself, $a_{ii} = 1$ for $i = 1, \dots, n$
- Reciprocal, $a_{ji} = \frac{1}{a_{ij}}$ for $i \neq j, i, j = 1, \dots, n$ (18)

- Transitive, $a_{ij} = \frac{a_{ik}}{a_{jk}}$ for $i, j, k = 1, \dots, n$ (19)

- where a_{ik} and a_{jk} are direct ratings (importance) of alternatives A_i ($i=1 \dots, n$) and A_j ($i=1 \dots, n$) with respect to the criteria C_k ($k=1 \dots n$) respectively, a_{ijk} is the relative importance of alternative A_i over A_j with respect to criteria C_k

The experts were asked to rate the degree of importance of the KPIs with respect to port GHG emission reduction potentials under their respective emission scopes. The data obtained is given in Appendix B. The PCM is then constructed using equation 18 and 19. The direct rating of alternatives addresses the issue of numerical inconsistencies in the PCM and reduces the time and labour required to complete all the pairwise comparison (Taira et al., 1996). Asking the DMs to make a pairwise comparison can be risky if they do not understand the logic of PCM. This risk is manifested in AHP survey conducted by Tomar and Borad (2012) involving 28 participants, out of the 22 responses received, 8 were not completely filled and out of the remaining 14 responses only 8 were consistent. For a PCM to be used to calculate weights of criteria and alternatives it must meet the conditions for consistency (Kaushik et al., 2024).

The judgements of DMs are converted to TFN using the scale in the Table 3. Let $\tilde{a}_{ij}^t = (l_{ij}^t, m_{ij}^t, u_{ij}^t)$ represents the judgment of a DM with respect to criteria k, Therefore, the judgments are aggregated using the weighted geometric mean given by equation 20. The aggregation of DMs judgement is shown in Appendix C.

$$\tilde{a}_{ij} = \left(g_1 \cdot \tilde{a}_{ij}^1 \otimes g_2 \cdot \tilde{a}_{ij}^2 \otimes \dots \otimes g_q \cdot \tilde{a}_{ij}^q \right)^{\frac{1}{q}} \quad (20)$$

Where g_i is the weight of the expert based on thier level of familiarity with green port concept using a scale of 0, 1, 2, 3 corresponding to not familiar, slightly familiar, averagely familiar and very familiar respectively. Hence, g_i is given by:

$$g_i = \frac{F_i}{\sum_{i=1}^n F_i} \times n \quad (21)$$

Where: F_i is the level of familiarity of expert i in accordance with the arithmetic scale (0,1,2,3) and n is the total number of experts. Therefore, the representative matrix combining the pairwise comparison of all DMs is given by:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \dots & 1 \end{bmatrix} \quad (22)$$

3.5.4 Evaluation of weights

The weights of the KPIs are calculated using Buckley (1985)'s FAHP technique which is effectively used by Murty et al. (2020) to identify the most important factor affecting the borrowing decision of micro-entrepreneurs. This technique involves the following steps:

Step 1

The first step involved taking geometric mean (r_i) of each row of the matrix as given by equation 23:

$$r_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{\frac{1}{n}} \quad (23)$$

Step 2

The inverse of the summation of the geometric means is calculated as follows

$$\left(\sum_{i=1}^n r_i \right)^{-1} = (r_1 + r_2 + \dots + r_n)^{-1} \quad (24)$$

Step 3.

The weight of each KPI (w_i) is calculated by multiplying the geometric mean of each row by the inverse of the summation of the geometric means as given by equation 25:

$$w_i = r_i \times \left(\sum_{i=1}^n r_i \right)^{-1} \quad (25)$$

Step 4.

The sum of weights should add up to one, otherwise the weights are normalized as follows,

$$\bar{w}_i = \frac{w_i}{\sum w_i} \quad (26)$$

3.5.5 Check for consistency

The issue of consistency is addressed in section 3.5.3, however, consistency ratio (C.R) is calculated to verify that the resultant representative PCMs of DMs are consistent.

$$C.R = \frac{C.I}{R.I} \quad (27)$$

Where C.I is the consistency index and R.I is random index which depends on the order of the matrix. Table 4 indicates the random index for a given $n \times n$ Matrix.

Table 4 Saaty's Random index

n	1	2	3	4	5	6	7	8	9	10
R. I	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Source: ((Saaty, 1990), in (El Hefnawy & Mohammed, 2014))

Consistency index is given by:

$$C.I = \frac{\lambda_{max} - n}{n - 1} \quad (28)$$

Where: λ_{max} is the maximum eigenvalue of the matrix and n is the order of the matrix.

3.5.6 Defuzzification

This is the process of converting the TFN into crisp numeric value. There are many techniques of defuzzification. However, the centre of area method is used.

$$\overline{w}_i = \frac{(l_i + m_i + u_i)}{3} \quad (29)$$

The construction of PCM, calculation of weights, consistency check and defuzzification were performed using Microsoft excel. The calculations are shown in Appendix D.

3.6 ANFIS Model

3.6.1 Principle of ANFIS

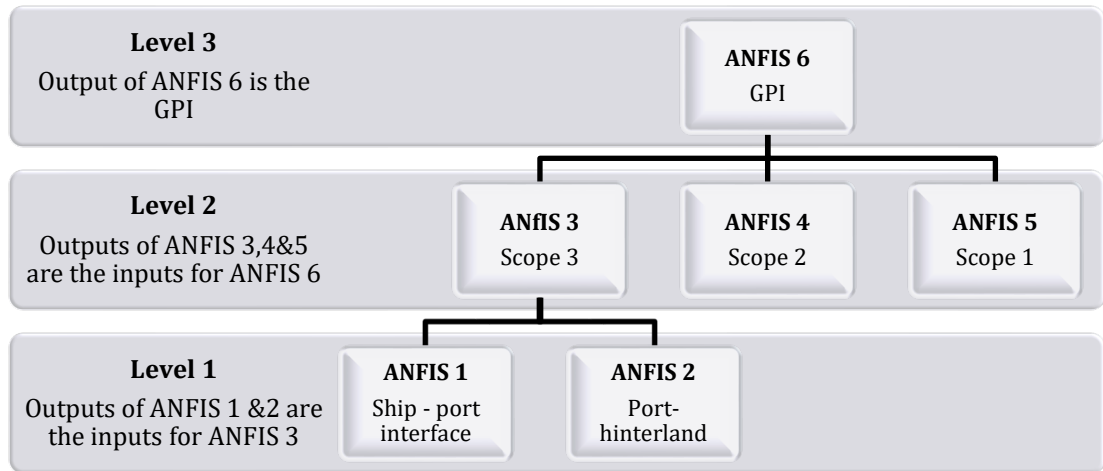
The key concept of the ANFIS training process is to provide an ANFIS output that matches the training data through optimization of MF parameters and fuzzy rules. Its learning algorithm includes least squares and gradient methods, used to estimate initial parameters and compute the mathematical relationship between input and output (Tan et al., 2017). The detailed explanation of the operating principles of multi-layered ANFIS network is given in Appendix E.

3.6.2 Structure of the ANFIS-based GPI model

Generally, the number of rules for a classical FIS is given by: $R = M^n$ Where: M is the number of MFs, n is the number of inputs and R is the number of rules. Going by the classical approach the number of rules for the 12 green port KPIs each with 3 MFs (low, average, high) will be $3^{12} = 531,441$ rules. This rule explosion leads to exponential increase in training time and difficulty in interpreting the results which may not even be accurate. Hierarchical ANFIS method which involves splitting inputs into smaller ANFIS models is used to solve this problem. This method is used by Tan et al. (2017) to measure country sustainability performance. Therefore, hierarchical ANFIS is used in this dissertation to develop the GPI as shown in Figure 10. In this method the outputs of the ANFIS in the lower levels are the inputs to the next level immediately above it. In the GPI model, scope 3 has 6 KPIs with 3 MFs. Classically,

this will require $3^6 = 729$ rules. However, using hierarchical ANFIS, the scope 3 KPIs are divided into two, ships related KPIs (OPS usage, JIT arrival and AFB) and hinterland related KPIs (GHT, EC and TC). Hence, ANFIS 1 which measures ship related green port performance has 27 rules and ANFIS 2 which measures the hinterland related green port performance also requires 27 rules. The overall scope 3 performance which uses ANFIS 1 and 2 as inputs requires 9 rules. Therefore, the total number of rules to measure scope 3 green port performance is 63. Hence, using hierarchical ANFIS reduces the number of rules from 729 to 63. ANFIS 4, ANFIS5 and ANFIS 6 requires 9, 81 and 27 rules respectively. These can be efficiently handled by ANFIS algorithm.

Figure 10 Structure of ANFIS-based GPI model



3.6.3 Mathematical Modelling of the GPI

The GPI can be modelled mathematically using the weights of the KPIs and emission scopes. These mathematical relations are used to provide training data for ANFIS-based GPI model. Let $x_1, x_2, x_3, \dots, x_{12}$ represents the scores of KPIs $k_1, k_2, k_3, \dots, k_{12}$ as defined in Table 2. Similarly, let S_1, S_2 and S_3 denotes the scores of emission scopes 1, 2 and 3 respectively. Therefore, the contribution of a KPI to green port performance is the product of its weight and score, given by $\bar{w}'_{ki} \otimes x_i$, where: $\bar{w}'_{ki}$ is the weight of KPI k_i and x_i is its score. Thus, the scores of the emission scopes are expressed as:

$$\text{Scope 1: } S_1 = (\bar{w}'_{k1} \otimes x_1) + (\bar{w}'_{k2} \otimes x_2) + (\bar{w}'_{k3} \otimes x_3) + (\bar{w}'_{k4} \otimes x_4) \quad (30)$$

$$\text{Scope 2: } S_2 = (\overline{w'}_{k5} \otimes x_5) + (\overline{w'}_{k6} \otimes x_6) \quad (31)$$

$$\text{Scope 3: } S_3 = (\overline{w'}_{k7} \otimes x_7) + (\overline{w'}_{k8} \otimes x_8) + (\overline{w'}_{k9} \otimes x_9) + (\overline{w'}_{k10} \otimes x_{10}) + (\overline{w'}_{k11} \otimes x_{11}) + (\overline{w'}_{k12} \otimes x_{12}) \quad (32)$$

The scope 3 inputs are grouped into two in order to enhance the analysis of the model. These sub groups are the ship related (S) and hinterland (h) green port performance which are evaluated using the following equations.

$$s = \left(\frac{\overline{w'}_{k7}}{\overline{w'}_{k7} + \overline{w'}_{k8} + \overline{w'}_{k9}} \otimes x_7 \right) + \left(\frac{\overline{w'}_{k8}}{\overline{w'}_{k7} + \overline{w'}_{k8} + \overline{w'}_{k9}} \otimes x_8 \right) + \left(\frac{\overline{w'}_{k9}}{\overline{w'}_{k7} + \overline{w'}_{k8} + \overline{w'}_{k9}} \otimes x_9 \right) \quad (33)$$

$$h = \left(\frac{\overline{w'}_{k10}}{\overline{w'}_{k10} + \overline{w'}_{k11} + \overline{w'}_{k12}} \otimes x_{10} \right) + \left(\frac{\overline{w'}_{k11}}{\overline{w'}_{k10} + \overline{w'}_{k11} + \overline{w'}_{k12}} \otimes x_{11} \right) + \left(\frac{\overline{w'}_{k12}}{\overline{w'}_{k10} + \overline{w'}_{k11} + \overline{w'}_{k12}} \otimes x_{12} \right) \quad (34)$$

Therefore, scope 3 green port performance can be evaluated using the scores s and h as follows:

$$S_3 = ((\overline{w'}_{k7} + \overline{w'}_{k8} + \overline{w'}_{k9}) \otimes s) + ((\overline{w'}_{k10} + \overline{w'}_{k11} + \overline{w'}_{k12}) \otimes h) \quad (35)$$

Finally, the GPI can be calculated using scores S_1 , S_2 and S_3 as given by equation 36.

$$GPI = (\overline{w'}_{s1} \otimes S_1) + (\overline{w'}_{s2} \otimes S_2) + (\overline{w'}_{s3} \otimes S_3) \quad (36)$$

Where: $\overline{w'}_{s1}$, $\overline{w'}_{s2}$ and $\overline{w'}_{s3}$ are the weights of GHG emission scope 1, 2 and 3 respectively.

3.6.4 Developing the ANFIS Models

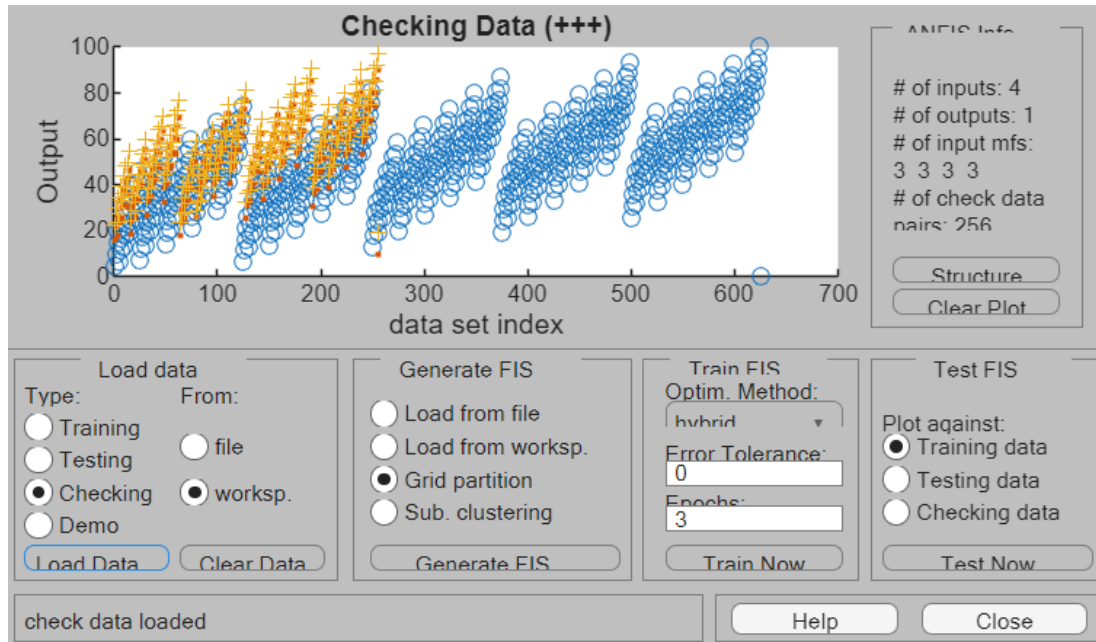
Developing a GPI model using ANFIS requires training of the ANFIS model with good quality data. Thus, the mathematical models developed are used to generate training data for the ANFIS models. The range of values for all the inputs is 0 – 100, since all of the KPIs are expressed in percentages. Therefore, to generate the training data from the mathematical models, five numbers are chosen at equal interval within the range of values. These numbers are 0, 25, 50, 75 and 100. Microsoft (MS) excel is used to compute the outputs of the mathematical models using these values as inputs

such that each combination of input values is unique. The number of combinations is given by:

$$\text{no. combinations} = V^n \quad (37)$$

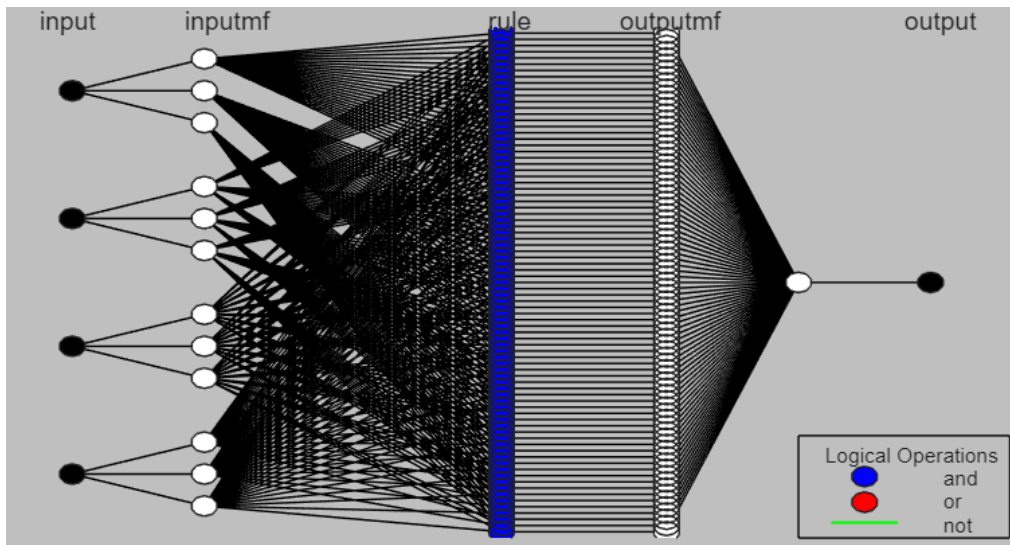
Where: V is the number of input values chosen and n is the number of input variables (KPIs). Using ANFIS 5 (Scope 1) as an example, there are $5^4 = 625$ possible combinations. The output of each combination of input values is calculated. These set of input and output values are used as training data. Similarly, another set of input values (10, 40, 70, 90) and (19, 37, 73, 97) are used to provide testing and checking data respectively to minimise the training error. The process is then repeated for all the other five ANFIS models to obtain their respective training data. Once all the data is set, it is loaded into the neuro fuzzy designer toolbox of MATLAB as shown in Figure 11.

Figure 11 Loading ANFIS training and checking data



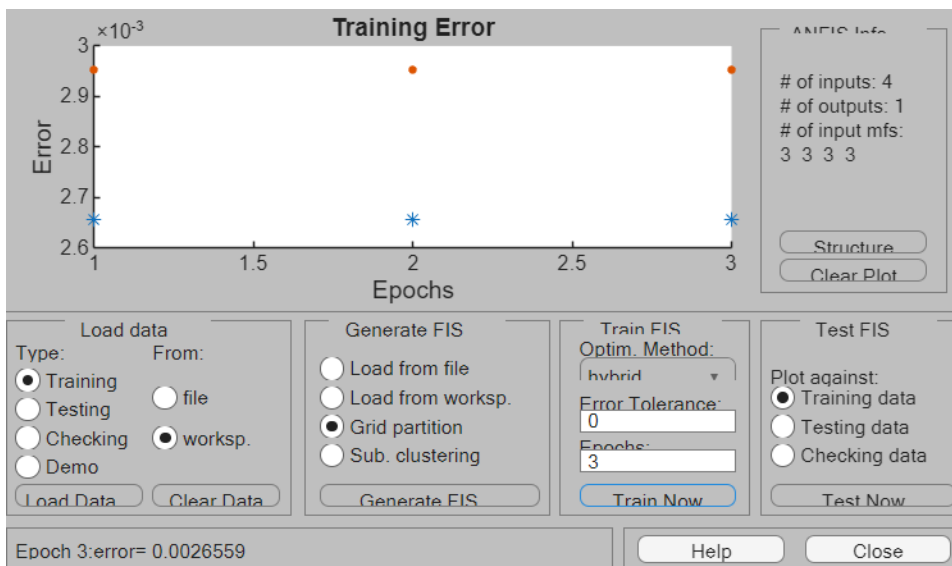
In the ANFIS 5 model, the scope 1 KPI scores are the inputs and the output is scope 1 GHG emission reduction performance. Thus, there are four inputs with three MFs each, resulting in 81 If – Then fuzzy rules. Figure 12 shows the structure of ANFIS 5 model indicating all the layers and operates as explained in Appendix E.

Figure 12 ANFIS 5 Model structure



Loading the training data prompts the ANFIS program to establish the initial MF parameters. The inputs and MFs are defined in accordance with the GPI input parameters (KPIs). Then training of the model commences. The training error most not be greater 0.1 according to Sun et al. (2015) as cited by Tan et al. (2017). This is monitored to ensure effective training of the models. In the case of ANFIS 5, the training error is significantly low as shown in Figure 13.

Figure 13 ANFIS 5 Training error



The trained ANFIS model automatically produces a set of fuzzy rules and MF parameters that fits the mathematical model. These rules and MFs are examined and

improved to ensure it produces accurate results. The If – Then fuzzy rules of all the ANFIS models are given in Appendix F. Figure 14 shows the MFs before and after training for the Energy efficiency (EE) KPI. It can be seen that the gaussian MFs have been transformed to triangular MFs after training. This is the case for all the other inputs (KPIs) of the ANFIS models since all the inputs have the same number of MFs and range of values. Besides, Figure 15 describes the properties of ANFIS 5 Model.

Figure 14 Membership functions of ANFIS 5 before and after training

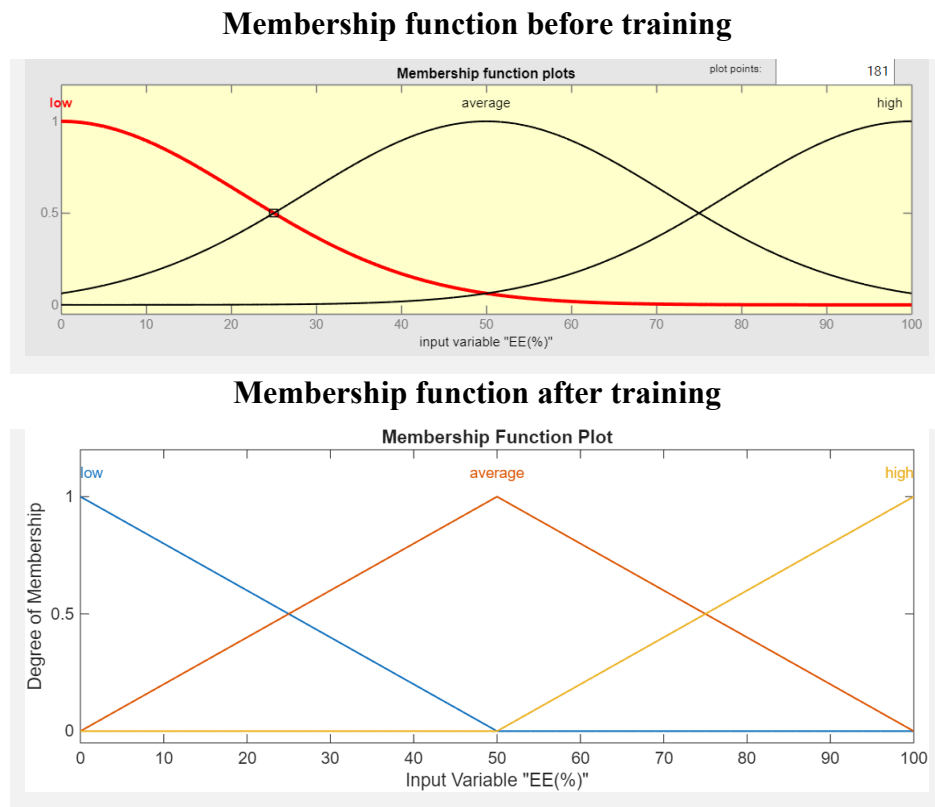
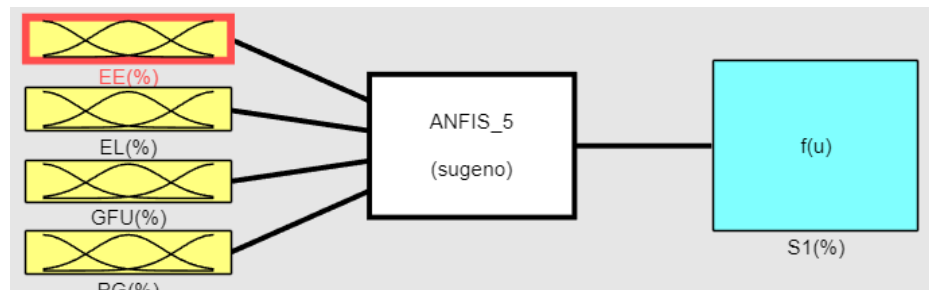


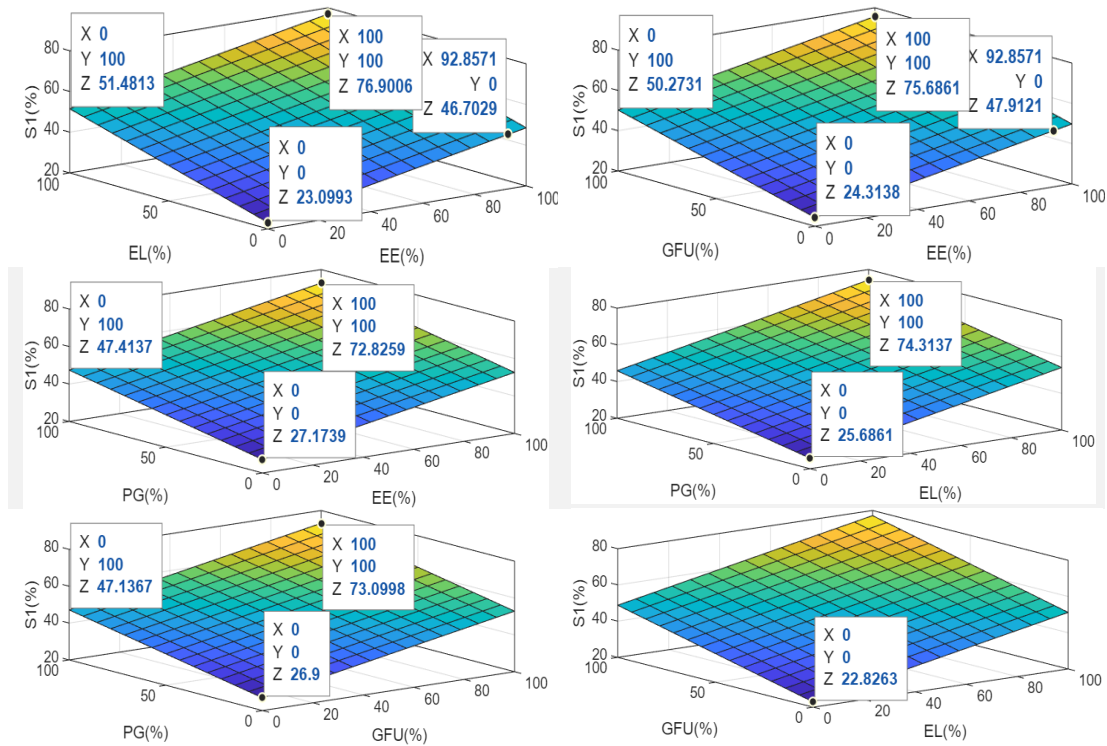
Figure 15 Properties of ANFIS 5 Model



Upon successful completion of training the ANFIS 5 model, the control surfaces and rule inferences are generated as shown in Figures 16 and 17 respectively. The control

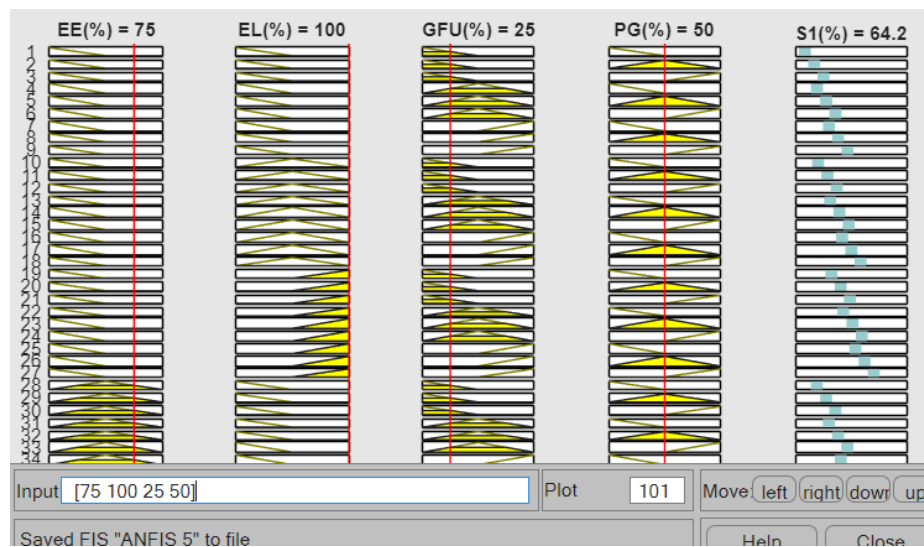
surface clearly shows the impact of varying the input values on the output. Two inputs are varied at a time while keeping the other two input at 50%. The data tip function of fuzzy logic toolbox of MATLAB is used to determine and pin the various combination of inputs (X & Y) values with their corresponding output (Z) values along the control surfaces.

Figure 16 Control Surfaces of ANFIS 5 Model



Additionally, the rule inference shown in Figure 17 is used to perform sensitivity analysis and validation of the ANFIS 5 model. Here, the inputs values are varied and the outputs are recorded. This gives an indication about the degree of sensitivity of model with respect to the inputs. The ANFIS 5 model is validated by using the mathematical model to evaluate the output using the same inputs fed into the rule inference of fuzzy logic toolbox. The two results are then compared. All the other ANFIS models are developed following the same steps as in ANFIS 5.

Figure 17 Rule Inference of ANFIS 5 Model



Chapter 4. Results and Discussion

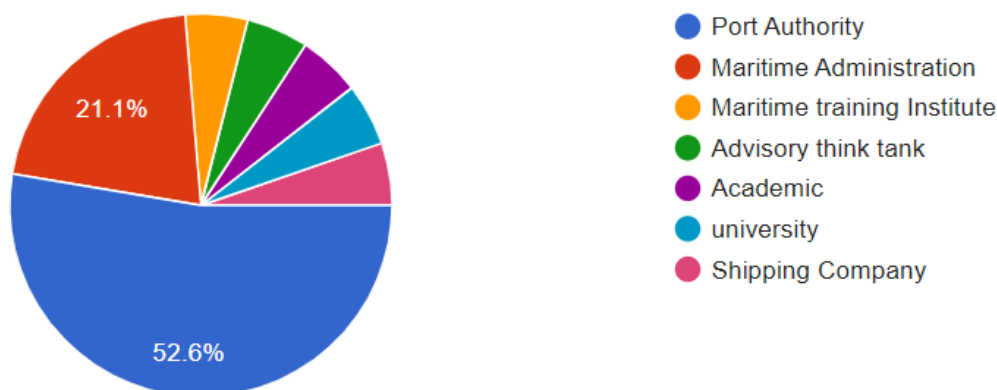
4.1 Introduction

The results of this research are presented and critically analysed in this chapter. The first step of this research identified 12 green port KPIs with respect to implementation of port GHG emission reduction measures through a comprehensive literature review as summarized in Table 2. This chapter begins by analysing the respondents to the questionnaire survey. The results obtained from the FAHP methodology are then discussed which are used as inputs to the mathematical models. Additionally, the weights obtained from the FAHP methodology are validated by calculating the weights using SMART. The control surfaces of the ANFIS-based GPI model are critically analysed and sensitivity analysis is conducted to validate and determine the robustness of the GPI model. Finally, illustrative examples are given to demonstrate how ports authorities or relevant stakeholders can use this GPI model to assess their performance in terms of implementation of GHG emission reduction measures.

4.2 Profile of respondents

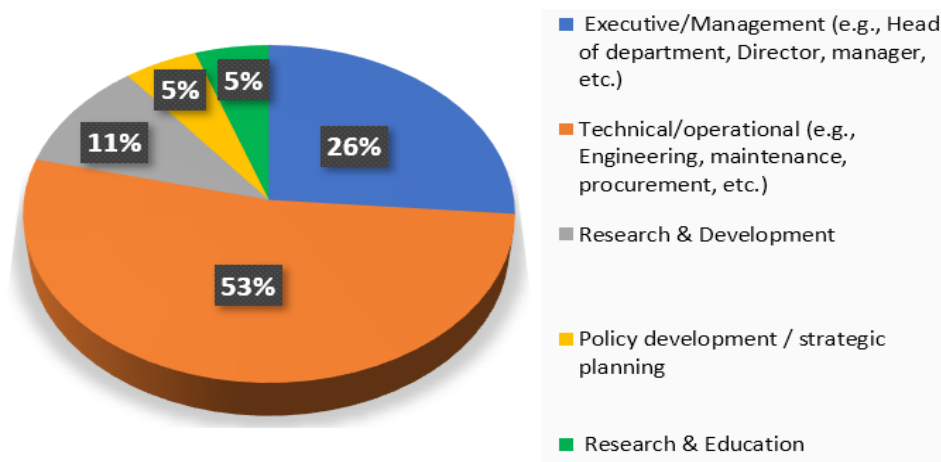
A total of 19 professionals and experts in maritime energy management or related disciplines responded to the questionnaire survey. They work in diverse and interrelated sectors within the maritime industry as shown in Figure 18. Majority of the respondents (52.6%) are from port authority, 21.1% from maritime administration and 5.3% from the remaining sectors each. Figure 18 summarizes the results

Figure 18 Organisations of respondents



The positions occupied by the respondents in their various institutions are predominantly technical and top-level management. Figure 19 shows the detail results.

Figure 19 Roles of respondents in their organisations



Additionally, the survey results showed that majority of the respondents are senior personnel with more than 10 years of working experience in the maritime sector as presented in Table 5.

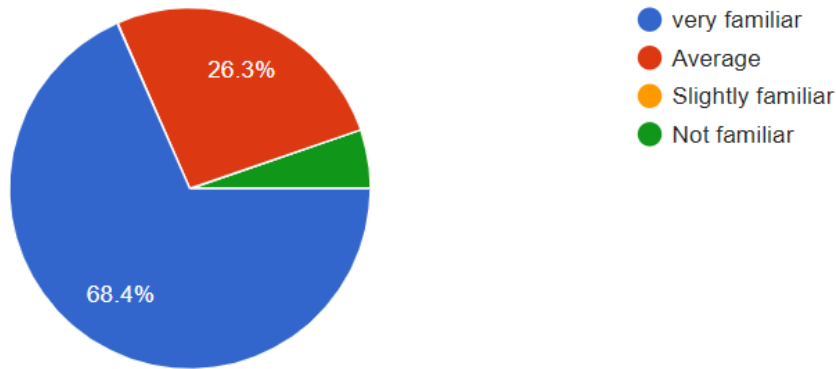
Table 5 Years of working experience of respondents.

Work experience (years)	frequency
0 - 5	3
6 - 10	5
11 - 15	1
16 - 20	2
21 - 25	5
26 - 30	2
31 - 35	1

4.3 Familiarity of respondents to green port concept

The degree of familiarity of the respondents to the green port concept was assessed and the results showed that the respondents do not have the same degree of familiarity as indicated in Figure 20. Thus, necessitating weighting of the responses based on their level of familiarity as described in section 3.5.3. One of the respondents is not familiar with the green port concept and therefore the response is not considered in the analysis.

Figure 20 Level of familiarity of respondents to green port concept



The normalised weights of the respondents are calculated using the arithmetic scale in Table 6 as inputs to equation 21. The results are given in Table 6.

Table 6 Weights of respondents

Level of familiarity Scale		Normalised Wight (g_i)
Very familiar	3	1.102
Average	2	0.735
Slightly familiar	1	0.367
Not familiar	0	0

4.4 Fuzzy AHP results

The pairwise comparison matrix is constructed from the expert responses as outlined in section 3.5.3. The pairwise comparison values of each respondent are multiplied by the weight of the respondent based on level of familiarity to green port concept. The detail results and calculations are given in Appendix D.

4.4.1 Scope 1 GHG emission reduction KPIs

Table 7 shows the representative PCM of scope 1 KPIs. The consistency ratio of this matrix is 4E-04 which is less than 0.1. Therefore, the PCM meets the condition for consistency, hence it can be used for calculation of weights. The crisp local weights obtained from the FAHP are presented in Table 8. It shows that Electrification is the most important KPI for scope 1 port GHG emission reduction. This is followed by green fuel utilisation, energy efficiency and port greenery respectively.

Table 7 Scope 1 PCM

	Energy Efficiency (EE)			Electrification (EL)			Green fuel (GFU)			Port Greenery (PG)		
EE	1	1	1	0.60	0.91	1.26	0.70	0.97	1.37	0.87	1.24	1.93
EL	0.80	1.10	1.65	1	1	1	0.76	1.05	1.64	0.96	1.34	2.05
GFU	0.73	1.03	1.42	0.61	0.95	1.32	1	1	1	0.85	1.26	1.96
PG	0.52	0.81	1.15	0.49	0.74	1.05	0.51	0.79	1.17	1	1	1

Table 8 Local Weights of scope 1 KPIs and Consistency of PCM

Scope 1 sub-Criteria	Crisp Local weight	Check for consistency	
Energy Efficiency	0.254	λ max	4.001
Electrification	0.284	C.I	3E-04
Green fuel utilisation	0.260	R.I	0.892
Port Greenery	0.202	C.R	4E-04

4.4.2 Scope 2 GHG emission reduction KPIs

Table 9 and 10 show the PCM and local weights of scope 2 KPIs respectively. Since the order of this matrix is 2, it does not require a consistency check. Besides, the R.I value for a 2X2 PCM is zero. The weights of the KPIs suggest that RE usage is the most important KPI for scope 2 port GHG emission reduction.

Table 9 Scope 2 PCM

	Renewable Energy (RE)			Smart/Microgrid (S/M)		
RE	1	1	1	0.96	1.33	2.21
S/M	0.45	0.75	1.04	1	1	1

Table 10 Local weights of scope 2 KPIs

Scope 2 sub-Criteria	Crisp Local weight
Renewable Energy	0.586
Smart/Microgrid	0.414

4.4.3 Scope 3 GHG emission reduction KPIs

The representative PCM of scope 3 port GHG emission reduction KPIs is shown in Table 11 and its consistency ratio is 6E-04. The PCM meets the consistency requirements and thus, used to calculate the weight of the KPIs as presented in Table 12. The weights of the KPIs shows that OPS usage is the most important KPI for scope

3 port GHG emission reduction followed by JIT arrival of ships, provision of AFB, addressing truck congestion, facilitating green hinterland transportation of cargo and green employee commuting respectively.

Table 11 Scope 3 PCM

	OPS usaga			JIT arrival			AF Bunkering (AFB)			Hinterland transport (HT)			Employee commuting (EC)			Truck congestion		
OPS	1	1	1	0.91	1.18	2.08	0.77	1.24	2.05	0.83	1.29	2.39	1.33	1.89	3.11	0.94	1.29	1.87
JIT	0.48	0.85	1.10	1	1	1	0.73	1.04	1.71	0.85	1.08	1.63	1.06	1.58	2.29	0.74	1.08	1.67
AFB	0.49	0.81	1.30	0.59	0.97	1.38	1	1	1	0.73	1.03	1.42	1.04	1.50	2.20	0.77	1.02	1.39
HT	0.42	0.78	1.20	0.61	0.93	1.17	0.70	0.97	1.38	1	1	1	0.98	1.44	2.01	0.68	0.98	1.51
EC	0.32	0.53	0.75	0.44	0.63	0.94	0.45	0.66	0.96	0.50	0.69	1.02	1	1	1	0.44	0.67	0.88
TC	0.53	0.78	1.06	0.60	0.93	1.35	0.72	0.98	1.30	0.66	1.02	1.46	1.14	1.49	2.27	1	1	1

Table 12 Local Weights of Scope 3 KPIs and Consistency of PCM

Scope 3 sub-Criteria	Crisp Local weight	Check for consistency	
OPS usage	0.219	$\lambda_{\max}$	5.003
Just in time arrival	0.178	C.I	7E-04
AF bunkering	0.168	R.I	1.12
Hinterland transport	0.160	C.R	6E-04
Employee commuting	0.111		
Truck congestion	0.165		

4.4.4 Port GHG emission Scopes

Table 13 shows the representative PCM of port GHG emission scopes which has been proven to be consistent since C.R is less than 0.1 as indicated in Table 14. The weights of the GHG emission scopes shown in Table 14 means that the highest priority for port GHG emission reduction is Scope 1 followed by scope 2 and scope 3.

Table 13 PCM of GHG emission scopes

	Scope1			Scope2			Scope3		
Scope1	1	1	1	0.82	1.06	1.71	0.91	1.25	2.08
Scope2	0.59	0.94	1.22	1	1	1	0.87	1.16	1.81
Scope3	0.48	0.80	1.10	0.55	0.86	1.15	1	1	1

Table 14 Weights of GHG emission Scopes

Emission scope	Criteria weights	Check for consistency	
Scope 1	0.380	$\lambda_{\max}$	3.004
Scope 2	0.339	C.I	0.002
Scope 3	0.281	R. I	0.58
		C.R	0.003

The weights of the GHG emission scopes, local and global weights of KPIs are summarised in Table 15. Considering the global weights, it can be seen that scope 2 KPIs carries the highest weights followed by scope 1 and scope 3 KPIs respectively.

Table 15 Summary of KPI and Emission scope weighting results

Emission scope (ES)	Weight of ES	KPI	Local Weight	Global Weight
Scope 1	0.380	Energy Efficiency	0.254	0.097
		Electrification	0.284	0.108
		Green fuel utilisation	0.260	0.099
		Port Greenery	0.202	0.077
Scope 2	0.339	Renewable Energy	0.586	0.198
		Smart/Microgrid	0.414	0.140
Scope 3	0.281	OPS usage	0.219	0.062
		Just in time arrival	0.178	0.050
		AF bunkering Facility	0.168	0.047
		Hinterland transport	0.160	0.045
		Employee commuting	0.111	0.031
		Truck congestion	0.165	0.046

SMART is used to validate the results obtained from the FAHP calculation of emission scopes and KPI weights. The results are presented in Tables 16 and 17. Using SMART, the weight of alternative with respect to criteria is given by:

$$w_i = \frac{a_{ik}}{\sum_{i=1}^n a_{ik}} \quad (38)$$

Equation 38 is used by Harker and Vargas (1987) and Risawandi and Rahim (2016) to evaluate weights of alternative with respect to criteria. The Microsoft excel calculation of weight using SMART is given in Appendix G.

The weights obtained from the two techniques (FAHP and SMART) are compared. It can be concluded that using SMART to directly calculate the weights does not change the ranking of the KPIs based on FAHP techniques. There are slight differences between the FAHP weights and the SMART weights which does not exceed ± 0.012 . This is because fuzziness of DMs is considered in the FAHP technique which is not the case in SMART. Thus, SMART has effectively been used to validate and showcase the robustness of FAHP methodology.

Table 16 Weights of emission Scopes (ES) using FAHP validated by SMART

Emission scope (ES)	FAHP Weight of ES	SMART Weight of ES	Difference of Weights	Ranking by FAHP	Ranking by SMART
Scope 1	0.380	0.368	0.012	1	1
Scope 2	0.339	0.342	-0.003	2	2
Scope 3	0.281	0.290	-0.009	3	3

Table 17 Weights of KPIs using FAHP validated by SMART

KPI	FAHP Local Weight	SMART Local Weight	FAHP Global Weight	SMART Global Weight	Diff of Global weight	Rank By FAHP	Rank by SMART
Energy Efficiency	0.254	0.257	0.097	0.095	0.002	5	5
Electrification	0.284	0.278	0.108	0.103	0.005	3	3
Green fuel utilisation	0.260	0.261	0.099	0.096	0.003	4	4
Port Greenery	0.202	0.204	0.077	0.075	0.002	6	6
Renewable Energy	0.586	0.575	0.198	0.197	0.001	1	1
Smart/ Microgrid	0.414	0.425	0.140	0.145	-0.005	2	2
OPS usage	0.219	0.213	0.062	0.062	0.000	7	7
Just in time arrival	0.178	0.179	0.050	0.052	-0.002	8	8
AF bunkering Facility	0.168	0.170	0.047	0.049	-0.002	9	9
Hinterland transport	0.160	0.163	0.045	0.0472	-0.002	11	11
Employee commuting	0.111	0.111	0.031	0.032	-0.001	12	12
Truck congestion	0.165	0.163	0.046	0.0474	-0.001	10	10

4.5 Analysis of the ANFIS models

The mathematical models established in section 3.6.3 are used to develop the ANFIS-based GPI model based on the weights of the KPIs in Table 17. The weight of the KPIs determines the inclination of the control surface and the point of intersection on the Z axis.

4.5.1 Control surfaces

The control surfaces show a linear relationship between inputs and outputs. Conceptually, this is because every percentage improvement of the KPIs will result in proportionate improvement in GPI. This means that the behaviour of the ANFIS-based GPI models aligns with expectations since the mathematical model used to provide training data are linear. Therefore, the difference between the control surfaces is the gradient along the (X -Z) and (Y – Z) plane. The blue portions on the control surface are the regions of low performance and the yellow areas indicates high performance regions. Moving along the control surface, the output of the ANFIS model can be viewed with its corresponding input values using data tip function of fuzzy logic toolbox. In practice, this tells the viewer what need to be done to achieve the output result. Thus, serving as a reliable prediction tool for PAs and relevant stakeholders. It provides them possible alternatives to achieve port emission reduction targets. For example, in Figure 21c, to achieve ship-based scope 3 port GHG emission reduction performance of 46% requires OPS utilisation of 28.6%, AFB of 50% and JIT berthing of 64.3%. The same result can be achieved by 0% OPS utilisation, AFB of 50% and JIT berthing of 100%. The control surfaces of the ANFIS models are shown in the Figures 21, 22, 23 and 24.

Figure 21 Control surfaces of ANFIS 1 Model

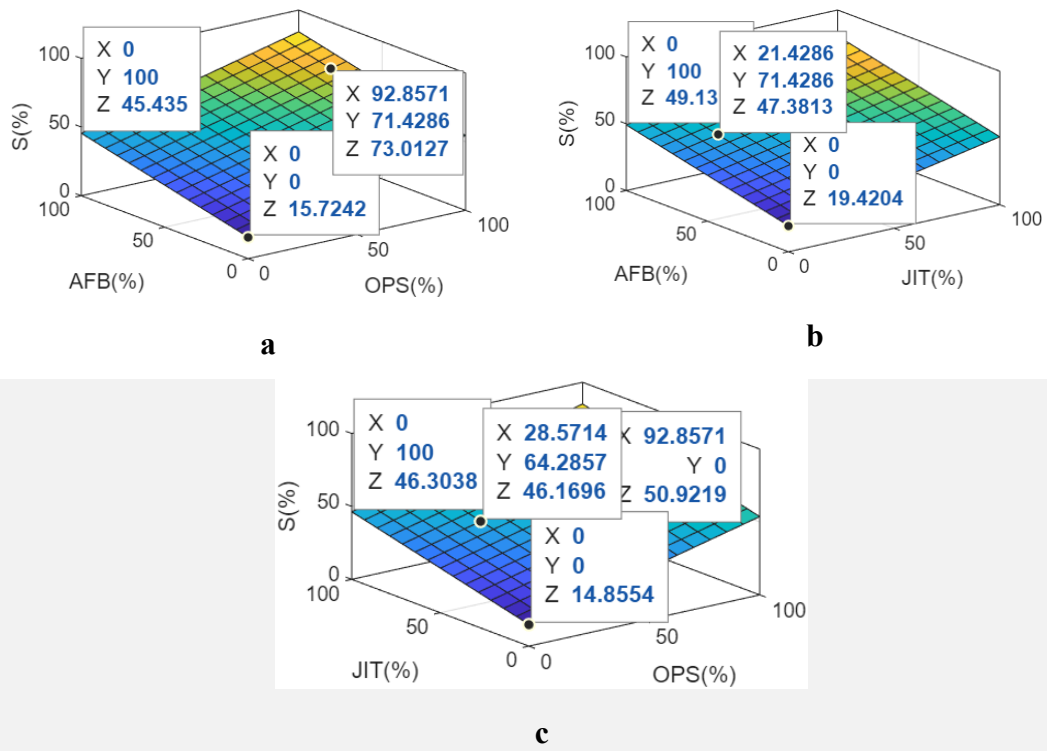


Figure 22 Control surfaces of ANFIS 2 Model

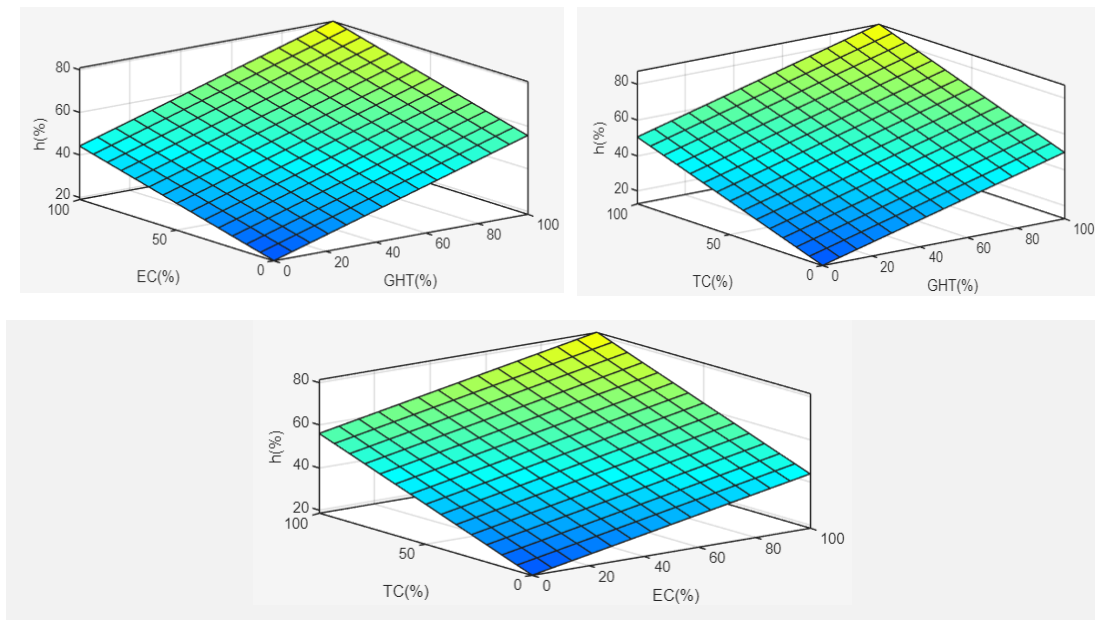


Figure 23 Control surfaces of ANFIS 3 and ANFIS 4 Model

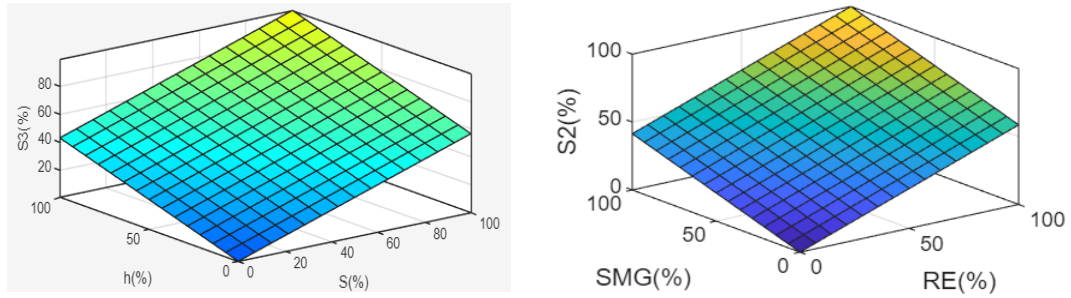
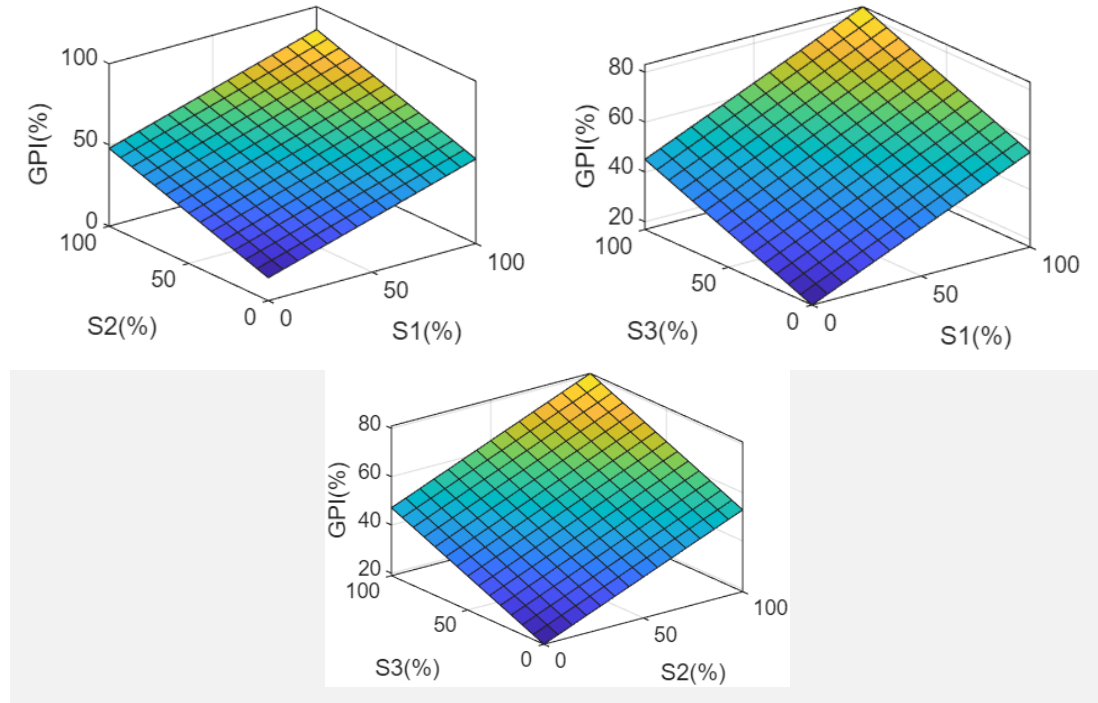


Figure 24 Control surfaces of ANFIS 6 Model



4.5.2 Sensitivity Analysis

ANFIS 1

Sensitivity analysis of ANFIS 1 is performed and the results are given in Table 18. Three tests were performed to determine the sensitivity of the output to each of the three KPIs. In test one, OPS usage and JIT arrival scores are kept constant at 50% while the AFB score was varied incrementally by 25%. It can be seen that for every 25% increase in AFB score, the output increases by 7.4%. Similarly, in test 2, for every

25% increase in JIT arrival score, the output increases by 7.9%. Likewise, in test 3, every 25% increase in OPS usage translates to 9.7% increase in output. Therefore, it can be concluded that the output of ANFIS 1 is most sensitive to OPS usage and least sensitive to AFB. The output of ANFIS 1 indicates GPI performance based on implementation of shipping related scope 3 port GHG emission reduction measures.

Table 18 Sensitivity results of ANFIS 1

	OPS usage (%)	JIT arrival (%)	AF bunkering (%)	S (%)	ΔS (%)
Test 1	50	50	0	35.1	0.0
	50	50	25	42.6	7.4
	50	50	50	50.0	7.4
	50	50	75	57.4	7.4
	50	50	100	64.9	7.4
Test 2	50	0	50	34.3	0.0
	50	25	50	42.1	7.9
	50	50	50	50.0	7.9
	50	75	50	57.9	7.9
	50	100	50	65.7	7.9
Test 3	0	50	50	30.6	0.0
	25	50	50	40.3	9.7
	50	50	50	50.0	9.7
	75	50	50	59.7	9.7
	100	50	50	69.4	9.7

ANFIS 2

The sensitivity analysis of ANFIS 2 is performed as in ANFIS 1 and the results are presented in Table 19. From the results it can be seen that the output of ANFIS 2 is most sensitive to reduction of truck congestion and least sensitive to green employee commuting. The output of ANFIS 2 gives performance of scope 3 port GHG emission reduction associated with implementation of hinterland measures.

Table 19 Sensitivity results of ANFIS 2

	GHT (%)	EC (%)	TC (%)	h(%)	Δh (%)
Test 1	50	50	0	31.1	0.0
	50	50	25	40.5	9.5
	50	50	50	50.0	9.5
	50	50	75	59.5	9.5
	50	50	100	68.9	9.5
Test 2	50	0	50	37.3	0.0
	50	25	50	43.7	6.3
	50	50	50	50.0	6.3
	50	75	50	56.3	6.3
	50	100	50	62.7	6.3
Test 3	0	50	50	31.6	0.0
	25	50	50	40.8	9.2
	50	50	50	50.0	9.2
	75	50	50	59.2	9.2
	100	50	50	68.4	9.2

ANFIS 3

Table 20 gives the sensitivity test results of ANFIS 3. It shows that the output is more sensitive to ship-based scope 3 port GHG emission reduction measures (S) than hinterland related measures (h). The overall output of ANFIS 3 model determines the performance of ports with respect to implementation of scope 3 port GHG emission reduction measures.

Table 20 Sensitivity results of ANFIS 3

	S (%)	h (%)	S3(%)	$\Delta S3$ (%)
Test 1	50	0	28.2	0.0
	50	25	39.1	10.9
	50	50	50.0	10.9
	50	75	60.9	10.9
	50	100	71.8	10.9
Test 2	0	50	21.8	0.0
	25	50	35.9	14.1
	50	50	50.0	14.1
	75	50	64.1	14.1
	100	50	78.2	14.1

ANFIS 4

The sensitivity test results of ANFIS 4 are given in Table 21. It can be concluded that the output of ANFIS 4 is more sensitive to RE usage than implementation of SMG.

The output of ANFIS 4 measures the performance of ports based on implementation of scope 2 port GHG emission reduction measures.

Table 21 Sensitivity results of ANFIS 4

	RE (%)	SMG (%)	S2 (%)	Δ S2 (%)
Test 1	50	0	29.3	0.0
	50	25	39.7	10.3
	50	50	50.0	10.3
	50	75	60.3	10.3
	50	100	70.7	10.3
Test 2	0	50	20.7	0.0
	25	50	35.3	14.7
	50	50	50.0	14.7
	75	50	64.7	14.7
	100	50	79.3	14.7

ANFIS 5

The sensitivity test results of ANFIS 5 are presented in Table 22. It shows that the output is most sensitive to electrification (7.1%) and least sensitive to port greenery (5.1%). Besides, the sensitivity of the output to energy efficiency and green fuel utilisation is almost equal. However, GFU is slightly more sensitive by 0.1%. The output of ANFIS 5 model shows the performance of the port with respect to implementation of scope 1 port GHG emission reduction measures.

Table 22 Sensitivity results of ANFIS 5

	EE (%)	EL (%)	GFU (%)	PG (%)	S1 (%)	Δ S1 (%)
Test 1	50	50	50	0	39.9	0.0
	50	50	50	25	44.9	5.1
	50	50	50	50	50.0	5.1
	50	50	50	75	55.1	5.1
	50	50	50	100	60.1	5.1
Test 2	50	50	0	50	37.0	0.0
	50	50	25	50	43.5	6.5
	50	50	50	50	50.0	6.5
	50	50	75	50	56.5	6.5
	50	50	100	50	63.0	6.5
Test 3	50	0	50	50	35.8	0.0
	50	25	50	50	42.9	7.1
	50	50	50	50	50.0	7.1
	50	75	50	50	57.1	7.1
	50	100	50	50	64.2	7.1
Test 4	0	50	50	50	37.3	0.0
	25	50	50	50	43.6	6.4
	50	50	50	50	50.0	6.4
	75	50	50	50	56.4	6.4
	100	50	50	50	62.7	6.4

ANFIS 6

The output of ANFIS 6 is the port GPI score. The sensitivity test shows that the GPI score is most sensitive to scope 1 port GHG emission reduction score, followed by scope 2 and 3 scores as presented in Table 23.

Table 23 Sensitivity results of ANFIS 6

	S1 (%)	S2 (%)	S3 (%)	GPI (%)	Δ GPI (%)
Test 1	50	50	0	35.9	0.0
	50	50	25	43.0	7.0
	50	50	50	50.0	7.0
	50	50	75	57.0	7.0
	50	50	100	64.1	7.0
Test 2	50	0	50	33.1	0.0
	50	25	50	41.5	8.5
	50	50	50	50.0	8.5
	50	75	50	58.5	8.5
	50	100	50	66.9	8.5
Test 3	0	50	50	31.0	0.0
	25	50	50	40.5	9.5
	50	50	50	50.0	9.5
	75	50	50	59.5	9.5
	100	50	50	69.0	9.5

4.6 Illustrative Example

An illustrative example is given to demonstrate how this ANFIS-based GPI model can be used by PAs or relevant stakeholders to assess port environmental sustainability performance with respect to implementation of GHG emission reduction measures as defined by the KPIs. Container terminal Port A and Port B from a developed and developing country respectively are considered with the following data:

Table 24 Profile of Port A

No.	Item	value
1	vessels call per year	4 550
2	Total port area (in hectares)	500
3	Container throughput per year	13 484 122 TEU
4	Reefer containers per year	1 021 843 TEU
5	Total cargo throughput yearly	286 953 686 tons
6	Number of terminals	5

Table 25 Profile of Port B

No.	Item	value
1	vessels call per year	1500
2	Total port area (in hectares)	206
3	Container throughput per year	2 005 850 TEU
4	Reefer containers per year	203 000 TEU
5	Number of terminals	4

Table 26 Scope 1 KPI data of Port A

Code	KPI	Value	Units
K1	Electricity consumption	340.8	GWh/year
	Fuel consumption	19 462.46	tons of diesel per year
K2	Number of electrified port equipment and machinery	450	pieces
	Total number of port equipment and machinery	970	pieces
K3	Green fuel utilization	5 000	tons
K4	Area covered by Port greenery	150	(hectares)

Table 27 Scope 1 KPI data of Port B

Code	KPI	Value	Units
K1	Electricity consumption	18	GWh/year
	Fuel consumption	7500	tons of diesel per year
K2	Number of electrified port equipment and machinery	53	pieces
	Total number of port equipment and machinery	530	pieces
K3	Green fuel utilization	0	tons
K4	Area covered by Port greenery	125	(hectares)

Table 28 Scope 2 KPI data of Port A

Code	KPI	value	Units
K5	Renewable energy usage:	320	GWh
K6	Electrical load covered by smart/microgrid	136	GWh

Table 29 Scope 2 KPI data of Port B

Code	KPI	value	Units
K5	Renewable energy usage:	14.4	GWh
K6	Electrical load covered by smart/microgrid	3.6	GWh

Table 30 Scope 3 KPI data of Port A

Code	KPI	Value	Units
K7	OPS usage	1245	vessels per year
K8	Just in time arrival	1365	vessels per year
K9	alternative fuel bunkered	1.2	Million tons
	Total conventional fuel bunkered	9.5	Million tons
K10	Containers transported to the hinterland using carbon neutral/ carbon free energy sources	4.55	Million TEU
K11	Number of employees travelling green	4200	people
	Total number of employees	6000	people
K12	Number of truck trips adhering to the truck appointment system	2.19	Million trips per year
	Truck traffic handled per year,	3.65	Million trips per year

Table 31 Scope 3 KPI data of Port B

Code	KPI	Value	Units
K7	OPS usage (pilot stage)	75	vessels per year
K8	Just in time arrival	180	vessels per year
K9	alternative fuel bunkered	0	Million tons
	Total conventional fuel bunkered	2.5	Million tons
K10	Containers transported to the hinterland using carbon neutral/ carbon free energy sources	0	Million TEU
K11	Number of employees travelling green	510	People
	Total number of employees	4000	People
K12	Number of truck trips adhering to the truck appointment system	0.311	Million trips per year
	Truck traffic handled per year,	1.278	Million trips per year

4.6.1 Quantification of ANFIS inputs (KPIs) for Port A and Port B

The KPI scores for both Port A and Port B are quantified using the mathematical equations proposed in section 3.4. and the results are presented in Table 32. The data presented in Tables 24-31 are used as inputs in the calculations. The step-by-step calculations are shown in Appendix H.

Table 32 KPI scores of Port A and Port B

		KPI Score %	
Code	KPIs	Port A	Port B
K1	Energy Efficiency	57	48
K2	Electrification	46	10
K3	Green fuel utilisation	26	0
K4	Port Greenery	30	61
K5	Renewable Energy	56	14
K6	Smart/Microgrid	40	20
K7	OPS usage	27	5
K8	Just in time arrival	30	12
K9	AF bunkering	11	0
K10	Green Hinterland transport	34	0
K11	Employee commuting	70	13
K12	Truck congestion	60	24

The quantified KPIs are fed into the ANFIS models sequentially to evaluate the GPI score of Port A and Port B. This is accomplished in six steps as described below.

Step 1.

This step evaluates the implementation of ship-based scope 3 port GHG emission reduction measures. The OPS, JIT and AFB scores are used as inputs as demonstrated in Figures 25 and 26 for Port A and B respectively.

Figure 25 Evaluation of Ship-based GPI performance of Port A

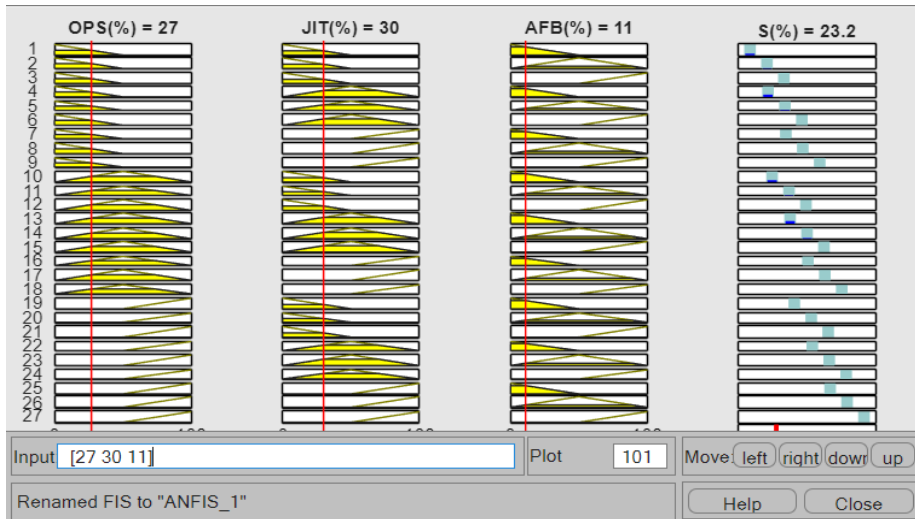
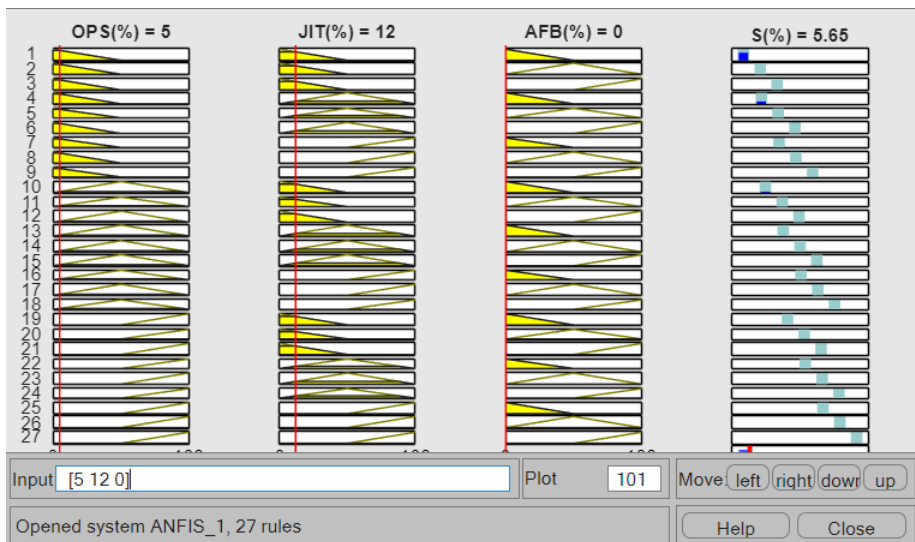


Figure 26 Evaluation of Ship-based GPI performance of Port B



Step 2

The hinterland related scope 3 port GHG emission reduction score (h) is evaluated using GHT, EC and TC scores as demonstrated in Figures 27 and 28 for Port A and Port B respectively.

Figure 27 Evaluation of hinterland GPI performance of Port A

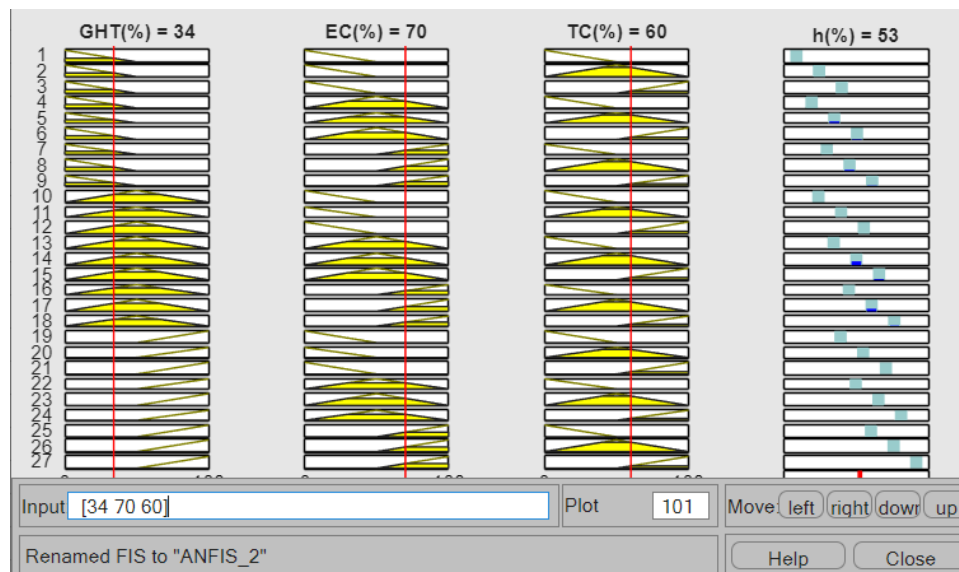
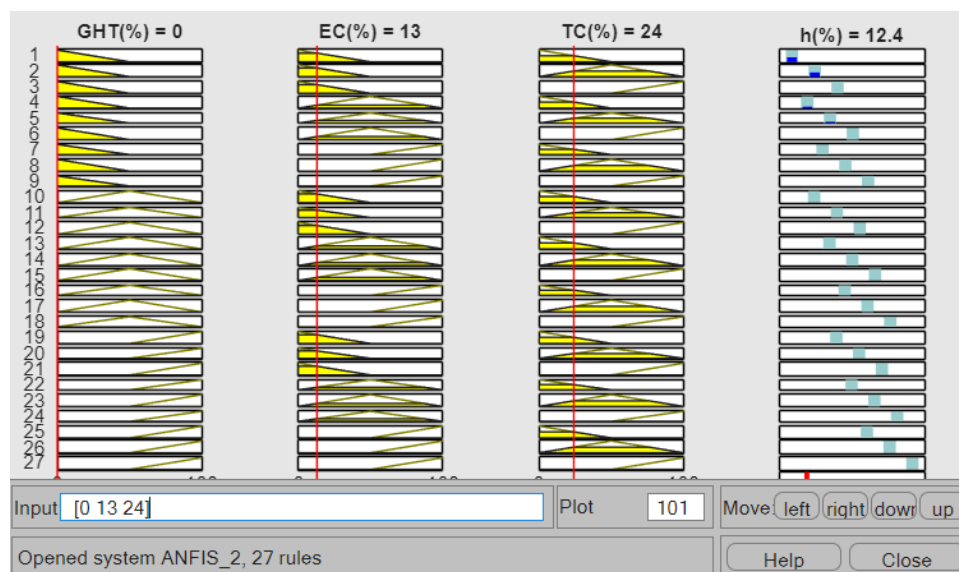


Figure 28 Evaluation of hinterland GPI performance of Port B



Step 3

In this step, the output results from Step 1(S) and 2 (h) are used as inputs to evaluate the overall implementation of scope 3 GHG emission reduction measures (S3) by Port A and Port B as shown in Figures 29 and 30 respectively.

Figure 29 Evaluation of scope 3 GPI performance of port A

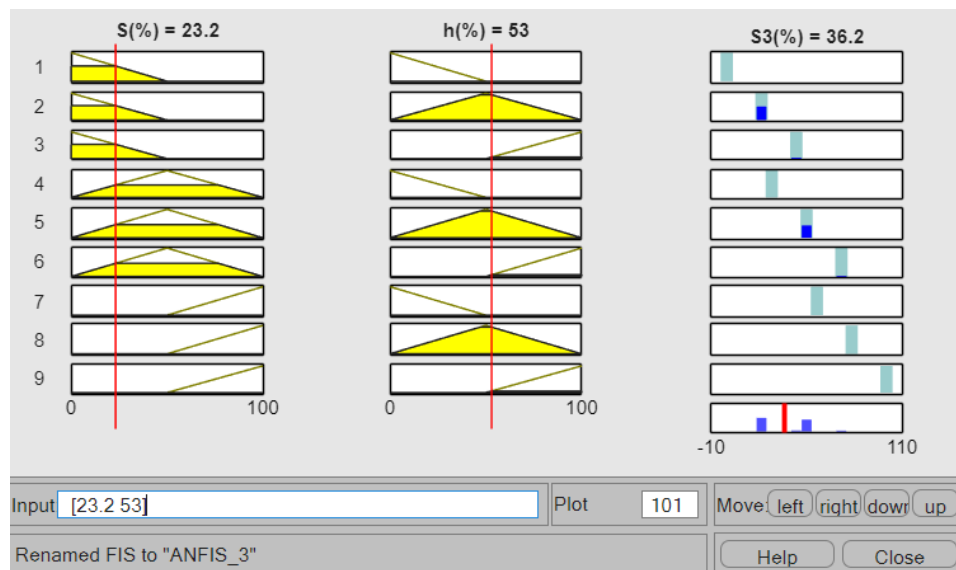
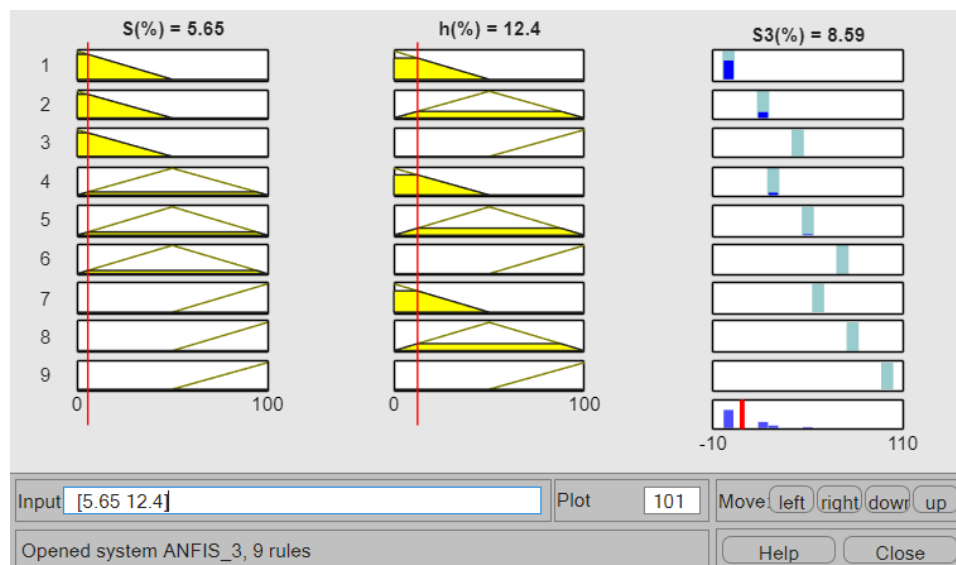


Figure 30 Evaluation of scope 3 GPI performance of port B



Step 4

This step assesses the implementation of scope 2 port GHG emission reduction measures using the RE usage and SMG scores of Port A and Port B as demonstrated in Figures 31 and 32 respectively.

Figure 31 Evaluation of scope 2 GPI performance of port A

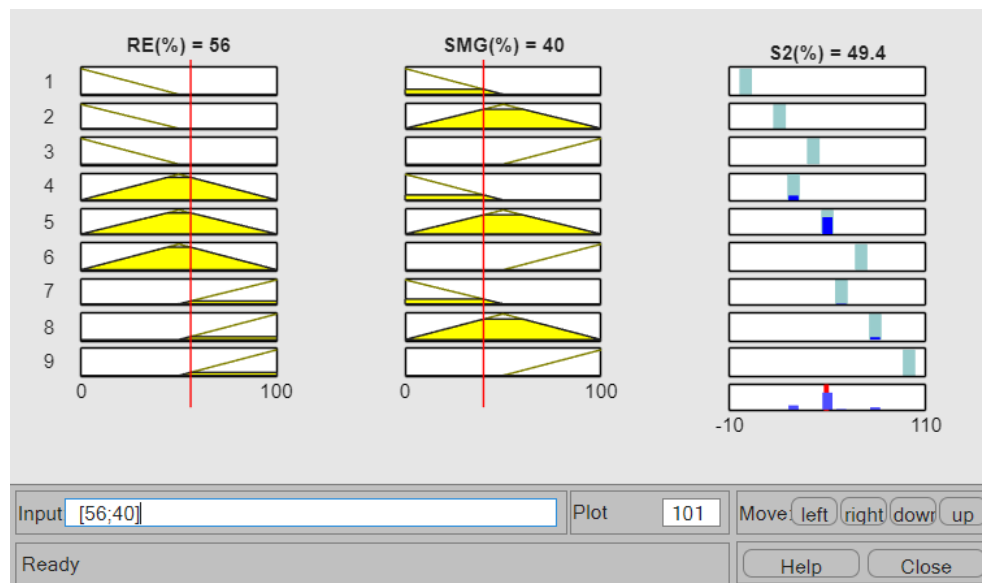
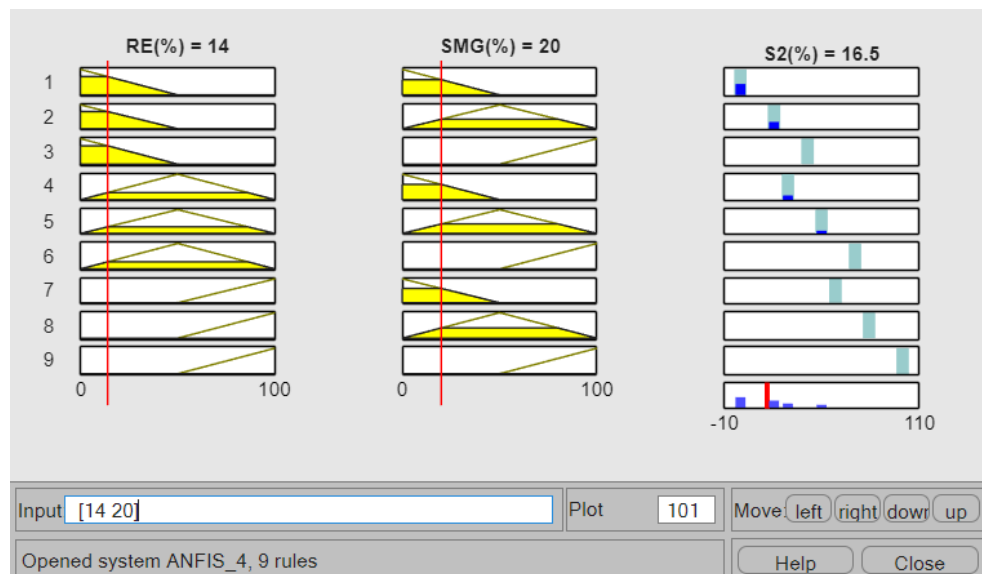


Figure 32 Evaluation of scope 2 GPI performance of port B



Step 5

In this step, the implementation of the scope 1 port GHG emission reduction measures are evaluated using the scope 1 KPI scores of Port A and Port B as demonstrated in Figures 33 and 34 respectively.

Figure 33 Evaluation of scope 1 GPI performance of port A

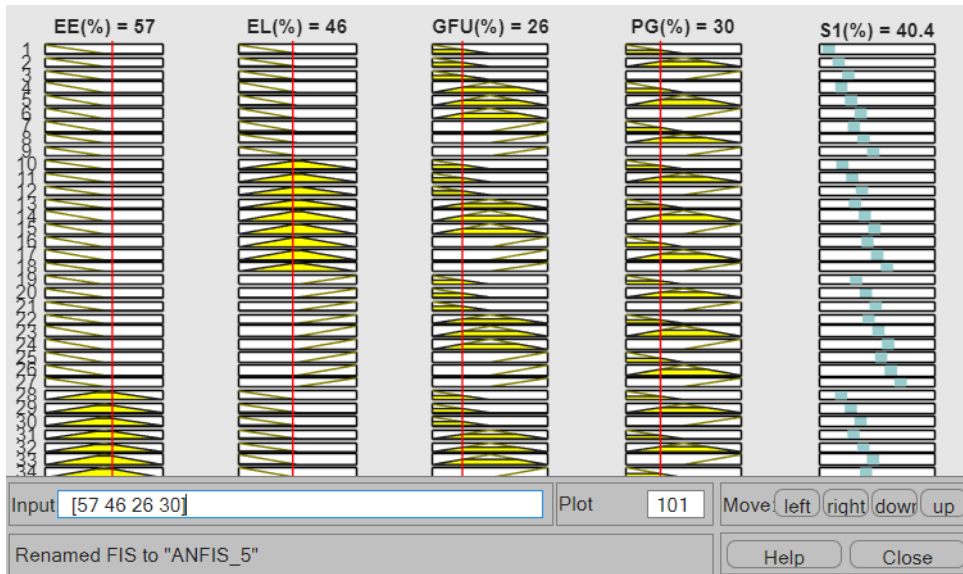
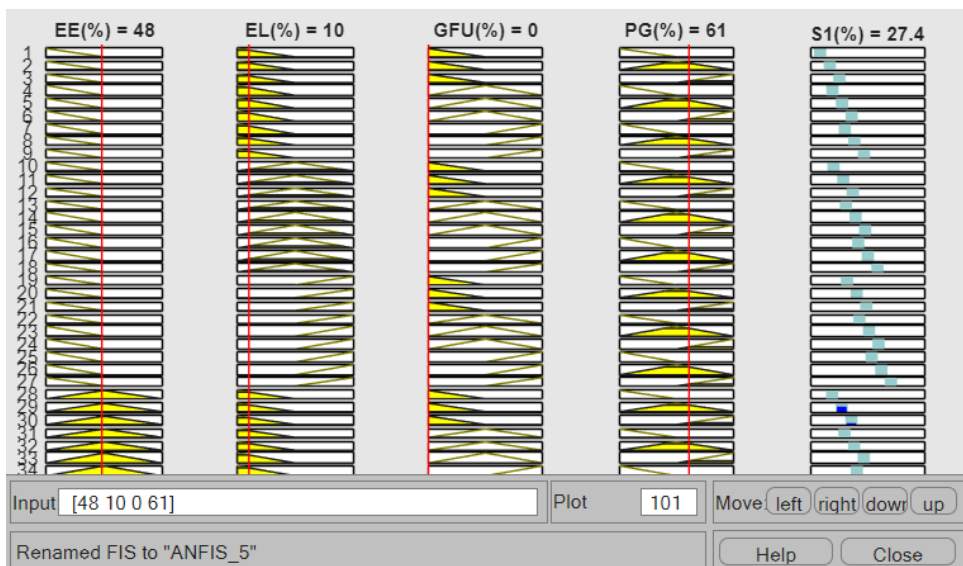


Figure 34 Evaluation of scope 1 GPI performance of port B



Step 6

Finally, the GPI score of Port A and Port B are evaluated using the outputs from step 3 (S3), step 4 (S2) and step 5 (S1). This is shown in Figures 35 and 36. The GPI score can be interpreted as follows: 0 – 20% is poor, 20.1 – 40% is fairly good, 40.1 – 60% is good, 60.1 – 80% is very good and 80.1 – 100% is excellent performance.

Figure 35 Evaluation of GPI score of port A

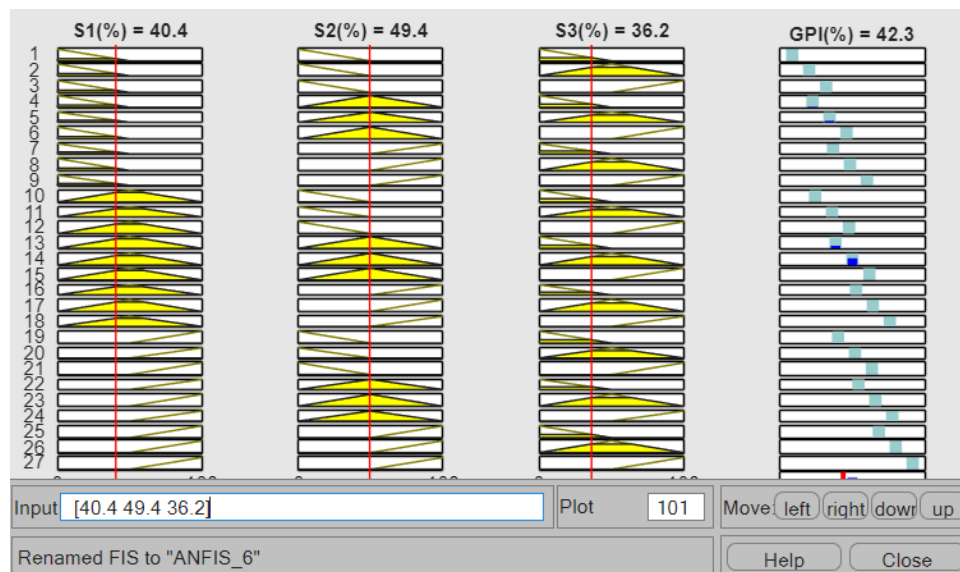
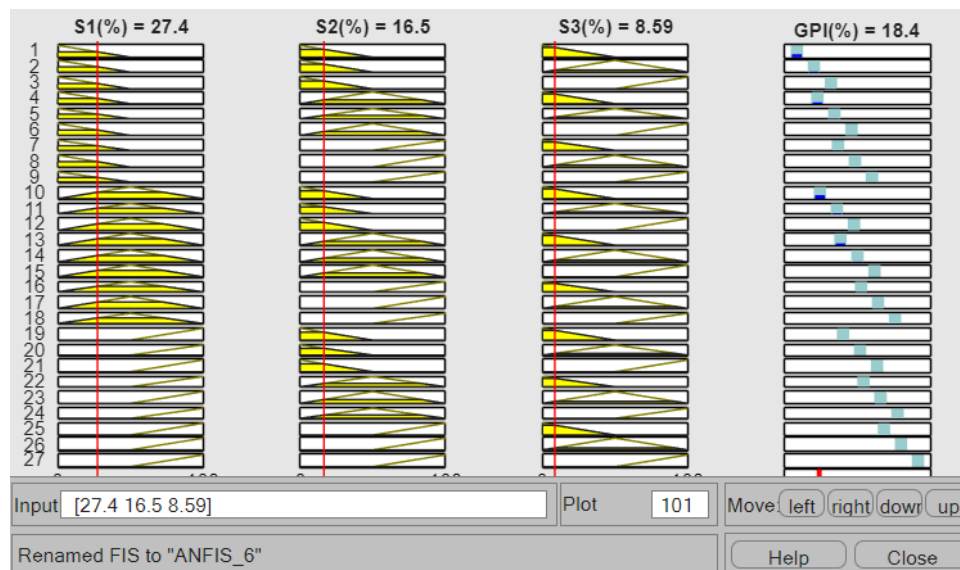


Figure 36 Evaluation of GPI score of port B



To validate the result obtained from the ANFIS-based GPI models, the GPI mathematical model is used to calculate the GPI of Port A and Port B. The results are found to be approximately the same for Port A and exactly the same for Port B as presented in Tables 33 and 34. This demonstrates that the ANFIS-based GPI model is efficient and working as expected. By extension. It also implies that the FIS rules effectively fit the mathematical equations used to train the ANFIS models. The superiority of ANFIS over mathematical modelling is the inherent ability of ANFIS to learn and deal with fuzziness simultaneously. The mathematical approach is rigid in this regard.

Table 33 Evaluation of Port A's GPI using Mathematical model in MS Excel

ES	Weight of ES	KPIs	Local Weight	Global Weight	KPI Score	GPI Score/KPI	
Scope 1	0.380	Energy Efficiency	0.254	0.097	57	5.51	
		Electrification	0.284	0.108	46	4.96	
		Green fuel utilisation	0.260	0.099	26	2.57	
		Port Greenery	0.202	0.077	30	2.31	
Scope 2	0.339	Renewable Energy	0.586	0.198	56	11.11	
		Smart/Microgrid	0.414	0.140	40	5.61	
Scope 3	0.281	OPS usage	0.219	0.062	27	1.66	
		Just in time arrival	0.178	0.050	30	1.50	
		AF bunkering Facility	0.168	0.047	11	0.52	
		Hinterland transport	0.160	0.045	34	1.53	
		Employee commuting	0.111	0.031	70	2.18	
		Truck congestion	0.165	0.046	60	2.78	
				Sum of KPI Weights	1.00	GPI of Port A	42.2

Table 34 Evaluation of Port B's GPI using Mathematical model in MS Excel

ES	Weight of ES	KPIs	Local Weight	Global Weight	KPI Score	GPI Score/KPI
Scope 1	0.380	Energy Efficiency	0.254	0.097	48	4.64
		Electrification	0.284	0.108	10	1.08
		Green fuel utilisation	0.260	0.099	0	0.00
		Port Greenery	0.202	0.077	61	4.69
Scope 2	0.339	Renewable Energy	0.586	0.198	14	2.78
		Smart/Microgrid	0.414	0.140	20	2.80
Scope 3	0.281	OPS usage	0.219	0.062	5	0.31
		Just in time arrival	0.178	0.050	12	0.60
		AF bunkering Facility	0.168	0.047	0	0.00
		Hinterland transport	0.160	0.045	0	0.00
		Employee commuting	0.111	0.031	13	0.40
		Truck congestion	0.165	0.046	24	1.11

4.7 Discussion

The illustrative examples demonstrated how this proposed ANFIS-based GPI model can be used to evaluate port environmental sustainability with respect to

implementation of GHG emission reduction measures. The ANFIS-based GPI model enables step-by-step analysis under each GHG emission scope.

4.7.1 Analysis of Port A's GPI Performance

The GPI score of Port A is 42.3% which is a good performance. Besides, analysis of the KPI scores presented in Table 33 revealed that the best performing KPI is green employee commuting (70%). However, it does not carry much global weight. The worst performing KPI is alternative fuel bunkering (11%). This is partly because the proportion of the global fleet operating on alternative fuels is small. RE usage in Port A is above average (56%) and smart/microgrid coverage of 40%. These scores translated into higher scope 2 performance because of their high weights. Furthermore, the quantification of the KPIs revealed that although Port A is electrifying its CHE (46%), the remaining CHE heavily relies on fossil fuels (74%). The performance in OPS usage, JIT berthing and green hinterland transportation of cargo are below average. Port A may consider performing root-cause analysis in these areas.

To improve, the GPI performance, Port A has number of options to explore. These choices may be influence by number of factors including sensitivity of the ANFIS models and economic factors. If port A is financially buoyant, it may consider improving its GPI score by investing in measures based on the sensitivity analysis of the ANFIS-based GPI model performed in section 4.5.2 which identified inputs having the greatest impact on the GPI score. Port A may consider prioritizing these inputs/KPIs. Otherwise, if Port A is financially constrained to a certain extent. It may have to do cost benefit analysis to identify which measures have a higher GPI improvement rate per unit cost.

4.7.2 Scenario Analysis of Port A's GPI score improvement

Assuming that Port A has a target of achieving a GPI score of 60% by 2030, Table 35 shows three possible scenarios to achieve this target and the baseline scenario with a corresponding GPI score of 42.3%. The first scenario considers improving four KPIs

with the highest global weights namely, RE usage, Smart/Microgrid coverage, electrification and green fuel utilisation respectively. Port A consumed 320 GWh of electricity from renewable sources out of the 340.8 GWh of electricity consumed annually. This means that the national grid is mainly RE or Port A has significant RE generation capacity to meet its energy demand. Therefore, Port A can continue electrifying its CHE and machinery which will be powered by RE. The remaining non electrified CHE can be powered by green fuels. Additionally, Port A may consider increasing the coverage of the Smart/Microgrid to manage peak load and benefit fully from RE and energy storage systems. Therefore, to achieve the 60% GPI score, Port A can work towards 81% electrification of CHE and machinery, green fuel utilisation of 70%, RE utilisation of 80% and Smart/Microgrid coverage of 75% by 2030. However, scenario 1 does not consider further improvement of measures to reduce scope 3 GHG emissions.

In Scenario 2, Port A can keep the KPI scores of Alternative fuel bunkering, green hinterland transportation of cargo and green employee commuting constant while working towards improving the rest of the KPI scores. In this scenario, the targeted KPI scores of RE usage, Smart/Microgrid coverage, electrification and green fuel utilisation are less ambitious compared to the first scenario.

However, the third scenario proposes improving all the KPI scores as shown in Table 35. Increasing the Alternative fuel bunkering by 35% depends on a number of factors including the demand for Alternative fuels which may be driven by national, regional and international regulations. This includes the EU ETS, Fuel EU Maritime, upcoming IMO market-based measures, etc. These regulations seek to reduce well-to-wake GHG emission from ships which can be achieved through the use of low or zero carbon fuels and onboard carbon capture and storage. This scenario takes into account the significant role of ports in decarbonising shipping and hinterland transportation of cargo by providing the enabling infrastructure and many more. Therefore, scenario 3 may be a very good pathway for Port A in this regard. Since, Port A is in a developed

country and has a very massive cargo throughput, it can therefore, work towards achieving GPI score of 60% by 2030 following any of the three scenarios

Table 35 Pathways to achieve 60% GPI score for Port A

		KPI Score %			
Code	KPIs	Baseline	Scenario 1	Scenario 2	Scenario 3
K1	Energy Efficiency	57	57	75	71
K2	Electrification	46	81	65	60
K3	Green fuel utilisation	26	70	45	43
K4	Port Greenery	30	30	65	60
K5	Renewable Energy	56	80	64	61
K6	Smart/Microgrid	40	75	62	58
K7	OPS usage	27	27	71	70
K8	Just in time arrival	30	30	50	48
K9	AF bunkering	11	11	11	35
K10	Hinterland transport	34	34	34	65
K11	Employee commuting	70	70	70	85
K12	Truck congestion	60	60	83	79
GPI Score of Port A		42.3	60.0	60.0	60.0

4.7.3 Analysis of Port B's GPI Performance

The GPI score of Port B is 18.4%. Analysing the KPI scores presented in Table 34, it can be seen that the worst performing KPIs are green fuel utilisation, alternative fuel bunkering and green hinterland transportation of cargo (0%) followed by OPS usage (5%) which is at the pilot stage. The best performing KPI is port greenery (61%). This is a low hanging fruit and Port B can capitalise and embark on more tree planting exercise to improve its environmental stewardship.

Port B is heavily reliant on fossil fuels for its energy needs. Fossil fuels represent about 83% of the total energy consumption in Port B. Besides, 80% of the total electricity consumption in Port B comes from RE sources. However, considering the total energy consumption, RE usage only accounts for 14%. Therefore, Port B can improve its GPI score by reducing fossil fuel consumption through electrification of CHE and increasing the utilisation of RE to power the electrified CHE.

4.7.4 Scenario Analysis of Port B's GPI Score Improvement

Assuming that Port B has a target of achieving a GPI score of 40% by 2030, Table 36 presents three possible scenarios to achieve this target. The baseline which is the current KPI scores of Port B and its corresponding GPI score are also shown in Table 36. To achieve the 40% GPI score, the first scenario proposes improvement in five KPIs namely: energy efficiency, electrification, port greenery, RE usage and Smart/Microgrid coverage. In this scenario, green fuel utilisation and the scope 3 KPIs remains the same as in the baseline scenario.

In the second scenario, Port B may consider improving eight KPI scores excluding green fuel utilisation, alternative fuel bunkering, green hinterland transportation of cargo and employee commuting as shown in Table 36. In the context of developing countries, achieving meaningful improvement in green fuel utilisation, alternative fuel bunkering, green hinterland transportation of cargo and green employee commuting requires high level commitment and proper planning involving the government and relevant stakeholders. Therefore, a realistic roadmap should be developed by Port B.

However, the third scenario considers improvement in all the KPIs to achieve the 40% GPI score. This is reflective of the key role of ports in maritime decarbonisation and achieving green supply chain. However, this may be a big challenge to achieve within five years considering the unavailability of necessary resources in developing countries. For example, in most developing countries the road and rail networks are not well developed. Additionally, the technologies required to produce green fuels at a low cost are not readily available.

Table 36 Pathways to achieve 40% GPI score for Port B

Code	KPIs	Baseline	KPI Score %		
			Scenario 1	Scenario 2	Scenario 3
K1	Energy Efficiency	48	60	55	53
K2	Electrification	10	55	45	34
K3	Green fuel utilisation	0	0	0	20
K4	Port Greenery	61	75	65	63
K5	Renewable Energy	14	61	54	48
K6	Smart/Microgrid	20	57	50	45
K7	OPS usage	5	5	35	33
K8	Just in time arrival	12	12	40	35
K9	AF bunkering	0	0	0	15
K10	Hinterland transport	0	0	0	25
K11	Employee commuting	13	13	13	28
K12	Truck congestion	24	24	54	45
GPI Score of Port B		18.4	40.0	40.0	40.0

4.7.5 Comparison of Port A and Port B GPI Score

The GPI score of Port A is 23.9 percentage points higher than Port B (18.4%). The performance of Port B in Port greenery KPI is 31 percentage point higher than port A. For the rest of the KPIs Port A out performs Port B. The low GPI score of Port B may be attributed to number of barriers developing countries generally encounter in their green maritime energy transition which include financial constrain, inadequate technical expertise and lack of awareness. A root cause analysis may be performed to have an in-depth understanding of the low GPI score of Port B. Port A is currently implementing all the 12 KPIs although there is still room for further improvement.

4.7.6 Recommendations for Port A and Port B

Both Port A and Port B should enhance their Operational efficiency, which will result in significant improvements of GPI. This is required to improve energy efficiency, effectively implement truck appointment system and facilitate JIT berthing of ships. Implementation of enabling GHG emission reduction policies and regulations can also improve GPI score of both ports. For example, both ports can mandate the use of shore power at berth once all the terminals are equipped with adequate shore connection plugs and enough capacity is available to meet the vessel electricity demand. A ban or

fine can also be imposed on high polluting trucks, thus facilitating the shift toward low emission technologies. Similarly, environmental dues can be implemented to ensure that polluting ships pay.

Besides, Port A and Port B should embark on a meaningful stakeholder engagement to device ways of improving their environment sustainability performance. An agreement between the Ports and local energy producing companies can be signed to provide the necessary infrastructure for the OPS. Similar agreements can be reached with technology providers and green fuel producing companies. This will reduce the financial burden on the Ports while improving their GPI score.

Chapter 5. Conclusion and Recommendation

5.1 Summary of work

This research identified 12 relevant KPIs that need to be implemented to reduce port GHG emissions through a comprehensive literature review. These KPIs are used as evaluation criteria for GPI. Although these KPIs are mentioned in many literatures, however, a methodology has not been developed to quantify them. This research therefore, proposes for the first time a methodology to quantify each of the KPIs using mathematical equations defined in section 3.4. FAHP technique was used to calculate the weight of the KPIs based on the opinions of heterogeneous experts. Additionally, this research provided a mathematical model for evaluating the GPI performance using the weights and scores of the KPIs. Recognising the inability of mathematical models in dealing with fuzziness, ANFIS methodology was used to develop the GPI model. The ANFIS training data is generated using the mathematical model. Besides, rigorous testing revealed the sensitivity of the individual ANFIS models to the KPIs. As a proof of concept, the given illustrative examples demonstrated how policy maker or PAs can use these models to evaluate their own GPI score and to compare GPI scores of ports.

5.2 Conclusion

The result of the KPI weighting shows that RE usage is the most important factor for port GHG emission reduction while green employee commuting is the least important factor. Similarly, the results concluded that scope 1 is the highest priority while scope 3 is the least priority in terms of implementation of port GHG emission reduction measures. Additionally, the results revealed that electrification, RE and OPS usage are the most important KPIs for scope 1, scope 2 and scope 3 port GHG emission reduction respectively.

The GPI score obtained from the proposed methodology has a broader implication. For example, the decomposable composite GPI score can be used by PAs to guide efforts towards data driven and environmentally sustainable investment roadmap. PAs can also use GPI to hold operators accountable by including realistic GPI targets in

concession agreements. The comparable GPI scores enables policy makers to align port GHG emission reduction policy with the global targets. Most importantly, for financiers, the verifiable nature of the KPIs enhances risk assessment, thus improving the credibility of sustainability-linked financial instruments. The methodology proposed in this research can be adopted to evaluate implementation of GHG emission reduction measures in shipyards and other carbon intensive industries.

The main contribution of this research is the provision of a comprehensive mechanism for policy makers and other relevant stakeholders to quantitatively assess green port performance with respect to implementation of the port GHG reduction measures. The ANFIS-based GPI model can be used by relevant stakeholders to set targets through critical examination of the control surfaces using the Data tip function of fuzzy logic toolbox. This will enable decision maker to know what needs to be done to meet the set targets.

The strength of FAHP and ANFIS hybrid methodology of indexing/benchmarking ports is that it does not reward ports unfairly. Each port is evaluated individually without taking reference to the best performing port. This is in contrast to DEA methodology of indexing which takes reference to the best performing entity (in this case port). Which means the best performing port will have a score of 100% using DEA. Hence, the best performing port may not be motivated to improve its GPI performance further. However, it is theoretically possible to achieve 100% GPI based on the methodology proposed in this dissertation. This is not possible in practice because it not possible to achieve 100% performance in all the KPIs. For example, 100% energy efficiency cannot be achieved. Therefore, the 100% GPI can be seen as an ideal case that ports can work towards. Hence providing a pathway towards zero GHG emission port operation. However, absolute zero emission is not possible especially if a comprehensive life cycle assessment is taken into account. Additionally, the proposed methodology for assessing port environmental sustainability is action oriented in contrast to direct GHG emission accounting approach.

5.3 Recommendation for further research

This research has created room for further research in many areas. For instance, in quantifying port energy efficiency KPI, the UN-ELAC's 2013 port energy consumption survey finding was used to establish the baseline for energy efficiency calculation. Further research can be conducted to investigate the changes in these values. Besides, their survey involved 41 container terminal ports out of which 30 are from Latin America and Caribbean. It is therefore important to note that the result may not be generalised to all regions. However, such researches are rare in literatures. Thus, it provides basis for reasonable assumption while creating more research opportunities. Besides, similar research should be conducted for bulk terminal port and multifunctional ports as a whole. This will provide a robust energy efficiency benchmark that can be used to calculate energy efficiency improvement KPI. In this research energy efficiency correction factor due to variation in the proportion of reefer containers handled by ports has been considered because of the impact of reefer containers on port energy consumption. Similarly, the proportion of transshipment containers also impact port energy consumption. A port handling higher volume of transshipment containers will have a reduced energy consumption per TEU. This is because there is limited horizontal movements. However, the correction factor due to variation in proportion of transshipment containers have not been considered because of unavailability of comprehensive data that shows the energy consumption per container transhipped. Further research may be conducted in this area.

Additionally, in quantifying the port greenery KPI, it has been noted by the author that different trees/plants have varying carbon sequestration potential. Hence, necessitating the introduction of a correction factor to accommodate these variations in the calculation. However, this requires further research beyond the scope and resources of this dissertation. A proposed approach to determine this correction factor is briefly discussed in section 3.4. Researchers can also look into the cost benefit analysis of implementing the identified port GHG reduction measures which can also provide a

balanced guide for policy makers and relevant stakeholders in developing data driven implementation strategy.

5.4 Call to action

PAs should adopt the proposed GPI to evaluate their environmental sustainability with respect to GHG mitigation efforts and annually publish it voluntarily. Policy makers can formulate policies that enables the effective implementation of port GHG emission reduction measures to complement the efforts of PAs. Besides, regional and international port organisations such as ESPO can use this approach to set targets for ports and assess them based on implementation of port GHG reduction measures. Additionally, availability of soft loans and green financing for port environmental sustainability projects will accelerate the implementation of port GHG reduction measures especially in developing countries.

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Appendices

A. Questionnaire Survey:

Section 1: Background

1. Which organization do you work for?
 - A. Port Authority
 - B. Maritime Administration
 - C. Maritime training Institute
 - D. Others. Please specify

2. What is your role in the organization?
 - A. Executive/Management (e.g., Head of department, Director, manager, etc.)
 - B. Technical/operational (e.g., Engineering, maintenance, procurement, etc.)
 - C. Regulatory compliance/Monitoring
 - D. Research & Development
 - E. Policy development / strategic planning
 - F. Sustainability/ Environmental strategist
 - G. Others, please specify

3. How long have you been working in the maritime sector?
.....

4. Are you familiar with the green port concept?
 - A. very familiar
 - B. Average
 - C. Slightly familiar
 - D. Not familiar

Section 2

1. Scope 1 emissions

These are direct GHG emissions resulting from port's own activities which can be controlled by the port. The Green port Key performance indicators (KPIs) used to evaluate scope 1 emissions are described in the table below.

Table 37 Description of Scope 1 KPIs

Code	KPI	Description
K1	Energy efficiency	Emission reduction due to improvement in energy efficiency
K2	Electrification	Emission reduction achieved by transitioning from fossil fuel powered to electrified port machinery and equipment. These equipment and machinery operate on electricity from the grid.
K3	Green fuel utilization	Emission reduction achieved from the use of green fuels power port machinery and vehicles (this includes green hydrogen, e-methanol, ammonia, biogas, biofuel)
K4	Port Greenery	CO ₂ removed from the atmosphere by port greenery initiative (tree planting, mangrove reforestation, etc.). This can be done along the shoreline, roadside, within the port or between port and hinterland.

Table 38 Scale of importance

Judgment	Degree of importance
Not important	1
Moderately important	2
Strongly important	3
Very strongly important	4
Extremely strong importance	5

Using the above scale, assess the degree of importance of the KPIs (K1 to K4) with respect to their contribution to scope 1 port GHG emission reduction based on your expert judgement.

Table 39 Ranking of Scope 1 KPIs based on degree of importance

Code	Scope 1 KPI	Degree of importance (1 to 5)
K1	Energy efficiency	
K2	Electrification	
K3	Green fuel utilization	
K4	Port Greenery	

Section 3

2. Scope 2 emission

This are GHG emissions related to the electricity and heat supply to the port. The Green port KPIs used to evaluate scope 2 emissions are described in the table below.

Table 4 Description Scope 2 KPIs

Code	KPI	Description
K5	Carbon neutral/ Renewable energy Usage	GHG emission reduction achieved by the utilization of carbon neutral/renewable energy to provide electricity and heat for the port. This includes wind, tidal, wave, geothermal, solar energy, biogas, e-methanol, green hydrogen, etc.
K6	Implementation of smart or microgrid	Enable efficient peak load management and energy storage. Hence, it optimizes electricity distribution and contributes to GHG emission reduction.

Table 2 Scale of importance

Judgment	Degree of importance
Not important	1
Moderately important	2
Strongly important	3
Very strongly important	4
Extremely strong importance	5

Using the above scale, assess the degree of importance of the KPIs (K5 and K6) with respect to their contribution to scope 2 port GHG emission reduction.

Table 5 Pairwise comparison for scope 2 KPIs based on degree of importance

Code	KPI	Degree of importance (1 to 5)
K5	Carbon neutral/Renewable energy Usage	
K6	Implementation of smart/microgrid	

Section 4

3. Scope 3 emissions

These are indirect GHG emissions related to port activities such as vessels calling the port, hinterland transportation of cargo and employee commuting. The Green port KPIs used to evaluate scope 3 emissions are described in the table below.

Table 6 Description Scope 3 KPIs

Code	KPI	Description
K7	Onshore Power Supply (OPS) usage	GHG emission reduction achieved by utilization of OPS by vessels calling the port.
K8	Just in time arrival	Emission reduction associated with vessel arriving just in time.

K9	Alternative fuel bunkering (AFB)	Availability of AFBF potentially attracting vessels utilizing such fuels to call the port.
K10	Green Hinterland transportation	Emission reduction achieved due to the utilization of carbon neutral/Zero carbon energy sources in transporting cargo to the hinterland (e.g., green hydrogen, e-methanol, biogas, ammonia, electric trucks or trains)
K11	Employee commuting	Emission reduction achieved by employee and port users traveling green (e.g., electric trains, electric cars or cars using alternative fuels)
K12	Truck congestion	Emission reduction due to reduction of truck congestion inside and outside the port.

Using the scale provided, assess the degree of importance of the KPIs (K7 to K11) with respect to their contribution to scope 3 port GHG emission reduction.

Table 7 Ranking of Scope 3 KPIs based on degree of importance

Code	KPI	Degree of importance (1 to 5)
K7	Onshore power supply (OPS) usage	
K8	Just in time arrival	
K9	Availability of alternative fuel bunkering facilities	
K10	Hinterland transportation	
K11	Employee commuting	
K12	Truck congestion	

Section 5

Assess the degree of importance of the GHG emission scopes (scope 1 to scope 3) based on their contribution to port GHG emission, using the scale provided

Table 8 ranking of the 3 scopes of GHG emission based on degree of importance

No.	GHG emission scopes	Degree of importance (1 to 5)
1	Scope 1	
2	Scope 2	
3	Scope 3	

B. Expert KPI rating

<i>Experts</i>	Scope 1 KPI rating				Scope 2 KPI rating	
	EE	EL	GFU	PG	RE	SMG
1	5	5	5	5	4	4
2	5	4	5	4	4	3
3	5	3	5	4	5	3
4	5	5	5	5	5	3
5	3	5	5	3	4	4
6	5	5	4	4	4	4
7	4	4	2	3	5	3
8	4	5	4	2	5	3
9	4	5	3	2	5	2
10	3	5	4	2	5	3
11	3	5	4	3	5	4
12	4	5	5	2	5	3
13	5	5	4	4	5	4
14	3	4	4	2	3	3
15	4	3	4	2	4	3
16	5	4	3	5	3	4
17	4	5	3	5	5	4
18	2	2	5	3	5	3
19	3	2	2	4	4	4

Scope 3 KPI rating

Rating of Emission scopes

Experts	OPS	JIT	AFB	GHT	EC	TC	S1	S2	S3
1	5	4	4	3	2	2	3	4	5
2	4	4	5	5	3	4	5	5	5
3	3	5	5	5	1	4	5	4	2
4	5	5	3	2	2	2	5	4	4
5	4	5	5	5	5	5	4	4	4
6	4	4	3	3	3	3	4	4	4
7	5	4	3	3	2	4	5	4	3
8	5	4	3	2	2	3	5	4	3
9	5	4	3	4	2	3	5	4	3
10	5	5	3	4	2	3	5	3	4
11	5	4	3	4	2	3	3	5	4
12	5	4	4	3	1	5	4	5	3
13	5	4	3	3	4	3	5	4	3
14	3	2	3	2	1	3	4	3	2
15	3	2	3	2	2	2	4	4	3
16	5	4	3	4	3	5	5	4	4
17	5	2	3	4	3	5	5	5	4
18	3	2	4	4	5	3	4	4	4
19	3	4	4	3	2	4	3	4	3

C. Aggregation Pairwise comparison (PC) of KPIs

Weighting of experts by level of familiarity to green port concept.

Expert	F_i	g_i
1	3	1.102
2	3	1.102
3	3	1.102
4	3	1.102
5	3	1.102
6	3	1.102
7	2	0.735
8	2	0.735
9	3	1.102
10	3	1.102
11	3	1.102
12	3	1.102
13	3	1.102
14	2	0.735
15	2	0.735
16	3	1.102
17	3	1.102
18	2	0.735
19	0	0
$\sum_{i=1}^n F_i$	49	18

g_i is calculated using equation 21 and aggregation by geometric mean

Fuzzified scope 1 Pairwise Comparison (PC)

Expert	k1vsK2			K1VsK3			K1VsK4			K2VsK3			K2VsK4			K3 Vs K4		
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1.25	3	1	1	1	1	1.25	3	0.3333	0.8	1	1	1	1	1	1.25	3
3	1	1.666667	3	1	1	1	1	1.25	3	0.3333	0.6	1	0.3333	0.75	1	1	1.25	3
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0.3333	0.6	1	0.3333	0.6	1	1	1	1	1	1	1	1	1.6667	3	1	1.6667	3
6	1	1	1	1	1.25	3	1	1.25	3	1	1.25	3	1	1.25	3	1	1	1
7	1	1	1	1	2	3	1	1.3333	3	1	2	3	1	1.3333	3	0.3333	0.6667	1
8	0.3333	0.8	1	1	1	1	1	2	3	1	1.25	3	2	2.5	4	1	2	3
9	0.3333	0.8	1	1	1.3333	3	1	2	3	1	1.6667	3	2	2.5	4	1	1.5	3
10	0.3333	0.6	1	0.3333	0.75	1	1	1.5	3	1	1.25	3	2	2.5	4	1	2	3
11	0.3333	0.6	1	0.5	0.75	1	1	1	1	1	1.25	3	1	1.6667	3	1	1.3333	3
12	0.3333	0.8	1	0.5	0.8	1	1	2	3	1	1	1	2	2.5	4	2	2.5	4
13	1	1	1	1	1.25	3	1	1.25	3	1	1.25	3	1	1.25	3	1	1	1
14	0.3333	0.75	1	0.3333	0.75	1	1	1.5	3	1	1	1	1	2	3	1	2	3
15	1	1.333333	3	1	1	1	1	2	3	0.3333	0.75	1	1	1.5	3	1	2	3
16	1	1.25	3	1	1.6667	3	1	1	1	1	1.3333	3	0.3333	0.8	1	0.3333	0.6	1
17	0.3333	0.8	1	1	1.3333	3	0.3333	0.8	1	1	1.6667	3	1	1	1	0.3333	0.6	1
18	1	1	1	0.25	0.4	0.5	0.3333	0.6667	1	0.25	0.4	0.5	0.3333	0.6667	1	1	1.6667	3
GeoMean	0.6137	0.921685	1.2765	0.7138	0.9841	1.3878	0.8851	1.2583	1.9569	0.771	1.0678	1.6666	0.9713	1.3652	2.0861	0.8654	1.27853	1.9885
Reciprocal	1.6295	1.08497	0.7834	1.4009	1.0161	0.7206	1.1298	0.7947	0.511	1.2971	0.9365	0.6	1.0295	0.7325	0.4794	1.1556	0.78215	0.5029

Weighted Fuzzified scope 1 Pairwise Comparison (PC)

This is obtained by first multiply the fuzzified pairwise comparison (PC) by the corresponding expert weight. The result is aggregated using geometric mean method. Additionally, equation 20 can be used to calculate the weighted fuzzified pairwise comparison values.

Expert	k1vsK2			K1VsK3			K1VsK4			K2VsK3			K2VsK4			K3 Vs K4		
1	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102
2	1.102	1.3776	3.3061	1.102	1.102	1.102	1.102	1.3776	3.3061	0.3673	0.8816	1.102	1.102	1.102	1.102	1.102	1.3776	3.3061
3	1.102	1.8367	3.3061	1.102	1.102	1.102	1.102	1.3776	3.3061	0.3673	0.6612	1.102	0.3673	0.8265	1.102	1.102	1.3776	3.3061
4	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102
5	0.3673	0.6612	1.102	0.3673	0.6612	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.8367	3.3061	1.102	1.8367	3.3061
6	1.102	1.102	1.102	1.102	1.3776	3.3061	1.102	1.3776	3.3061	1.102	1.3776	3.3061	1.102	1.3776	3.3061	1.102	1.102	1.102
7	0.7347	0.7347	0.7347	0.7347	1.4694	2.2041	0.7347	0.9796	2.2041	0.7347	1.4694	2.2041	0.7347	0.9796	2.2041	0.2449	0.4898	0.7347
8	0.2449	0.5878	0.7347	0.7347	0.7347	0.7347	0.7347	1.4694	2.2041	0.7347	0.9184	2.2041	1.4694	1.8367	2.9388	0.7347	1.4694	2.2041
9	0.3673	0.8816	1.102	1.102	1.4694	3.3061	1.102	2.2041	3.3061	1.102	1.8367	3.3061	2.2041	2.7551	4.4082	1.102	1.6531	3.3061
10	0.3673	0.6612	1.102	0.3673	0.8265	1.102	1.102	1.6531	3.3061	1.102	1.3776	3.3061	2.2041	2.7551	4.4082	1.102	2.2041	3.3061
11	0.3673	0.6612	1.102	0.551	0.8265	1.102	1.102	1.102	1.102	1.102	1.3776	3.3061	1.102	1.8367	3.3061	1.102	1.4694	3.3061
12	0.3673	0.8816	1.102	0.551	0.8816	1.102	1.102	2.2041	3.3061	1.102	1.102	1.102	2.2041	2.7551	4.4082	2.2041	2.7551	4.4082
13	1.102	1.102	1.102	1.102	1.3776	3.3061	1.102	1.3776	3.3061	1.102	1.3776	3.3061	1.102	1.3776	3.3061	1.102	1.102	1.102
14	0.2449	0.551	0.7347	0.2449	0.551	0.7347	0.7347	1.102	2.2041	0.7347	0.7347	0.7347	0.7347	1.4694	2.2041	0.7347	1.4694	2.2041
15	0.7347	0.9796	2.2041	0.7347	0.7347	0.7347	0.7347	1.4694	2.2041	0.2449	0.551	0.7347	0.7347	1.102	2.2041	0.7347	1.4694	2.2041
16	1.102	1.3776	3.3061	1.102	1.8367	3.3061	1.102	1.102	1.102	1.102	1.4694	3.3061	0.3673	0.8816	1.102	0.3673	0.6612	1.102
17	0.3673	0.8816	1.102	1.102	1.4694	3.3061	0.3673	0.8816	1.102	1.102	1.8367	3.3061	1.102	1.102	1.102	0.3673	0.6612	1.102
18	0.7347	0.7347	0.7347	0.1837	0.2939	0.3673	0.2449	0.4898	0.7347	0.1837	0.2939	0.3673	0.2449	0.4898	0.7347	0.7347	1.2245	2.2041
GeoMean	0.6043	0.9075	1.2569	0.7029	0.969	1.3665	0.8715	1.239	1.9269	0.7591	1.0514	1.641	0.9564	1.3442	2.0541	0.8521	1.2589	1.9579

Fuzzified scope 2 Pairwise Comparison (PC)

Fuzzified scope 2 PC				Weighted Fuzzified scope 2 PC			
Expert	K5 Vs K6			Expert	K5 Vs K6		
1	1	1	1	1	1.102	1.102	1.102
2	1	1.333	3	2	1.102	1.469	3.306
3	1	1.667	3	3	1.102	1.837	3.306
4	1	1.667	3	4	1.102	1.837	3.306
5	1	1	1	5	1.102	1.102	1.102
6	1	1	1	6	1.102	1.102	1.102
7	1	1.667	3	7	0.735	1.224	2.204
8	1	1.667	3	8	0.735	1.224	2.204
9	2	2.5	4	9	2.204	2.755	4.408
10	1	1.667	3	10	1.102	1.837	3.306
11	1	1.25	3	11	1.102	1.378	3.306
12	1	1.667	3	12	1.102	1.837	3.306
13	1	1.25	3	13	1.102	1.378	3.306
14	1	1	1	14	0.735	0.735	0.735
15	1	1.333	3	15	0.735	0.98	2.204
16	0.333	0.75	1	16	0.367	0.827	1.102
17	1	1.25	3	17	1.102	1.378	3.306
18	1	1.667	3	18	0.735	1.224	2.204
GM	0.978	1.354	2.247	GM	0.963	1.333	2.212

Fuzzified scope 3 PC

Expert	K7 K8			K7K9			K7K10			K7K11			K7K12			K8K9			K8K10		
1	1	1.25	3	1	1.25	3	1	1.6667	3	2	2.5	4	2	2.5	4	1	1	1	1	1.333333	3
2	1	1	1	0.3333	0.8	1	0.3333	0.8	1	1	1.3333	3	1	1	1	0.3333	0.8	1	0.333333	0.8	1
3	0.3333	0.6	1	0.3333	0.6	1	0.3333	0.6	1	2	3	4	0.3333	0.75	1	1	1	1	1	1	1
4	1	1	1	1	1.6667	3	2	2.5	4	2	2.5	4	2	2.5	4	1	1.6667	3	2	2.5	4
5	0.3333	0.8	1	0.3333	0.8	1	0.3333	0.8	1	0.3333	0.8	1	0.3333	0.8	1	1	1	1	1	1	1
6	1	1	1	1	1.3333	3	1	1.3333	3	1	1.3333	3	1	1.3333	3	1	1.3333	3	1	1.333333	3
7	1	1.25	3	1	1.6667	3	1	1.6667	3	2	2.5	4	1	1.25	3	1	1.3333	3	1	1.333333	3
8	1	1.25	3	1	1.6667	3	2	2.5	4	2	2.5	4	1	1.6667	3	1	1.3333	3	1	2	3
9	1	1.25	3	1	1.6667	3	1	1.25	3	2	2.5	4	1	1.6667	3	1	1.3333	3	1	1	1
10	1	1	1	1	1.6667	3	1	1.25	3	2	2.5	4	1	1.6667	3	1	1.6667	3	1	1.25	3
11	1	1.25	3	1	1.6667	3	1	1.25	3	2	2.5	4	1	1.6667	3	1	1.3333	3	1	1	1
12	1	1.25	3	1	1.25	3	1	1.6667	3	4	5	5	1	1	1	1	1	1	1	1.333333	3
13	1	1.25	3	1	1.6667	3	1	1.6667	3	1	1.25	3	1	1.6667	3	1	1.3333	3	1	1.333333	3
14	1	1.5	3	1	1	1	1	1.5	3	2	3	4	1	1	1	0.3333	0.6667	1	1	1	1
15	1	1.5	3	1	1	1	1	1.5	3	1	1.5	3	1	1.5	3	0.3333	0.6667	1	1	1	1
16	1	1.25	3	1	1.6667	3	1	1.25	3	1	1.6667	3	1	1	1	1	1.3333	3	1	1	1
17	2	2.5	4	1	1.6667	3	1	1.25	3	1	1.6667	3	1	1	1	0.3333	0.6667	1	0.333333	0.5	1
18	1	1.5	3	0.3333	0.75	1	0.3333	0.75	1	0.3333	0.6	1	1	1	1	0.3333	0.5	1	0.333333	0.5	1
	0.92	1.193	2.114	0.783	1.255	2.08	0.846	1.309	2.426	1.352	1.917	3.154	0.956	1.305	1.901	0.737	1.051	1.732	0.8654	1.0967	1.6558

K8K11			K8K12			K9K10			K9K11			K9K12			K10K11			K10K12			K11K12			
1	2	3	1	2	3	1	1.3333	3	1	2	3	1	2	3	1	1.5	3	1	1.5	3	1	1	1	
1	1.3333	3	1	1	1	1	1	1	1	1.6667	3	1	1.25	3	1	1.6667	3	1	1.25	3	0.3333	0.75	1	
4	5	5	1	1.25	3	1	1	1	4	5	5	1	1.25	3	4	5	5	1	1.25	3	0.2	0.25	0.3333	
2	2.5	4	2	2.5	4	1	1.5	3	1	1.5	3	1	1.5	3	1	1	1	1	1	1	1	1	1	
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
1	1.3333	3	1	1.3333	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
1	2	3	1	1	1	1	1	1	1	1.5	3	0.3333	0.75	1	1	1.5	3	0.3333	0.75	1	0.3333	0.5	1	
1	2	3	1	1.3333	3	1	1.5	3	1	1.5	3	1	1	1	1	1	1	0.3333	0.6667	1	0.3333	0.6667	1	
1	2	3	1	1.3333	3	0.3333	0.75	1	1	1.5	3	1	1	1	1	1	2	3	1	1.3333	3	0.3333	0.6667	1
2	2.5	4	1	1.6667	3	0.3333	0.75	1	1	1.5	3	1	1	1	1	1	2	3	1	1.3333	3	0.3333	0.6667	1
1	2	3	1	1.3333	3	0.3333	0.75	1	1	1.5	3	1	1	1	1	1	2	3	1	1.3333	3	0.3333	0.6667	1
3	4	5	0.3333	0.8	1	1	1.3333	3	3	4	5	0.3333	0.8	1	2	3	4	0.3333	0.6	1	0.2	0.2	0.25	
1	1	1	1	1.3333	3	1	1	1	0.3333	0.75	1	1	1	1	0.3333	0.75	1	1	1	1	0.3333	1.3333	1	
1	2	3	0.3333	0.6667	1	1	1.5	3	2	3	4	1	1	1	1	2	3	0.3333	0.6667	1	0.25	0.3333	0.5	
1	1	1	1	1	1	1	1.5	3	1	1.5	3	1	1.5	2	1	1	1	1	1	1	1	1	1	
1	1.3333	3	0.3333	0.8	1	0.3333	0.75	1	1	1	1	0.3333	0.6	1	1	1.3333	3	0.3333	0.8	1	0.3333	0.6	1	
0.3333	0.6667	1	0.25	0.4	0.5	0.3333	0.75	1	1	1	1	0.3333	0.6	1	1	1.3333	3	0.3333	0.8	1	0.3333	0.6	1	
0.25	0.4	0.5	0.3333	0.6667	1	1	1	1	0.3333	0.8	1	1	1.3333	3	0.3333	0.8	1	1	1.3333	3	1	1.6667	3	
1.08	1.606	2.325	0.754	1.093	1.693	0.737	1.043	1.442	1.056	1.528	2.237	0.783	1.04	1.41	0.993	1.464	2.046	0.693	0.997	1.533	0.447	0.681	0.891	

Weighted Fuzzified scope 3 PC

Expert	K7 K8			K7K9			K710			K7K11			K7K12			K8K9			K8K10		
1	1.102	1.378	3.306	1.102	1.378	3.306	1.102	1.837	3.306	2.204	2.755	4.408	2.204	2.755	4.408	1.102	1.102	1.102	1.102	1.469	3.306
2	1.102	1.102	1.102	0.367	0.882	1.102	0.367	0.882	1.102	1.102	1.469	3.306	1.102	1.102	1.102	0.367	0.882	1.102	0.367	0.882	1.102
3	0.367	0.661	1.102	0.367	0.661	1.102	0.367	0.661	1.102	2.204	3.306	4.408	0.367	0.827	1.102	1.102	1.102	1.102	1.102	1.102	1.102
4	1.102	1.102	1.102	1.102	1.837	3.306	2.204	2.755	4.408	2.204	2.755	4.408	2.204	2.755	4.408	1.102	1.837	3.306	2.204	2.755	4.408
5	0.367	0.882	1.102	0.367	0.882	1.102	0.367	0.882	1.102	0.367	0.882	1.102	0.367	0.882	1.102	1.102	1.102	1.102	1.102	1.102	1.102
6	1.102	1.102	1.102	1.102	1.469	3.306	1.102	1.469	3.306	1.102	1.469	3.306	1.102	1.469	3.306	1.102	1.469	3.306	1.102	1.469	3.306
7	0.735	0.918	2.204	0.735	1.224	2.204	0.735	1.224	2.204	1.469	1.837	2.939	0.735	0.918	2.204	0.735	0.98	2.204	0.735	0.98	2.204
8	0.735	0.918	2.204	0.735	1.224	2.204	1.469	1.837	2.939	1.469	1.837	2.939	0.735	1.224	2.204	0.735	0.98	2.204	0.735	1.469	2.204
9	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.378	3.306	2.204	2.755	4.408	1.102	1.837	3.306	1.102	1.469	3.306	1.102	1.102	1.102
10	1.102	1.102	1.102	1.102	1.837	3.306	1.102	1.378	3.306	2.204	2.755	4.408	1.102	1.837	3.306	1.102	1.837	3.306	1.102	1.378	3.306
11	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.378	3.306	2.204	2.755	4.408	1.102	1.837	3.306	1.102	1.469	3.306	1.102	1.102	1.102
12	1.102	1.378	3.306	1.102	1.378	3.306	1.102	1.837	3.306	4.408	5.51	5.51	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.469	3.306
13	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.837	3.306	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.469	3.306	1.102	1.469	3.306
14	0.735	1.102	2.204	0.735	0.735	0.735	0.735	1.102	2.204	1.469	2.204	2.939	0.735	0.735	0.735	0.245	0.49	0.735	0.735	0.735	0.735
15	0.735	1.102	2.204	0.735	0.735	0.735	0.735	1.102	2.204	0.735	1.102	2.204	0.735	1.102	2.204	0.245	0.49	0.735	0.735	0.735	0.735
16	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.102	1.102	1.102	1.469	3.306	1.102	1.102	1.102
17	2.204	2.755	4.408	1.102	1.837	3.306	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.102	1.102	0.367	0.735	1.102	0.367	0.551	1.102
18	0.735	1.102	2.204	0.245	0.551	0.735	0.245	0.551	0.735	0.245	0.441	0.735	0.735	0.735	0.735	0.245	0.367	0.735	0.245	0.367	0.735
GM	0.906	1.175	2.081	0.771	1.236	2.048	0.833	1.289	2.389	1.331	1.887	3.106	0.941	1.285	1.872	0.726	1.035	1.705	0.852	1.08	1.63

K8K11			K8K12			K9K10			K9K11			K9K12			K10K11			K10K12			K11K12		
1.102	2.204	3.306	1.102	2.204	3.306	1.102	1.469	3.306	1.102	2.204	3.306	1.102	2.204	3.306	1.102	1.653	3.306	1.102	1.653	3.306	1.102	1.102	
1.102	1.469	3.306	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.837	3.306	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.378	3.306	0.367	0.827	
4.408	5.51	5.51	1.102	1.378	3.306	1.102	1.102	1.102	1.102	4.408	5.51	5.51	1.102	1.378	3.306	4.408	5.51	5.51	1.102	1.378	3.306	0.22	0.276
2.204	2.755	4.408	2.204	2.755	4.408	1.102	1.653	3.306	1.102	1.653	3.306	1.102	1.653	3.306	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	
1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	
1.102	1.469	3.306	1.102	1.469	3.306	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	
0.735	1.469	2.204	0.735	0.735	0.735	0.735	0.735	0.735	0.735	1.102	2.204	0.245	0.551	0.735	0.735	1.102	2.204	0.245	0.551	0.735	0.245	0.367	
0.735	1.469	2.204	0.735	0.98	2.204	0.735	1.102	2.204	0.735	1.102	2.204	0.735	0.735	0.735	0.735	0.735	0.735	0.245	0.49	0.735	0.245	0.49	
1.102	2.204	3.306	1.102	1.469	3.306	0.367	0.827	1.102	1.102	1.653	3.306	1.102	1.102	1.102	1.102	2.204	3.306	1.102	1.469	3.306	0.367	0.735	
2.204	2.755	4.408	1.102	1.837	3.306	0.367	0.827	1.102	1.102	1.653	3.306	1.102	1.102	1.102	1.102	2.204	3.306	1.102	1.469	3.306	0.367	0.735	
1.102	2.204	3.306	1.102	1.469	3.306	0.367	0.827	1.102	1.102	1.653	3.306	1.102	1.102	1.102	1.102	2.204	3.306	1.102	1.469	3.306	0.367	0.735	
3.306	4.408	5.51	0.367	0.882	1.102	1.102	1.469	3.306	3.306	4.408	5.51	0.367	0.882	1.102	2.204	3.306	4.408	0.367	0.661	1.102	0.22	0.22	
1.102	1.102	1.102	1.102	1.469	3.306	1.102	1.102	1.102	0.367	0.827	1.102	1.102	1.102	1.102	0.367	0.827	1.102	1.102	1.102	1.102	0.367	1.469	
0.735	1.469	2.204	0.245	0.49	0.735	0.735	1.102	2.204	1.469	2.204	2.939	0.735	0.735	0.735	0.735	1.469	2.204	0.245	0.49	0.735	0.184	0.245	
0.735	0.735	0.735	0.735	0.735	0.735	0.735	1.102	2.204	0.735	1.102	2.204	0.735	1.102	1.469	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	
1.102	1.469	3.306	0.367	0.882	1.102	0.367	0.827	1.102	1.102	1.102	1.102	0.367	0.661	1.102	1.102	1.469	3.306	0.367	0.882	1.102	0.367	0.661	
0.367	0.735	1.102	0.276	0.441	0.551	0.367	0.827	1.102	1.102	1.102	1.102	0.367	0.661	1.102	1.102	1.469	3.306	0.367	0.882	1.102	0.367	0.661	
0.184	0.294	0.267	0.245	0.49	0.735	0.735	0.735	0.735	0.245	0.588	0.735	0.735	0.98	2.204	0.245	0.588	0.735	0.98	2.204	0.735	1.224	0.244	
1.063	1.581	2.289	1.422	1.077	1.667	0.726	1.027	1.42	1.04	1.504	2.203	0.771	1.024	1.388	0.978	1.442	2.014	0.683	0.982	1.509	0.44	0.67	

Fuzzified PC of emission scopes

EXPER T	S1 Vs S2			S1Vs S3			S2 Vs S3		
1	0.33333	0.75	1	0.333	0.6	1	0.333	0.8	1
2	1	1	1	1	1	1	1	1	1
3	1	1.25	3	2	2.5	4	1	2	3
4	1	1.25	3	1	1.25	3	1	1	1
5	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1
7	1	1.25	3	1	1.66667	3	1	1.333333	3
8	1	1.25	3	1	1.66667	3	1	1.333333	3
9	1	1.25	3	1	1.66667	3	1	1.333333	3
10	1	1.66667	3	1	1.25	3	0.333	0.75	1
11	0.33333	0.6	1	0.333	0.75	1	1	1.25	3
12	0.33333	0.8	1	1	1.33333	3	1	1.666667	3
13	1	1.25	3	1	1.66667	3	1	1.333333	3
14	1	1.33333	3	1	2	3	1	1.5	3
15	1	1	1	1	1.33333	3	1	1.333333	3
16	1	1.25	3	1	1.25	3	1	1	1
17	1	1	1	1	1.25	3	1	1.25	3
18	1	1	1	1	1	1	1	1	1
GeoMean	0.83268	1.07722	1.73	0.92	1.2714	2.114	0.885	1.180266	1.841

Weighted Fuzzified PC of emission scopes

EXPERT		Si Vs S2			S1Vs S3			S2 Vs S3		
1	0.367	0.827	1.102	0.367	0.661	1.102	0.367	0.882	1.102	
2	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	
3	1.102	1.378	3.306	2.204	2.755	4.408	1.102	2.204	3.306	
4	1.102	1.378	3.306	1.102	1.378	3.306	1.102	1.102	1.102	
5	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	
6	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	1.102	
7	0.7347	0.9184	2.2041	0.7347	1.2245	2.2041	0.7347	0.9796	2.2041	
8	0.7347	0.9184	2.2041	0.7347	1.2245	2.2041	0.7347	0.9796	2.2041	
9	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.469	3.306	
10	1.102	1.837	3.306	1.102	1.378	3.306	0.367	0.827	1.102	
11	0.367	0.661	1.102	0.367	0.827	1.102	1.102	1.378	3.306	
12	0.367	0.882	1.102	1.102	1.469	3.306	1.102	1.837	3.306	
13	1.102	1.378	3.306	1.102	1.837	3.306	1.102	1.469	3.306	
14	0.7347	0.9796	2.2041	0.7347	1.4694	2.2041	0.7347	1.102	2.2041	
15	0.7347	0.7347	0.7347	0.7347	0.9796	2.2041	0.7347	0.9796	2.2041	
16	1.102	1.378	3.306	1.102	1.378	3.306	1.102	1.102	1.102	
17	1.102	1.102	1.102	1.102	1.378	3.306	1.102	1.378	3.306	
18	0.7347	0.7347	0.7347	0.7347	0.7347	0.7347	0.7347	0.7347	0.7347	
GM	0.82	1.061	1.705	0.906	1.252	2.081	0.872	1.162	1.813	

D. Calculation of weights by FAHP

Calculation of local weights for Scope 1 emission																			
	Energy Efficiency (EE)			Electrification (EL)			Green fuel (GFU)			Port Greenery (PG)			Gemetric mean (GMV)			Fuzzy weights		Crisp value	
EE	1	1	1	0.6	0.91	1.26	0.7	0.969	1.3665	0.8715	1.239	1.927	0.78	1.0217	1.34878	0.257	0.254	0.252	0.25
EL	0.8	1.1	1.65	1	1	1	0.76	1.051	1.641	0.9564	1.344	2.054	0.872	1.1171	1.53684	0.287	0.278	0.287	0.28
GFU	0.73	1.03	1.42	0.61	0.95	1.32	1	1	1	0.8521	1.259	1.958	0.785	1.0543	1.38406	0.259	0.262	0.258	0.26
PG	0.52	0.81	1.15	0.49	0.74	1.05	0.51	0.794	1.1736	1	1	1	0.599	0.831	1.0893	0.197	0.207	0.203	0.20

Calculation of local weights for Scope 2 emission													
	Renewable Energy (RE)			Smart/Microgrid (S/M)			Geometric mean (GMV)			Fuzzy weights			Crisp value
RE	1	1	1	0.96	1.33	2.21	0.98	1.154	1.4873	0.5934	0.571	0.593	0.586
S/M	0.45	0.75	1.04	1	1	1	0.67	0.866	1.0192	0.4066	0.429	0.407	0.414
	Sum of GMV						1.65	2.021	2.5065			Sum	1.000
	Reciprocal of GMV						0.6	0.495	0.399				

Calculation of local weights for Scope 3 emission																		
	OPS usaga			JIT arrival			AF Bunkering (AFB)			Hinterland transport (HT)			Employee commuting (EC)			Truck congestion		
OPS	1	1	1	0.91	1.18	2.08	0.77	1.24	2.05	0.83	1.29	2.39	1.33	1.89	3.11	0.94	1.29	1.87
JIT	0.48	0.85	1.10	1	1	1	0.73	1.04	1.71	0.85	1.08	1.63	1.06	1.58	2.29	0.74	1.08	1.67
AFB	0.49	0.81	1.30	0.59	0.97	1.38	1	1	1	0.73	1.03	1.42	1.04	1.50	2.20	0.77	1.02	1.39
HT	0.42	0.78	1.20	0.61	0.93	1.17	0.70	0.97	1.38	1	1	1	0.98	1.44	2.01	0.68	0.98	1.51
EC	0.32	0.53	0.75	0.44	0.63	0.94	0.45	0.66	0.96	0.50	0.69	1.02	1	1	1	0.44	0.67	0.88
TC	0.53	0.78	1.06	0.60	0.93	1.35	0.72	0.98	1.30	0.66	1.02	1.46	1.14	1.49	2.27	1	1	1
	Sum of GMV															4.417	6.102	8.508
	Reciprocal of GMV															0.226	0.164	0.118
																	sum	1.00

Calculation of local weights of scope1, scope2 and scope3 emission																	
	Scope1			Scope2			Scope3			Geometric mean			Fuzzy weights		Crisp value		Weights
Scope1	1	1	1	0.82	1.06	1.71	0.91	1.25	2.08	0.90556	1.0991	1.525	0.386	0.36485	0.390108	0.38	0.38
Scope2	0.59	0.94	1.22	1	1	1	0.87	1.16	1.81	0.79948	1.0309	1.303	0.341	0.34221	0.333168	0.34	0.34
Scope3	0.48	0.80	1.10	0.55	0.86	1.15	1	1	1	0.64236	0.8825	1.082	0.274	0.29294	0.276724	0.28	0.28
									</								

Layer 1 (Fuzzification): This is a layer with adaptive nodes which allows the shapes of membership functions to be modified according to the training data. The MFs can generally be defined as follows:

$$O_i^1 = \mu A_i(x) \quad (39)$$

Where: A_i is the fuzzy set (linguistic label), O_i^1 is the MF of A_i and x is the input value.

Layer 2 (Implication): The MFs are multiplied in this layer and the outputs of each node shows the firing strength (w_i) of the rule. This is given by the equation 31:

$$O_i^2 = w_i = \mu A_i(x) \times \mu B_i(y) \quad i = 1, 2 \quad (40)$$

Layer 3 (Normalization): In this layer the ratio of the firing strength of each rule to the sum of the firing strengths of all rules is evaluated. The output is given by eq.32:

$$O_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2} \quad i = 1, 2 \quad (41)$$

Layer 4 (Defuzzification): This layer performs the defuzzification by using fuzzy rules with weighing factors ($\bar{w}_i$) produced in layer 3. The output of this layer can be expressed as:

$$O_i^4 = \bar{w}_i \int_i = \bar{w}_i (p_i x + q_i y + r_i) \quad i = 1, 2 \quad (42)$$

Where: p_i , q_i and r_i are the consequent parameters

Layer 5 (Aggregation): This is the final layer which calculates the final output results of the ANFIS by summing all the incoming signals or results from layer 4. The overall output is given by:

$$O_i^5 = z = \sum_{i=1}^2 \bar{w}_i \int_i = \frac{w_1(p_1 x + q_1 y + r_1) + w_2(p_2 x + q_2 y + r_2)}{w_1 + w_2}, \quad i = 1, 2 \quad (43)$$

These principles of operation are explained by Tan et al. (2017), Jung and Choi (2015) and Ramadan et al. (2022)

F. ANFIS If – Then rules

ANFIS 1

	Rule	Weight	Name
1	If OPS(%) is low and JIT(%) is low and AFB(%) is low then S(%) is out1mf1	1	rule1
2	If OPS(%) is low and JIT(%) is low and AFB(%) is average then S(%) is out1mf2	1	rule2
3	If OPS(%) is low and JIT(%) is low and AFB(%) is high then S(%) is out1mf3	1	rule3
4	If OPS(%) is low and JIT(%) is average and AFB(%) is low then S(%) is out1mf4	1	rule4
5	If OPS(%) is low and JIT(%) is average and AFB(%) is average then S(%) is out1mf5	1	rule5
6	If OPS(%) is low and JIT(%) is average and AFB(%) is high then S(%) is out1mf6	1	rule6
7	If OPS(%) is low and JIT(%) is high and AFB(%) is low then S(%) is out1mf7	1	rule7
8	If OPS(%) is low and JIT(%) is high and AFB(%) is average then S(%) is out1mf8	1	rule8
9	If OPS(%) is low and JIT(%) is high and AFB(%) is high then S(%) is out1mf9	1	rule9
10	If OPS(%) is average and JIT(%) is low and AFB(%) is low then S(%) is out1mf10	1	rule10
11	If OPS(%) is average and JIT(%) is low and AFB(%) is average then S(%) is out1mf11	1	rule11
12	If OPS(%) is average and JIT(%) is low and AFB(%) is high then S(%) is out1mf12	1	rule12
13	If OPS(%) is average and JIT(%) is average and AFB(%) is low then S(%) is out1mf13	1	rule13
14	If OPS(%) is average and JIT(%) is average and AFB(%) is average then S(%) is out1mf14	1	rule14
15	If OPS(%) is average and JIT(%) is average and AFB(%) is high then S(%) is out1mf15	1	rule15
16	If OPS(%) is average and JIT(%) is high and AFB(%) is low then S(%) is out1mf16	1	rule16
17	If OPS(%) is average and JIT(%) is high and AFB(%) is average then S(%) is out1mf17	1	rule17
18	If OPS(%) is average and JIT(%) is high and AFB(%) is high then S(%) is out1mf18	1	rule18
19	If OPS(%) is high and JIT(%) is low and AFB(%) is low then S(%) is out1mf19	1	rule19
20	If OPS(%) is high and JIT(%) is low and AFB(%) is average then S(%) is out1mf20	1	rule20
21	If OPS(%) is high and JIT(%) is low and AFB(%) is high then S(%) is out1mf21	1	rule21
22	If OPS(%) is high and JIT(%) is average and AFB(%) is low then S(%) is out1mf22	1	rule22
23	If OPS(%) is high and JIT(%) is average and AFB(%) is average then S(%) is out1mf23	1	rule23
24	If OPS(%) is high and JIT(%) is average and AFB(%) is high then S(%) is out1mf24	1	rule24
25	If OPS(%) is high and JIT(%) is high and AFB(%) is low then S(%) is out1mf25	1	rule25
26	If OPS(%) is high and JIT(%) is high and AFB(%) is average then S(%) is out1mf26	1	rule26
27	If OPS(%) is high and JIT(%) is high and AFB(%) is high then S(%) is out1mf27	1	rule27

ANFIS 2

	Rule	Weight	Name
1	If GHT(%) is low and EC(%) is low and TC(%) is low then h(%) is out1mf1	1	rule1
2	If GHT(%) is low and EC(%) is low and TC(%) is average then h(%) is out1mf2	1	rule2
3	If GHT(%) is low and EC(%) is low and TC(%) is high then h(%) is out1mf3	1	rule3
4	If GHT(%) is low and EC(%) is average and TC(%) is low then h(%) is out1mf4	1	rule4
5	If GHT(%) is low and EC(%) is average and TC(%) is average then h(%) is out1mf5	1	rule5
6	If GHT(%) is low and EC(%) is average and TC(%) is high then h(%) is out1mf6	1	rule6
7	If GHT(%) is low and EC(%) is high and TC(%) is low then h(%) is out1mf7	1	rule7
8	If GHT(%) is low and EC(%) is high and TC(%) is average then h(%) is out1mf8	1	rule8
9	If GHT(%) is low and EC(%) is high and TC(%) is high then h(%) is out1mf9	1	rule9

10	If GHT(%) is average and EC(%) is low and TC(%) is low then h(%) is out1mf10	1	rule10
11	If GHT(%) is average and EC(%) is low and TC(%) is average then h(%) is out1mf11	1	rule11
12	If GHT(%) is average and EC(%) is low and TC(%) is high then h(%) is out1mf12	1	rule12
13	If GHT(%) is average and EC(%) is average and TC(%) is low then h(%) is out1mf13	1	rule13
14	If GHT(%) is average and EC(%) is average and TC(%) is average then h(%) is out1mf14	1	rule14
15	If GHT(%) is average and EC(%) is average and TC(%) is high then h(%) is out1mf15	1	rule15
16	If GHT(%) is average and EC(%) is high and TC(%) is low then h(%) is out1mf16	1	rule16
17	If GHT(%) is average and EC(%) is high and TC(%) is average then h(%) is out1mf17	1	rule17
18	If GHT(%) is average and EC(%) is high and TC(%) is high then h(%) is out1mf18	1	rule18
19	If GHT(%) is high and EC(%) is low and TC(%) is low then h(%) is out1mf19	1	rule19
20	If GHT(%) is high and EC(%) is low and TC(%) is average then h(%) is out1mf20	1	rule20
21	If GHT(%) is high and EC(%) is low and TC(%) is high then h(%) is out1mf21	1	rule21
22	If GHT(%) is high and EC(%) is average and TC(%) is low then h(%) is out1mf22	1	rule22
23	If GHT(%) is high and EC(%) is average and TC(%) is average then h(%) is out1mf23	1	rule23
24	If GHT(%) is high and EC(%) is average and TC(%) is high then h(%) is out1mf24	1	rule24
25	If GHT(%) is high and EC(%) is high and TC(%) is low then h(%) is out1mf25	1	rule25
26	If GHT(%) is high and EC(%) is high and TC(%) is average then h(%) is out1mf26	1	rule26
27	If GHT(%) is high and EC(%) is high and TC(%) is high then h(%) is out1mf27	1	rule27

ANFIS 3

	Rule	Weight	Name
1	If S(%) is low and h(%) is low then S3(%) is out1mf1	1	rule1
2	If S(%) is low and h(%) is average then S3(%) is out1mf2	1	rule2
3	If S(%) is low and h(%) is in2mf3 then S3(%) is out1mf3	1	rule3
4	If S(%) is average and h(%) is low then S3(%) is out1mf4	1	rule4
5	If S(%) is average and h(%) is average then S3(%) is out1mf5	1	rule5
6	If S(%) is average and h(%) is in2mf3 then S3(%) is out1mf6	1	rule6
7	If S(%) is high and h(%) is low then S3(%) is out1mf7	1	rule7
8	If S(%) is high and h(%) is average then S3(%) is out1mf8	1	rule8
9	If S(%) is high and h(%) is in2mf3 then S3(%) is out1mf9	1	rule9

ANFIS 4

	Rule	Weight	Name
1	If RE(%) is low and SMG(%) is low then S3(%) is out1mf1	1	rule1
2	If RE(%) is low and SMG(%) is average then S3(%) is out1mf2	1	rule2
3	If RE(%) is low and SMG(%) is high then S3(%) is out1mf3	1	rule3
4	If RE(%) is average and SMG(%) is low then S3(%) is out1mf4	1	rule4
5	If RE(%) is average and SMG(%) is average then S3(%) is out1mf5	1	rule5
6	If RE(%) is average and SMG(%) is high then S3(%) is out1mf6	1	rule6
7	If RE(%) is high and SMG(%) is low then S3(%) is out1mf7	1	rule7
8	If RE(%) is high and SMG(%) is average then S3(%) is out1mf8	1	rule8
9	If RE(%) is high and SMG(%) is high then S3(%) is out1mf9	1	rule9

ANFIS 5

	Rule	Weight	Name
1	If EE(%) is low and EL(%) is low and GFU(%) is low and PG(%) is low then S1(%) is out1mf1	1	rule1
2	If EE(%) is low and EL(%) is low and GFU(%) is low and PG(%) is average then S1(%) is out1mf2	1	rule2
3	If EE(%) is low and EL(%) is low and GFU(%) is low and PG(%) is high then S1(%) is out1mf3	1	rule3
4	If EE(%) is low and EL(%) is low and GFU(%) is average and PG(%) is low then S1(%) is out1mf4	1	rule4
5	If EE(%) is low and EL(%) is low and GFU(%) is average and PG(%) is average then S1(%) is out1mf5	1	rule5
6	If EE(%) is low and EL(%) is low and GFU(%) is average and PG(%) is high then S1(%) is out1mf6	1	rule6
7	If EE(%) is low and EL(%) is low and GFU(%) is high and PG(%) is low then S1(%) is out1mf7	1	rule7
8	If EE(%) is low and EL(%) is low and GFU(%) is high and PG(%) is average then S1(%) is out1mf8	1	rule8
9	If EE(%) is low and EL(%) is low and GFU(%) is high and PG(%) is high then S1(%) is out1mf9	1	rule9
10	If EE(%) is low and EL(%) is average and GFU(%) is low and PG(%) is low then S1(%) is out1mf10	1	rule10
11	If EE(%) is low and EL(%) is average and GFU(%) is low and PG(%) is average then S1(%) is out1mf11	1	rule11
12	If EE(%) is low and EL(%) is average and GFU(%) is low and PG(%) is high then S1(%) is out1mf12	1	rule12
13	If EE(%) is low and EL(%) is average and GFU(%) is average and PG(%) is low then S1(%) is out1mf13	1	rule13
14	If EE(%) is low and EL(%) is average and GFU(%) is average and PG(%) is average then S1(%) is out1mf14	1	rule14
15	If EE(%) is low and EL(%) is average and GFU(%) is average and PG(%) is high then S1(%) is out1mf15	1	rule15
16	If EE(%) is low and EL(%) is average and GFU(%) is high and PG(%) is low then S1(%) is out1mf16	1	rule16
17	If EE(%) is low and EL(%) is average and GFU(%) is high and PG(%) is average then S1(%) is out1mf17	1	rule17
18	If EE(%) is low and EL(%) is average and GFU(%) is high and PG(%) is high then S1(%) is out1mf18	1	rule18
19	If EE(%) is low and EL(%) is high and GFU(%) is low and PG(%) is low then S1(%) is out1mf19	1	rule19
20	If EE(%) is low and EL(%) is high and GFU(%) is low and PG(%) is average then S1(%) is out1mf20	1	rule20
21	If EE(%) is low and EL(%) is high and GFU(%) is low and PG(%) is high then S1(%) is out1mf21	1	rule21
22	If EE(%) is low and EL(%) is high and GFU(%) is average and PG(%) is low then S1(%) is out1mf22	1	rule22
23	If EE(%) is low and EL(%) is high and GFU(%) is average and PG(%) is average then S1(%) is out1mf23	1	rule23
24	If EE(%) is low and EL(%) is high and GFU(%) is average and PG(%) is high then S1(%) is out1mf24	1	rule24
25	If EE(%) is low and EL(%) is high and GFU(%) is high and PG(%) is low then S1(%) is out1mf25	1	rule25
26	If EE(%) is low and EL(%) is high and GFU(%) is high and PG(%) is average then S1(%) is out1mf26	1	rule26
27	If EE(%) is low and EL(%) is high and GFU(%) is high and PG(%) is high then S1(%) is out1mf27	1	rule27
28	If EE(%) is average and EL(%) is low and GFU(%) is low and PG(%) is low then S1(%) is out1mf28	1	rule28
29	If EE(%) is average and EL(%) is low and GFU(%) is low and PG(%) is average then S1(%) is out1mf29	1	rule29
30	If EE(%) is average and EL(%) is low and GFU(%) is low and PG(%) is high then S1(%) is out1mf30	1	rule30
31	If EE(%) is average and EL(%) is low and GFU(%) is average and PG(%) is low then S1(%) is out1mf31	1	rule31
32	If EE(%) is average and EL(%) is low and GFU(%) is average and PG(%) is average then S1(%) is out1mf32	1	rule32
33	If EE(%) is average and EL(%) is low and GFU(%) is average and PG(%) is high then S1(%) is out1mf33	1	rule33
34	If EE(%) is average and EL(%) is low and GFU(%) is high and PG(%) is low then S1(%) is out1mf34	1	rule34
35	If EE(%) is average and EL(%) is low and GFU(%) is high and PG(%) is average then S1(%) is out1mf35	1	rule35
36	If EE(%) is average and EL(%) is low and GFU(%) is high and PG(%) is high then S1(%) is out1mf36	1	rule36

37	If EE(%) is average and EL(%) is average and GFU(%) is low and PG(%) is low then S1(%) is out1mf37	1	rule37
38	If EE(%) is average and EL(%) is average and GFU(%) is low and PG(%) is average then S1(%) is out1mf38	1	rule38
39	If EE(%) is average and EL(%) is average and GFU(%) is low and PG(%) is high then S1(%) is out1mf39	1	rule39
40	If EE(%) is average and EL(%) is average and GFU(%) is average and PG(%) is low then S1(%) is out1mf40	1	rule40
41	If EE(%) is average and EL(%) is average and GFU(%) is average and PG(%) is average then S1(%) is out1mf41	1	rule41
42	If EE(%) is average and EL(%) is average and GFU(%) is average and PG(%) is high then S1(%) is out1mf42	1	rule42
43	If EE(%) is average and EL(%) is average and GFU(%) is high and PG(%) is low then S1(%) is out1mf43	1	rule43
44	If EE(%) is average and EL(%) is average and GFU(%) is high and PG(%) is average then S1(%) is out1mf44	1	rule44
45	If EE(%) is average and EL(%) is average and GFU(%) is high and PG(%) is high then S1(%) is out1mf45	1	rule45
46	If EE(%) is average and EL(%) is high and GFU(%) is low and PG(%) is low then S1(%) is out1mf46	1	rule46
47	If EE(%) is average and EL(%) is high and GFU(%) is low and PG(%) is average then S1(%) is out1mf47	1	rule47
48	If EE(%) is average and EL(%) is high and GFU(%) is low and PG(%) is high then S1(%) is out1mf48	1	rule48
49	If EE(%) is average and EL(%) is high and GFU(%) is average and PG(%) is low then S1(%) is out1mf49	1	rule49
50	If EE(%) is average and EL(%) is high and GFU(%) is average and PG(%) is average then S1(%) is out1mf50	1	rule50
51	If EE(%) is average and EL(%) is high and GFU(%) is average and PG(%) is high then S1(%) is out1mf51	1	rule51
52	If EE(%) is average and EL(%) is high and GFU(%) is high and PG(%) is low then S1(%) is out1mf52	1	rule52
53	If EE(%) is average and EL(%) is high and GFU(%) is high and PG(%) is average then S1(%) is out1mf53	1	rule53
54	If EE(%) is average and EL(%) is high and GFU(%) is high and PG(%) is high then S1(%) is out1mf54	1	rule54
55	If EE(%) is high and EL(%) is low and GFU(%) is low and PG(%) is low then S1(%) is out1mf55	1	rule55
56	If EE(%) is high and EL(%) is low and GFU(%) is low and PG(%) is average then S1(%) is out1mf56	1	rule56
57	If EE(%) is high and EL(%) is low and GFU(%) is low and PG(%) is high then S1(%) is out1mf57	1	rule57
58	If EE(%) is high and EL(%) is low and GFU(%) is average and PG(%) is low then S1(%) is out1mf58	1	rule58
59	If EE(%) is high and EL(%) is low and GFU(%) is average and PG(%) is average then S1(%) is out1mf59	1	rule59
60	If EE(%) is high and EL(%) is low and GFU(%) is average and PG(%) is high then S1(%) is out1mf60	1	rule60
61	If EE(%) is high and EL(%) is low and GFU(%) is high and PG(%) is low then S1(%) is out1mf61	1	rule61
62	If EE(%) is high and EL(%) is low and GFU(%) is high and PG(%) is average then S1(%) is out1mf62	1	rule62
63	If EE(%) is high and EL(%) is low and GFU(%) is high and PG(%) is high then S1(%) is out1mf63	1	rule63
64	If EE(%) is high and EL(%) is average and GFU(%) is low and PG(%) is low then S1(%) is out1mf64	1	rule64
65	If EE(%) is high and EL(%) is average and GFU(%) is low and PG(%) is average then S1(%) is out1mf65	1	rule65
66	If EE(%) is high and EL(%) is average and GFU(%) is low and PG(%) is high then S1(%) is out1mf66	1	rule66
67	If EE(%) is high and EL(%) is average and GFU(%) is average and PG(%) is low then S1(%) is out1mf67	1	rule67
68	If EE(%) is high and EL(%) is average and GFU(%) is average and PG(%) is average then S1(%) is out1mf68	1	rule68
69	If EE(%) is high and EL(%) is average and GFU(%) is average and PG(%) is high then S1(%) is out1mf69	1	rule69
70	If EE(%) is high and EL(%) is average and GFU(%) is high and PG(%) is low then S1(%) is out1mf70	1	rule70
71	If EE(%) is high and EL(%) is average and GFU(%) is high and PG(%) is average then S1(%) is out1mf71	1	rule71
72	If EE(%) is high and EL(%) is average and GFU(%) is high and PG(%) is high then S1(%) is out1mf72	1	rule72
73	If EE(%) is high and EL(%) is high and GFU(%) is low and PG(%) is low then S1(%) is out1mf73	1	rule73
74	If EE(%) is high and EL(%) is high and GFU(%) is low and PG(%) is average then S1(%) is out1mf74	1	rule74
75	If EE(%) is high and EL(%) is high and GFU(%) is low and PG(%) is high then S1(%) is out1mf75	1	rule75
76	If EE(%) is high and EL(%) is high and GFU(%) is average and PG(%) is low then S1(%) is out1mf76	1	rule76
77	If EE(%) is high and EL(%) is high and GFU(%) is average and PG(%) is average then S1(%) is out1mf77	1	rule77
78	If EE(%) is high and EL(%) is high and GFU(%) is average and PG(%) is high then S1(%) is out1mf78	1	rule78
79	If EE(%) is high and EL(%) is high and GFU(%) is high and PG(%) is low then S1(%) is out1mf79	1	rule79
80	If EE(%) is high and EL(%) is high and GFU(%) is high and PG(%) is average then S1(%) is out1mf80	1	rule80
81	If EE(%) is high and EL(%) is high and GFU(%) is high and PG(%) is high then S1(%) is out1mf81	1	rule81

ANFIS 6

	Rule	Weight	Name
1	If S1(%) is low and S2(%) is low and S3(%) is low then GPI(%) is out1mf1	1	rule1
2	If S1(%) is low and S2(%) is low and S3(%) is average then GPI(%) is out1mf2	1	rule2
3	If S1(%) is low and S2(%) is low and S3(%) is high then GPI(%) is out1mf3	1	rule3
4	If S1(%) is low and S2(%) is average and S3(%) is low then GPI(%) is out1mf4	1	rule4
5	If S1(%) is low and S2(%) is average and S3(%) is average then GPI(%) is out1mf5	1	rule5
6	If S1(%) is low and S2(%) is average and S3(%) is high then GPI(%) is out1mf6	1	rule6
7	If S1(%) is low and S2(%) is high and S3(%) is low then GPI(%) is out1mf7	1	rule7
8	If S1(%) is low and S2(%) is high and S3(%) is average then GPI(%) is out1mf8	1	rule8
9	If S1(%) is low and S2(%) is high and S3(%) is high then GPI(%) is out1mf9	1	rule9
10	If S1(%) is average and S2(%) is low and S3(%) is low then GPI(%) is out1mf10	1	rule10
11	If S1(%) is average and S2(%) is low and S3(%) is average then GPI(%) is out1mf11	1	rule11
12	If S1(%) is average and S2(%) is low and S3(%) is high then GPI(%) is out1mf12	1	rule12
13	If S1(%) is average and S2(%) is average and S3(%) is low then GPI(%) is out1mf13	1	rule13
14	If S1(%) is average and S2(%) is average and S3(%) is average then GPI(%) is out1mf14	1	rule14
15	If S1(%) is average and S2(%) is average and S3(%) is high then GPI(%) is out1mf15	1	rule15
16	If S1(%) is average and S2(%) is high and S3(%) is low then GPI(%) is out1mf16	1	rule16
17	If S1(%) is average and S2(%) is high and S3(%) is average then GPI(%) is out1mf17	1	rule17
18	If S1(%) is average and S2(%) is high and S3(%) is high then GPI(%) is out1mf18	1	rule18
19	If S1(%) is high and S2(%) is low and S3(%) is low then GPI(%) is out1mf19	1	rule19
20	If S1(%) is high and S2(%) is low and S3(%) is average then GPI(%) is out1mf20	1	rule20
21	If S1(%) is high and S2(%) is low and S3(%) is high then GPI(%) is out1mf21	1	rule21
22	If S1(%) is high and S2(%) is average and S3(%) is low then GPI(%) is out1mf22	1	rule22
23	If S1(%) is high and S2(%) is average and S3(%) is average then GPI(%) is out1mf23	1	rule23
24	If S1(%) is high and S2(%) is average and S3(%) is high then GPI(%) is out1mf24	1	rule24
25	If S1(%) is high and S2(%) is high and S3(%) is low then GPI(%) is out1mf25	1	rule25
26	If S1(%) is high and S2(%) is high and S3(%) is average then GPI(%) is out1mf26	1	rule26
27	If S1(%) is high and S2(%) is high and S3(%) is high then GPI(%) is out1mf27	1	rule27

G. Calculation of weights by SMART

Aggregation of weighted expert rating by geometric mean

Expert	EE	EL	GFU	PG	RE	SG	OPS	JIT	AFB	GHT	EC	TC	S1	S2	S3
1	5.5102	5.5102	5.5102	5.5102	4.40816	4.40816	5.5102	4.40816	4.40816	3.30612	2.20408	2.20408	3.30612	4.40816	5.5102
2	5.5102	4.40816	5.5102	4.40816	4.40816	3.30612	4.40816	4.40816	5.5102	5.5102	3.30612	4.40816	5.5102	5.5102	5.5102
3	5.5102	3.30612	5.5102	4.40816	5.5102	3.30612	3.30612	5.5102	5.5102	5.5102	1.10204	4.40816	5.5102	4.40816	2.20408
4	5.5102	5.5102	5.5102	5.5102	5.5102	3.30612	5.5102	5.5102	3.30612	2.20408	2.20408	2.20408	5.5102	4.40816	4.40816
5	3.30612	5.5102	5.5102	3.30612	4.40816	4.40816	4.40816	5.5102	5.5102	5.5102	5.5102	5.5102	4.40816	4.40816	4.40816
6	5.5102	5.5102	4.40816	4.40816	4.40816	4.40816	4.40816	4.40816	3.30612	3.30612	3.30612	3.30612	4.40816	4.40816	4.40816
7	2.93878	2.93878	1.46939	2.20408	3.67347	2.20408	3.67347	2.93878	2.20408	2.20408	1.46939	2.93878	3.67347	2.93878	2.20408
8	2.93878	3.67347	2.93878	1.46939	3.67347	2.20408	3.67347	2.93878	2.20408	1.46939	1.46939	2.20408	3.67347	2.93878	2.20408
9	4.40816	5.5102	3.30612	2.20408	5.5102	2.20408	5.5102	4.40816	3.30612	4.40816	2.20408	3.30612	5.5102	4.40816	3.30612
10	3.30612	5.5102	4.40816	2.20408	5.5102	3.30612	5.5102	5.5102	3.30612	4.40816	2.20408	3.30612	5.5102	3.30612	4.40816
11	3.30612	5.5102	4.40816	3.30612	5.5102	4.40816	5.5102	4.40816	3.30612	4.40816	2.20408	3.30612	3.30612	5.5102	4.40816
12	4.40816	5.5102	5.5102	2.20408	5.5102	3.30612	5.5102	4.40816	4.40816	3.30612	1.10204	5.5102	4.40816	5.5102	3.30612
13	5.5102	5.5102	4.40816	4.40816	5.5102	4.40816	5.5102	4.40816	3.30612	3.30612	4.40816	3.30612	5.5102	4.40816	3.30612
14	2.20408	2.93878	2.93878	1.46939	2.20408	2.20408	2.20408	1.46939	2.20408	1.46939	0.73469	2.20408	2.93878	2.20408	1.46939
15	2.93878	2.20408	2.93878	1.46939	2.93878	2.20408	2.20408	1.46939	2.20408	1.46939	1.46939	1.46939	2.93878	2.93878	2.20408
16	5.5102	4.40816	3.30612	5.5102	3.30612	4.40816	5.5102	4.40816	3.30612	4.40816	3.30612	5.5102	5.5102	4.40816	4.40816
17	4.40816	5.5102	3.30612	5.5102	5.5102	4.40816	5.5102	2.20408	3.30612	4.40816	3.30612	5.5102	5.5102	5.5102	4.40816
18	1.46939	1.46939	3.67347	2.20408	3.67347	2.20408	2.20408	1.46939	2.93878	2.93878	3.67347	2.20408	2.93878	2.93878	2.93878
Geo Mean	3.87742	4.20688	3.93989	3.08157	4.37204	3.23005	4.2345	3.548	3.37445	3.23515	2.20909	3.24473	4.31818	4.00864	3.39639

Calculation of normalised weights

k1	k2	k3	k4	Sum
3.8774179	4.20688	3.93989	3.08157	15.1058
Wk1	Wk2	Wk3	Wk4	
0.257	0.278	0.261	0.204	

K5	k6	Sum
4.3720401	3.23005	7.60209
Wk5	Wk6	
0.575	0.425	

k7	k8	k9	k10	k11	k12	Sum
4.2344992	3.548	3.37445	3.23515	2.20909	3.24473	19.8459
Wk7	Wk8	Wk9	Wk10	Wk11	Wk12	Wk13
0.213	0.179	0.170	0.163	0.111	0.163	

S1	S2	S3	Sum
4.3181751	4.00864	3.39639	11.7232
WS1	WS2	WS3	
0.3683444	0.34194	0.28972	

H. Quantification of ANFIS inputs for Port A and Port B

Port A

Energy efficiency.

E_T = Electricity consumption + fuel consumption.

However, the units of the two energy consumptions are different. Hence the conversion factor of 9.94 KWh per litres of diesel equivalent is used to harmonise the units. Assuming density of diesel oil to be 0.85 kg/litre, the volume of 1 ton of diesel is calculated as:

$$V = \frac{1000}{0.85} = 1176.47 \text{ liters}$$

$$E_T = 340.8 + \frac{(19\,462.46 \times 1176.47 \times 9.94)}{1000000} = 568.396 \text{ GWh/year}$$

Using eq.3

$$R = \frac{n_{RC}}{n_{DC}} = \frac{1\,021\,843}{13\,484\,122 - 1\,021\,843} = 0.082$$

The corresponding $C_f = 6.83$ using eq.2.

$$EEF_{ref} = 165.5 - C_f = 165.5 - (6.83 \times 9.94) = 97.61 \text{ KWh/TEU}$$

$$EEF_{CT} = \frac{E_T}{C_T} = \frac{568\,396\,000}{13\,484\,122} = 42.153 \text{ KWh/TEU}$$

$$EEF_{Imp} = \frac{EEF_{ref} - EEF_{CT}}{EEF_{ref}} \times 100 = \frac{97.61 - 42.15}{97.61} \times 100 = 57\%$$

Improvement in energy efficiency is 57%/

Electrification

Using eq.6, the percentage of electrified port equipment and machinery can be calculated as:

$$EL_{PEM} = \frac{n_{pem}}{n_{tpem}} \times 100 = \frac{450}{970} \times 100 = 46\%$$

Green fuel utilization

Equation 7 is used to quantify this KPI as show below:

$$GFU = \frac{T_{Gfu}}{T_{Tf}} \times 100 = \frac{5000}{19\,462.46} \times 100 = 26\%$$

Port Greenery

This is quantified using eq.8 as shown below:

$$PG = \frac{A_{PG}}{A_T} \times C_a \times 100 = \frac{150}{500} \times 1 \times 100 = 30\%$$

Renewable energy usage

Eq. 10 is used to calculate this KPI.

$$REU = \frac{E_{REU}}{E_T} \times 100 = \frac{320}{568.4} \times 100 = 56\%$$

Implementation of Smart and Microgrid

This is quantified using eq.11 as follows:

$$SMG = \frac{L_{SMG}}{L_T} \times 100 = \frac{136}{340.8} \times 100 = 40\%$$

OPS usage. Calculated using Eq.12

$$OPS_{usage} = \frac{n_{ops}}{n_{ts}} \times 100 = \frac{1245}{4550} \times 100 = 27\%$$

Just in time arrival: Calculated using Eq.13

$$JIT_{arrival} = \frac{n_{jit}}{n_{ts}} \times 100 = \frac{1365}{4550} \times 100 = 30\%$$

Alternative fuel bunkering Calculated using Eq.14

$$AF_{bunkering} = \frac{TAF_{bunkered}}{TF_{bunkered}} \times 100 = \frac{1.2}{1.2 + 9.5} \times 100 = 11\%$$

Green hinterland transportation of cargo: Calculated using Eq.15

$$GHT = \frac{C_{TG}}{C_T} \times 100 = \frac{4\,550\,000}{13\,484\,122} \times 100 = 34\%$$

Employee commuting Calculated using Eq.16

$$EC = \frac{Emp_{TG}}{Emp_T} \times 100 = \frac{4\,200}{6000} \times 100 = 70\%$$

Truck congestion Calculated using Eq.17

$$TC = \frac{TN_{TAS}}{TN_{Trucks}} \times 100 = \frac{2.19}{3.65} \times 100 = 60\%$$

Port B

Energy efficiency.

E_T = Electricity consumption + fuel consumption.

$$E_T = 18 + \frac{(7500 \times 1176.47 \times 9.94)}{1000000} = 105.706 GWh/year$$

Using eq.3

$$R = \frac{n_{RC}}{n_{DC}} = \frac{203000}{2005850 - 203000} = 0.113$$

The corresponding $C_f = 6.42$ using eq.2.

$$EEF_{ref} = 165.5 - C_f = 165.5 - (6.42 \times 9.94) = 101.685 \text{KWh/TEU}$$

$$EEF_{CT} = \frac{E_T}{C_T} = \frac{105705839}{2005850} = 52.6991 \text{KWh/TEU}$$

$$EEF_{Imp} = \frac{EEF_{ref} - EEF_{CT}}{EEF_{ref}} \times 100 = \frac{101.69 - 52.70}{101.69} \times 100 = 48\%$$

Improvement in energy efficiency is 48%

Electrification

Using eq.6, the percentage of electrified port equipment and machinery can be calculated as:

$$EL_{PEM} = \frac{n_{pem}}{n_{tpem}} \times 100 = \frac{53}{530} \times 100 = 10\%$$

Green fuel utilization

Equation 7 is used to quantify this KPI as show below:

$$GFU = \frac{T_{Gfu}}{T_{Tf}} \times 100 = \frac{0}{7500} \times 100 = 0\%$$

Port Greenery

This is quantified using eq.8 as shown below:

$$PG = \frac{A_{PG}}{A_T} \times C_a \times 100 = \frac{125}{206} \times 1 \times 100 = 61\%$$

Renewable energy usage

Eq. 10 is used to calculate this KPI.

$$REU = \frac{E_{REU}}{E_T} \times 100 = \frac{14.4}{105.706} \times 100 = 14\%$$

Implementation of Smart and Microgrid

This is quantified using eq.11 as follows:

$$SMG = \frac{L_{SMG}}{L_T} \times 100 = \frac{3.6}{18} \times 100 = 20\%$$

OPS usage. Calculated using Eq.12

$$OPS_{usage} = \frac{n_{ops}}{n_{ts}} \times 100 = \frac{75}{1500} \times 100 = 5\%$$

Just in time arrival: Calculated using Eq.13

$$JIT_{arrival} = \frac{n_{jit}}{n_{ts}} \times 100 = \frac{180}{1500} \times 100 = 12\%$$

Alternative fuel bunkering Calculated using Eq.14

$$AF_{bunkering} = \frac{TA_{F_{bunkered}}}{TF_{bunkered}} \times 100 = \frac{0}{0 + 2.5} \times 100 = 0\%$$

Green hinterland transportation of cargo: Calculated using Eq.15

$$GHT = \frac{C_{TG}}{C_T} \times 100 = \frac{0}{2005850} \times 100 = 0\%$$

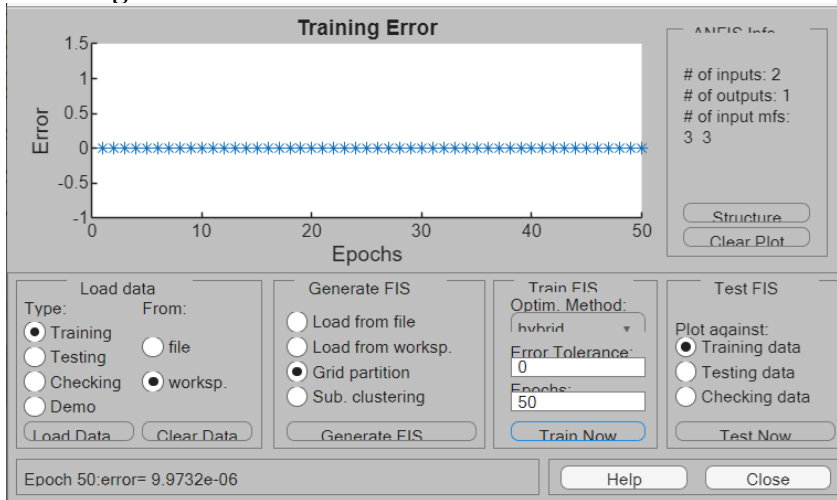
Employee commuting Calculated using Eq.16

$$EC = \frac{Emp_{TG}}{Emp_T} \times 100 = \frac{510}{4000} \times 100 = 13\%$$

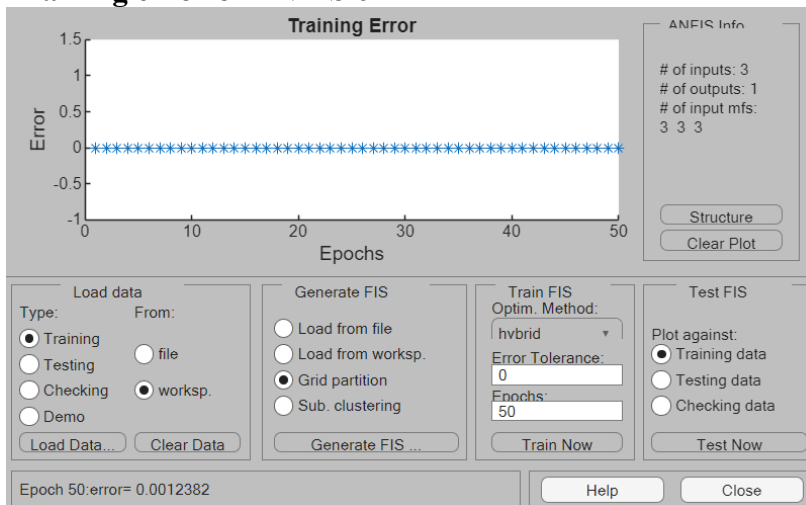
Truck congestion Calculated using Eq.17

$$TC = \frac{TN_{TAS}}{TN_{Trucks}} \times 100 = \frac{0.311}{1.278} \times 100 = 24\%$$

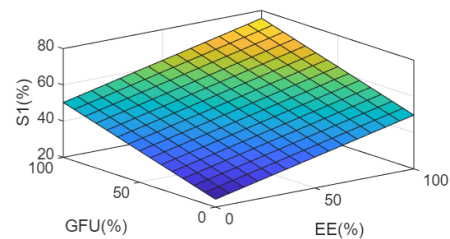
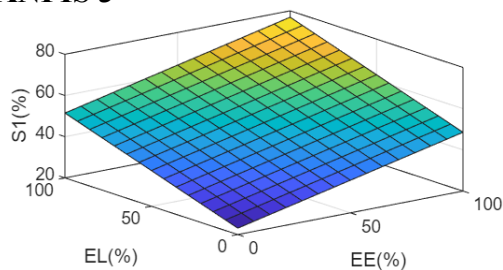
Training error of ANFIS 4

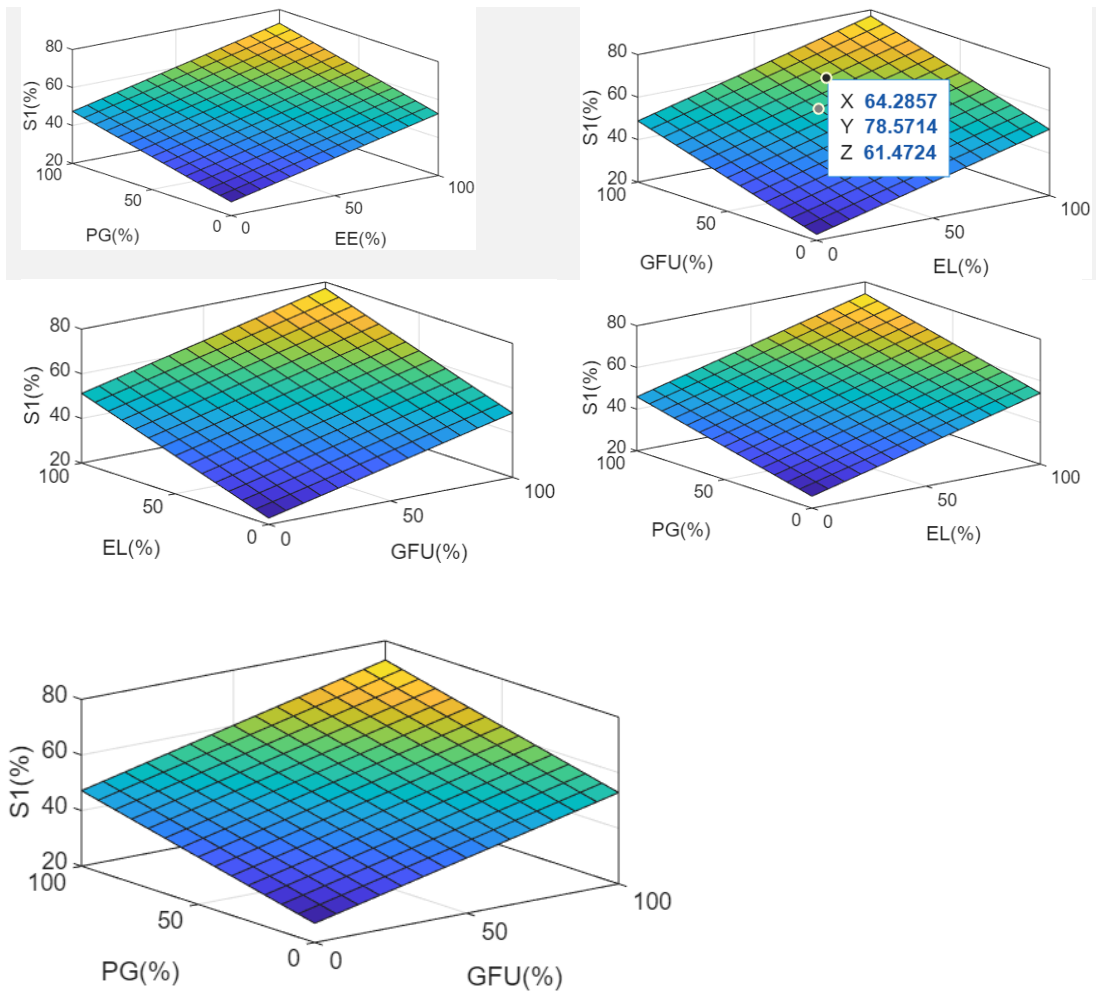


Training error of ANFIS 6

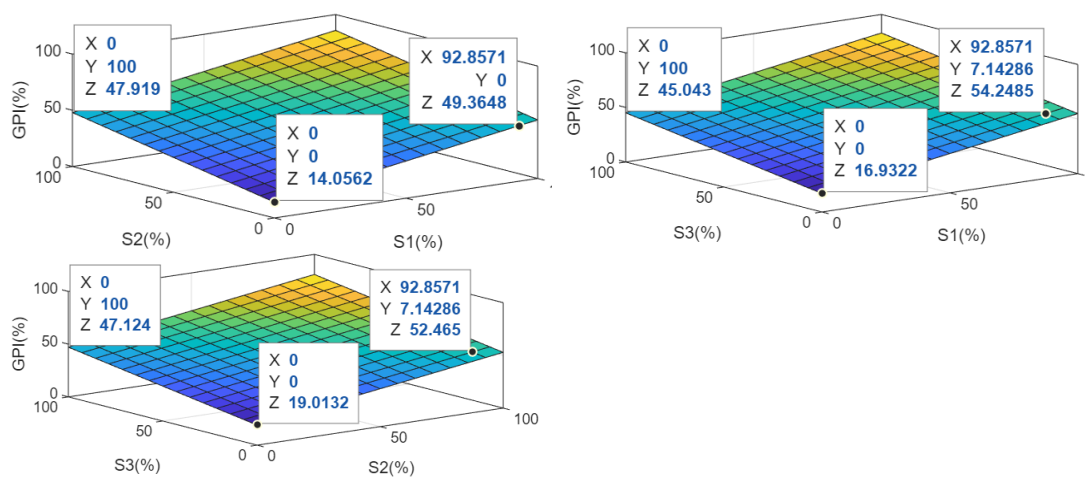


Additional control surface diagrams ANFIS 3





ANFIS 6



Summary of Port GHG reduction Measure

Scope	Code	KPI	Source
Scope 1	K1	Energy efficiency	(Alamoush et al., 2020; Chiu et al., 2014; Fei et al., 2025; Sdoukopoulos et al., 2019)
	K2	Electrification of port equipment and machinery	(Alamoush et al., 2020; Chiu et al., 2014; GEF et al., 2018b; Sdoukopoulos et al., 2019; Yang & Chang, 2013)
	K3	Green fuel utilization	(Alamoush et al., 2020; Chiu et al., 2014)
	K4	Port Greenery	(Chiu et al., 2014)
Scope 2	K5	Carbon neutral/ Renewable energy Usage	(Alamoush et al., 2020; Chiu et al., 2014; Fei et al., 2025)
	K6	Implementation of smart or microgrid	(Alamoush et al., 2020; Yiğit et al., 2016)
Scope 3	K7	Onshore Power Supply (OPS) usage	(Alamoush et al., 2020; Chiu et al., 2014; GEF et al., 2018b)
	K8	Just in time arrival	(Alamoush et al., 2020; Jia et al., 2017)
	K9	Alternative fuel bunkering (AFB)	(Alamoush et al., 2020; Styhre et al., 2017)
	K10	Green Hinterland transportation	(Alamoush et al., 2020; Chiu et al., 2014)
	K11	Employee commuting	(Azarkamand, Ferré and Darbra 2020; Sdoukopoulos et al., 2019)
	K12	Truck congestion	(Alamoush et al., 2020; Sdoukopoulos et al., 2019)