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Green Corridor: A Probability Model to Study Technology Diffusion in a Network

by

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Abstract

Zero carbon alternate fuels and zero emission technologies in shipping have been a widely discussed topic in the shipping industry for the past few years. Global climate change crisis urges the shipping industry to take action that go beyond the sole reliance on operational measures to achieve net-zero Greenhouse gases (GHG) emissions by 2050.

In this study, we assess the importance of shipping ports to accelerate their decarbonisation measures by establishing green shipping corridors between two ports. A green shipping corridor is a shipping route where zero-carbon emission ships and other emission reduction measures or policies are deployed to reduce the GHG emissions in the entire value chain. A rudimentary network model was used to study the adoption of green shipping corridors. The objective was to analyse, how a green corridor will accelerate the uptake of green fuel technologies in a network of ports. The network consists of five nodes (ports) and seven arcs (green corridor routes). The network propagation was investigated as a probability function of Research and Development (R&D). Furthermore, the network was simulated based on Linear Threshold model with different scenarios to understand the significance of various operational parameters.

It was observed that nodal centrality was an important measure in the adoption of green corridors within the network. Arcs connected to the central nodes got adopted faster relative to non-central arcs. Moreover, the initial probability (TRL) of the port influenced, the rate of technological uptake. The adoption of the network as a whole was fastest when node E was considered as the source node (high probability of uptake). This key finding shows that, policy makers should direct policies towards ports with lower level of TRL and bridge the gap between a developed port and a developing port, to attain a faster adoption of a technology diffusion in the entire network.

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List of abbreviations

GHG - Greenhouse gases

CFC – Chlorofluorocarbons

CO2 **–** Carbon di oxide

CFC - Chlorofluorocarbon

IMO – International Maritime Organisation

UN – United Nations

COP - Conference of the Parties

SZEF – Scalable zero emission fuel

LTM – Linear threshold model

TRL – Technological readiness level

TV – Threshold value

CRL - Commercial readiness level

CII - Carbon Intensity Indicator

EEXI - Energy efficiency existing index

EEDI - Energy efficiency design index

CFD – Contract for difference

DOI – Diffusion of innovation

CAPEX – Capital expenditures

OPEX – Operating expenditures

1 Chapter - Introduction

1.1 Background

Climate change alters the earths weather patterns, which are massively impacted by the human activities such as burning of fossil fuels and deforestation. These activities led to release of greenhouse gases (GHG) into the atmosphere. Burning fossil fuels is responsible for 75% of the Carbon-di-oxide (CO2) emissions created by people since 1980; the remaining 25% comes from other land uses, such as agriculture and logging (Miller, 2014). These gases get accumulated in the lower part of the atmosphere forming a CO2 blanket that prevents solar radiation from reflecting off the surface of the earth, it also increases the ultraviolet radiation, due to decrease in stratospheric ozone caused by accumulation of chlorofluorocarbon gases (CFCs).

Figure 1 shows the temperature of earth has raised by approximately 0.08℃ per decade since 1880, the rate of warming of earth since 1980 has more than doubled to 0.18℃ per decade. In 2022, the earth was 0.86℃ warmer than the 20th century (Rebecca and Luann, 2023)

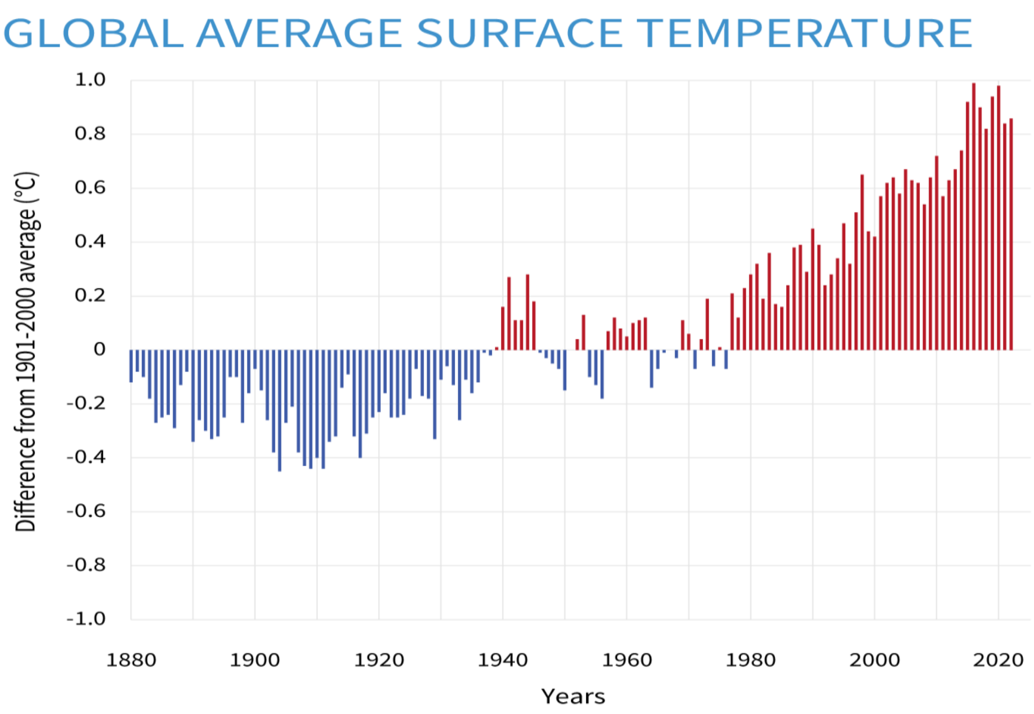


Figure 1 Global average surface temperature
Source: (Rebecca and Luann, 2023)

A warm planet causes rise in sea level and thermal expansion of water, intense heatwaves, change in rainfall patterns and disruption to our ecosystems. These disruptions cause melting of ice caps increasing the sea level, posing risks to coastal communities and ecosystems. One of the main functions of CO2 is to absorb heat, which results in ocean acidification which harms the marine life and coral reefs (IMO, 2023). Heatwaves have become more frequent leading to severe impact on human health such as heat related illness and deaths. The degree of risk associated with climatic change is particularly severe for individuals with issues of cardiovascular, respiratory, rental or immune systems. Furthermore, it can increase the food and water insecurity, displace populations and increase the frequency of natural disasters due to extreme weather events.

The global shipping emissions represents for 1076 million tonnes of CO2, which accounts to around 3% of GHG (EU, n.d.). It significantly impacts climate change, both in terms of the operational difficulties and environmental issues. Due to the use of fossil fuels in ship engines, shipping has a huge impact on global emissions. There is huge international efforts and initiatives to reduce the GHG in the shipping industry to adopt cleaner and more sustainable practises. The International Maritime Organization (IMO), a UN agency responsible for shipping, has put up steps to minimize the carbon footprint in this sector. The IMO strategy includes to reach net-zero GHG emissions from international shipping close to 2050 (IMO, 2023), additionally to ensure an uptake of alternative zero and near-zero GHG fuels by 2030. This has encouraged shipping companies to investigate and invest in cutting-edge technology and adopt cleaner and more sustainable practices. Decarbonizing the supply chain by reduction of carbon footprint in the sector, thereby contributing to achieve the global climate change goals.

Maritime decarbonisation is a complex issue which requires, efforts and strategies aimed at transitioning to cleaner and more sustainable fuels and technologies to minimize the environmental impact. However, there are lot of innovation gaps in the maritime industry which are mighty challenges in developing a new green fuel technology and reaching net zero GHG by 2050. A total investment of around 87% will be required for land-based infrastructure and low-carbon fuel production facilities. Depending on the production method, the total expenditure required between 2030 and 2050 to halve shipping's emissions comes to over $1 trillion, or an average of $50 billion to $70 billion each year for 20 years. It will take an additional $400 billion in expenditures over the next 20 years for shipping to fully decarbonize by 2050, bringing the total to $1.4 trillion to $1.9 trillion (UMAS, 2020). These investments include the production of low carbon fuels, storage and bunker infrastructure for low carbon fuels. Remaining 13 % of investments are related to ships, equipment's, machinery, retrofit and onboard storage needed for a ship to run on low carbon fuels in newbuilds. Maritime organisation is finding ways to initiate a change which will encourage all stakeholders to take actions and make substantial investments in developing a green fuel technology to meet the sustainability goals. Green corridors are one such initiative which was established to decarbonize the value chain of the entire network. The availability of green fuels in the Green Corridor can enable shipping companies to adopt more sustainable practices and reduce their carbon footprint. The Los Angeles-Shanghai Green Shipping Corridor will be the first green shipping corridor in the world, according to an announcement made on January 28th, 2022 by the Port of Los Angeles, the Port of Shanghai, and C40 Cities (Sadiq and Mark, 2023). These would allow policy makers to create an ecosystem with regulatory measures, financial incentives and safety related measures to foster a new green fuel technology adoption, production to mobilize demand for green shipping and to lower the cost of production of green fuels (Elena and Jesse, 2023). The concepts of green shipping corridors are explained in chapter 2.

1.2 Problem Identification

Decarbonizing the maritime sector requires a mammoth effort from all the parties involved to work towards reaching the sustainability goals with a progressive and collaborative mindset. This transition is aimed to reduce the negative environmental effects of maritime activities, by switching to cleaner, more sustainable fuels through technology adoption of green fuels. The objective of maritime decarbonization is to significantly reduce the carbon footprint of the sector, support global climate goals, and guarantee the long-term viability of maritime transportation.

Developing new fuel technologies is a complex and difficult task, it involves extensive research - testing, research and development, financial considerations, expertise funding from both private and public sectors to ensure efficient fuels to meet the emission reduction goals. Integrating these new technologies within existing framework requires meticulous planning and coordination to adhere the safety and environmental standards. It becomes more complex to maintain feedstock sources, fuel production, safety systems in supply facilities, ship design such as retrofit, propulsion and fuel storage and safety measures to create new infrastructure which requires customer preferences and adoption that play a significant impact in market acceptability (Petersen et al., 2021).

Despite these obstacles, substantial advancements have been made in fields in developing this new fuel technology. To overcome these obstacles and propel the shift to sustainable energy solutions; ongoing collaboration, innovation, and policy support are very crucial. To achieve this, the industry needs to explore and adopt alternative fuels that are both feasible and environmentally friendly. The use of green fuels in the shipping industry can significantly reduce greenhouse gas emissions and help mitigate the impact of shipping on the environment. The adoption of zero emission fuels in shipping sector will eventually follow an S-curve (Stephen, 2020) like it has always been the case with all past industrial technological transformations. It has multiple pathways that are in various levels of technology adoption and operational readiness. To resolve this issue, green corridors is one such initiative which is expected to bridge the gap between stakeholders in jointly collaborating in the value chain to create a net positive impact. A regulatory structure with policies, financial incentives, safety standards, safety measures, increase production and demand for green shipping to encourage the adoption of new green fuel technologies while bringing down production costs. But there is no quantitate evidence to prove if the concept of green corridor will be successful and whether it will infuse a change towards a faster adoption of green fuel technology. This has given me an opportunity to simulate the concept of green corridors using a network diffusion model to identify some key elements and findings that help in studying the adoption dynamics in the new technology.

1.3 Research question and Sub research question

Guided by the problem identification, the researcher addresses the research question:

How can green corridors help in accelerating the adoption of a new technology through an entire network?

The main goal of the study is to research, how having a green corridor can help in the adoption process of a new fuel technology. Further, the objective was to study whether any key parameter or findings which would help in the faster adoption of the technology through the entire network.

The following sub-research questions were used to adequately respond to the main research question:

1. What is the best methodological approach to study the adoption of a new technology?
2. Is network centrality an important parameter in the adoption of new technology?
3. How should the stakeholders prioritize their strategy for a faster adoption of a new technology in a network?
4. What are the various parameters affecting the adoption dynamics of a new technology in a network?

1.4 Research design and methodology

The research was focused on the qualitative study using data collected from various sources by referring through several publications, company reports, e-books and research papers.

A probability study using a network diffusion model was used to analyze the acceleration of a new technology adoption. This model was used to answer main research question and to address the different conditions posed in answering the sub research question one (1). Sub research question two (2) was analyzed through the empirical study on the main measures and parameters which were used in the network diffusion model.

Sub research question three (3) was used to suggest policy recommendations to accelerate the adoption process of a new technology. The policies were proposed from the key findings obtained through the model simulations.

Sub research question (4) analyzed the various parameters that affected the dynamics of the adoption process of a new technology. Different scenarios were constructed in the network model using practical assumptions to study the adoption process, having the same input values.

1.5 Thesis structure

Chapter 1 introduces the subject and the context of study regarding the global warming and climate change crisis. It then identifies, the research gap and problem identification followed by the research and sub research questions. Further, the research methodology used for this study was also discussed.

Chapter 2 will form the literature review about the concepts of green corridors and provides the importance and the key drivers which are essential for the building blocks of zero emission shipping. The concept of innovation of diffusion through network diffusion models are also introduced, which are an essential part of the green corridor research study.

Chapter 3 focuses on the methodology part on, how a network diffusion model is selected and a simple network was constructed as a replication of ports to foresee the technology adoption of green fuel technologies. The model was used to study, whether use of green shipping corridors will foster this change even faster. A probability study through linear threshold model was used to find the results.

Chapter 4 will present the output and main results from the model. The results for different scenarios were analyzed to answer the sub-research questions. Sensitivity analysis was performed to assess the robustness of the model and to check the effectiveness of different variables and parameters that was used to run the model and obtain the results.

Chapter 5 provides the conclusions of the study. Key findings of the research that enables the policy makers to find an optimal adoption of a new technology that will accelerate the decarbonization process in the value chain. It also outlines the limitations of the study and suggest further research which was not explored in this research.

2 Chapter - Literature Review

This chapter will begin with an introduction to green corridors for shipping and their importance and impacts. Some key elements to form the green corridor is also discussed in sub sections. In addition, the main drivers and challenges for the implementation of green corridors is discussed in this chapter.

2.1 Background of Green corridors in shipping

The goal of Paris agreement is to hold *"the increase int the global average temperature to well below 2.0℃ above pre-industrial level and take efforts to limit the global average temperature increase to 1.5℃ by the above pre industrial levels"* (UNFCC, 2015). The United Nation (UN) international climate body known as Conference of the Parties (COP) are held each year to review the process of the sustainability goals and its adoption. In 2021, COP26 was held in Glasgow and an important event where for the first time the countries involved officially wanted to increase their ambition to achieve the Paris climate agreement goal (Christian and Coen, 2021).

With the climate goal in mind, over 20 countries including the United States, United Kingdom, Netherlands, Denmark etc had signed the Clydebank declaration which aims to support the promotion of at least 6 green corridors by 2025 and many more by 2030 (ABS, 2022). Maritime decarbonisation is complex issue as there are multiple pathways at different levels of technological readiness. The major challenge is to accelerate the operational efficiency and scale up the low and zero carbon fuels. Maritime decarbonisation has numerous moving parts and since the industry is so diverse, fragmented and globally regulated, it poses a major challenge to tackle this issue. Green corridors are expected to help reduce the challenge between the fuel infrastructure, ships, fuel producers, shipping companies and stakeholders in the value chain. These corridors can involve in a network of ports, a point-to-point route or a single port corridor.

As per (Dorthe et al., 2022) green corridors mean - ***green*** here refers to the fundamental focus of the corridor is to reduce emission, it is for zero emission maritime routes between two or more ports. While in the case of US DOS, it refers to both low and zero carbon shipping routes which are considered within the definition of green corridor. ***Corridors*** here refers to specific geographical connection between two or more locations that could serve as an enabling environment to help reduce emissions. A corridor can also create a favourable atmosphere for innovative business ideas, policies and regulations that assist firms in achieving low or zero carbon emissions (ABS, 2022).

Green corridors allow policymakers to develop an enabling environment with targeted regulatory actions, financial incentives, and safety standards, which can leverage favourable conditions to accelerate faster. Additionally, they can create conditions that will encourage demand for green shipping on particular routes. Finally, by causing spillover effects that lower shipping emissions on adjacent corridors, green corridors can aid in the acceleration of decarbonization.

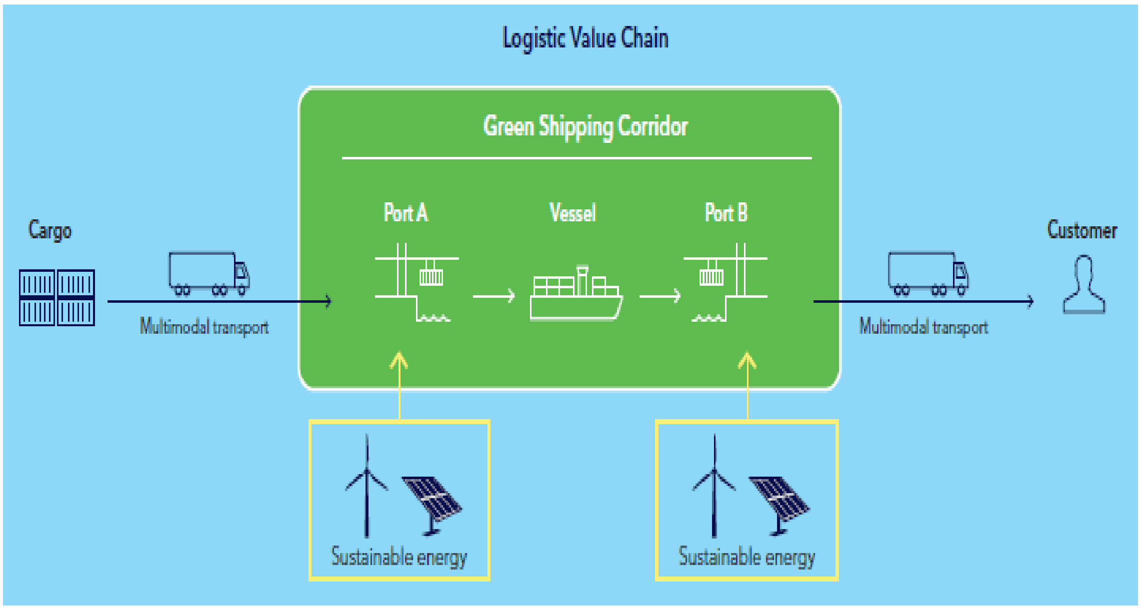


Figure 2 Green Shipping corridor
Source: (Dorthe et al., 2022)

Figure 2 explains the concept of green corridors, ***"the green corridor can be defined as the zero-emission shipping route between two or more ports".*** The value chain of the green corridor involves many numbers of players such as cargo owners, charterers, ports, ship owners, energy producers and suppliers, operators, banks, customers and others that need to cooperate and comply with the green shipping corridor ecosystem.

2.2 Importance of green corridors for shipping

IMO GHG emission strategy has a goal to uptake zero GHG emission technologies, fuels and or energy sources to represent at least 5% of energy used in international shipping by 2030 and reach net zero by 2050. Getting to Zero Coalition is an association of 70 companies in the maritime, energy, infrastructure, and financial sectors backed by government bodies (Mr. Toft, 2019). By 2030, the Coalition's ambitious goal for the marine sector, commercially viable deep sea zero emission boats powered by zero emission fuels will be in service. The steps required to achieve the cutting-edge target of 5% Scalable zero emission fuel (SZEF) by 2030 are as crucial as ever and demonstrate the scope of the challenge faced by the maritime industry (Jasmina, 2021). There is a path towards substantial progress to 5% SZEF that can be reached with clear, timely, and urgent action, and shipping industry can do its fair part to help address the ongoing climate emergency.

This adoption rate 5% target for 2030 encourages engagement and action from all parties involved and stakeholders, such as:

- Fuel producing companies have instilled a greater confidence in expecting demand which encourages them to plan for green fuel development projects.
- Encourage cargo owners to invest in and collaborate across supply chains by, for example, charging a premium for zero-emission fuels on a portion of their freight that corresponds to that percentage.
- Financial institutions can collaborate with research organisation to quantify the amount of investment required across the value chain.
- Shipping companies will be encouraged to purchase new building green ships and retrofits their existing fleet.

- Regulators and policy makers can be contacted to guarantee that level playing conditions are set up to facilitate the transfer.

Both public and private sector needs to align with the sustainability goals and collaborate to achieve its goal to enable the framework for the innovation process across the value chain in the network. This collaboration should establish target research and development to address the industries innovation gaps. Figure 3 shows the three pillars (*Industry roadmap to zero emission shipping*, 2022) which are essential to lay the foundation to reach the 5% SZEF by 2030 and for zero-emission shipping future are: -

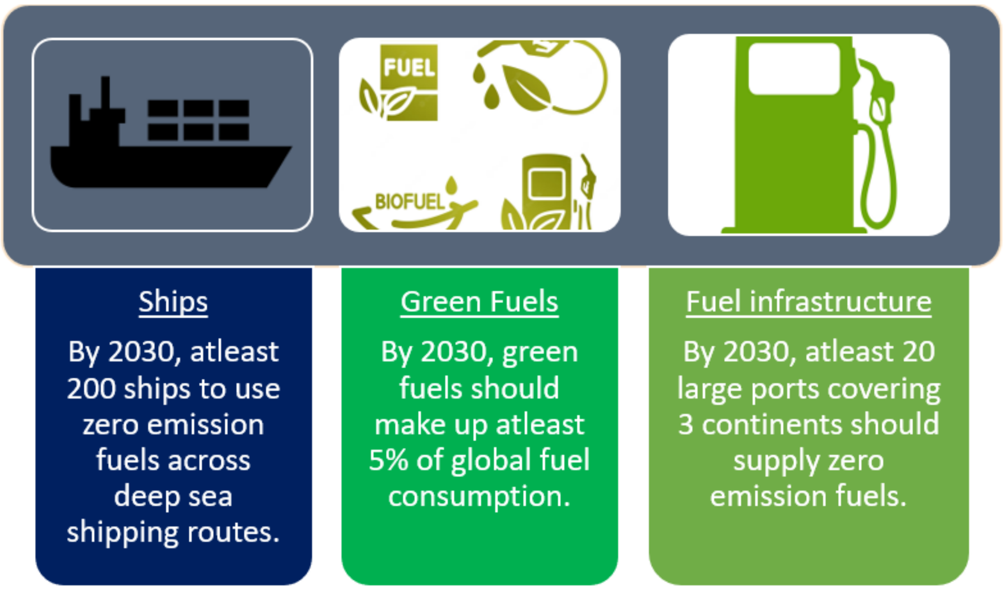
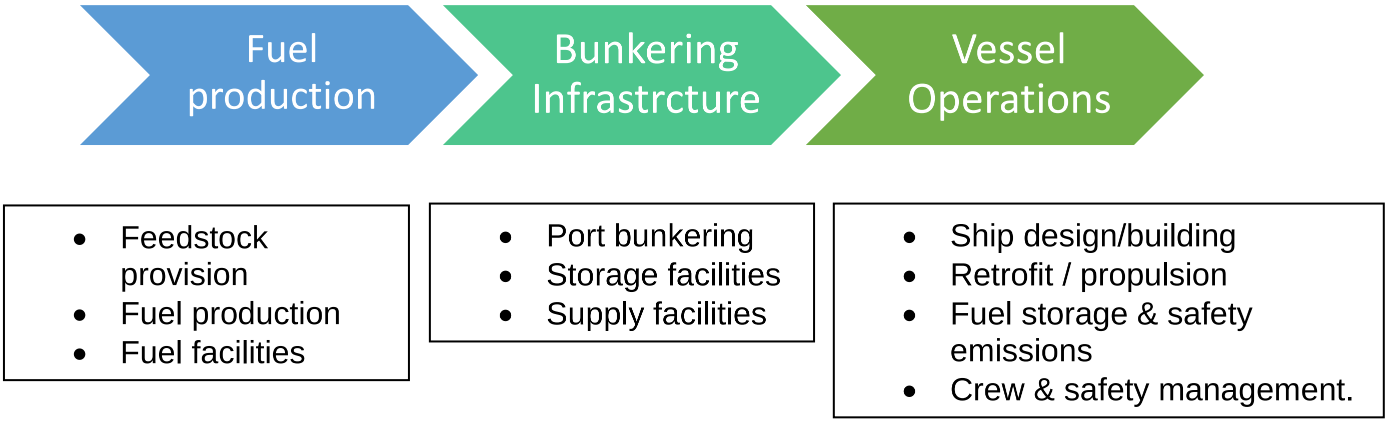


Figure 3 Three pillars to reach 5% SZEF
Source: Author

Innovation is essential for successfully decarbonizing the maritime industry. By 2030, the sector is expected to be guided towards a transformative turning point by concentrating on every link in the value chain; including ships, fuel production, and port fuel infrastructure. The plan calls for transforming ships to run on zero-emission fuels and upgrading the global port system to accommodate ships running on these green fuels. To direct innovation in green fuel technologies, a thorough value chain study is being conducted to close the gap and meet the goal of 5% SZEF by 2030, for which technological improvements are essential.

In order to achieve economically viable zero-emission shipping, the goal was to determine and organize the requirements for innovation along the whole value chain that reflect the technology readiness level (TRL) of a new technology. Below is a glimpse of a value chain that needs to be technology ready.



2.3 Main Drivers for the Implementation of green shipping corridors

The establishment of green corridors plays a crucial role in the endeavour to reduce the GHG emissions and mitigate the environment impact of shipping. The implementation of green corridors is driven by several key factors. A systematic and thorough approach to handle a particular set of criteria is required to effectively build and maintain a green corridor. Four key elements (ABS, 2022) must be considered when forming a green corridor as seen in the figure 4.

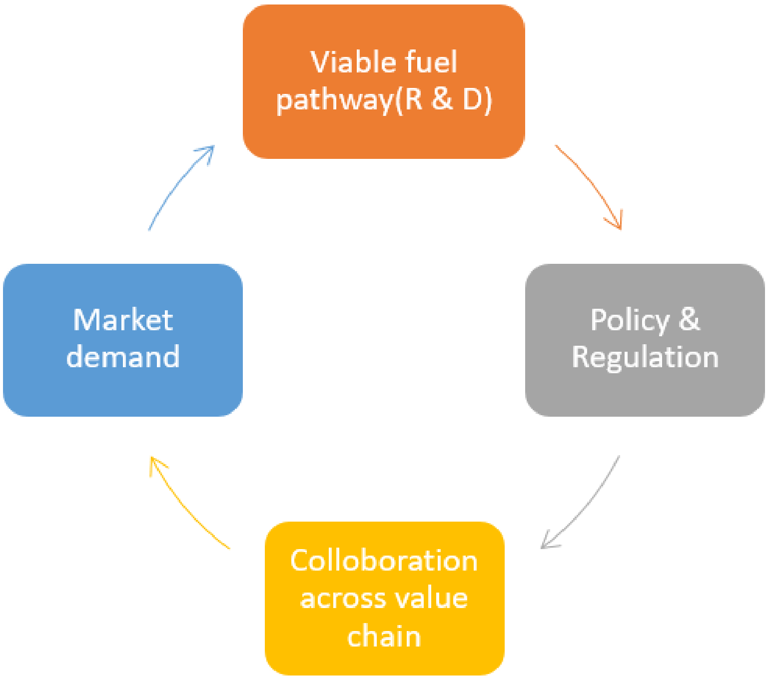


Figure 4 Key elements to form a green corridor for shipping
Source: Author

2.3.1 Collaboration across the value chain

Every green corridor program must start with a shared commitment across the whole value chain. A green corridor essentially reflects a group effort to decarbonize the entire value chain, bringing stakeholders together to address a common problem. Green corridors bring the first movers who share the risk at the early stage. Following the initial development phase scaling up phase will enable the creation of extra routes, longer routes, and an increase in the number of vessels operating in the corridor and subsequently contribute to the development of alternate fuels that lead to reduced cost and develop measures to fill the innovation gaps across the value chain to decarbonize a specific geographic area. The entire value chain of the network is seen in figure 5.

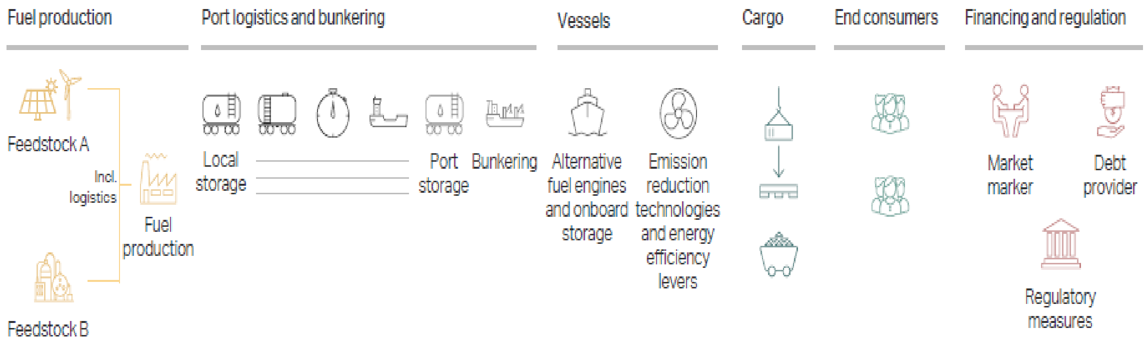


Figure 5 Entire value chain of the network
Source: (Maersk Mc-kinney Moller centre, 2022)

All value chain participants must work together for a green corridor to succeed, especially where their operational boundaries intersect. Over time, the entire corridor will work as a cohesive unit, helping both to decarbonize the maritime sector and unlock previously untapped economic potential. To avoid problems at the intersection of various stakeholders, joint efforts should be built on open communication, development of trust, and the backing of clearly defined agreements and policies.

Since the signing of Clydebank declaration, (Maersk Mc-kinney Moller centre, 2022) suggests 21 green corridor (as seen in figure 6) initiatives have emerged (as on 2023) with more than 113 stakeholders participating across the value chain to collaborate and work towards the common target. For a green corridor to be successful, communication and collaboration within the stakeholders in the value chain are some key features to accelerate the progress of green corridor initiatives.

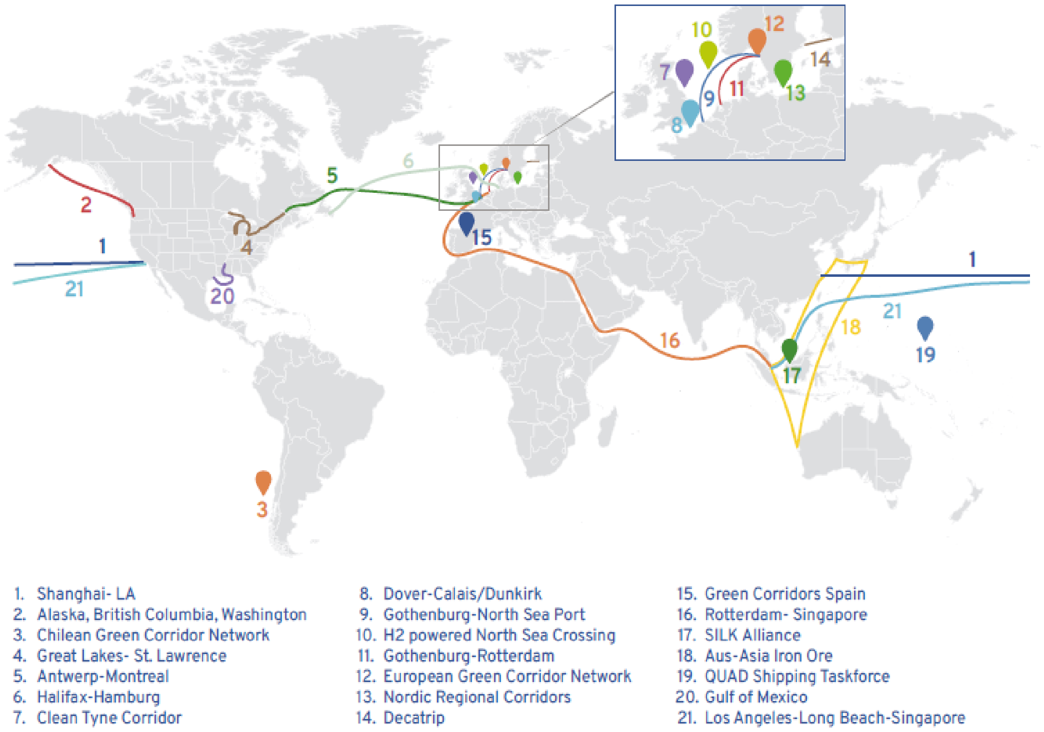


Figure 6 21 Green corridors initiatives as on 2023
Source: (Elena, 2022)

Six corridors out of these 21 is expected to be implemented by 2026 (Elena, 2022). Vast majority of 21 of these initiatives are still in the initiation stage and a very few on the feasibility assessment stage / implementation of a plan. These initiatives have prompted collaborations across the value chain to establish a successful green corridor across the trade route. The most involved stakeholders in the value chain are the port authorities, vessel owners and the researchers as seen in the figure 7.

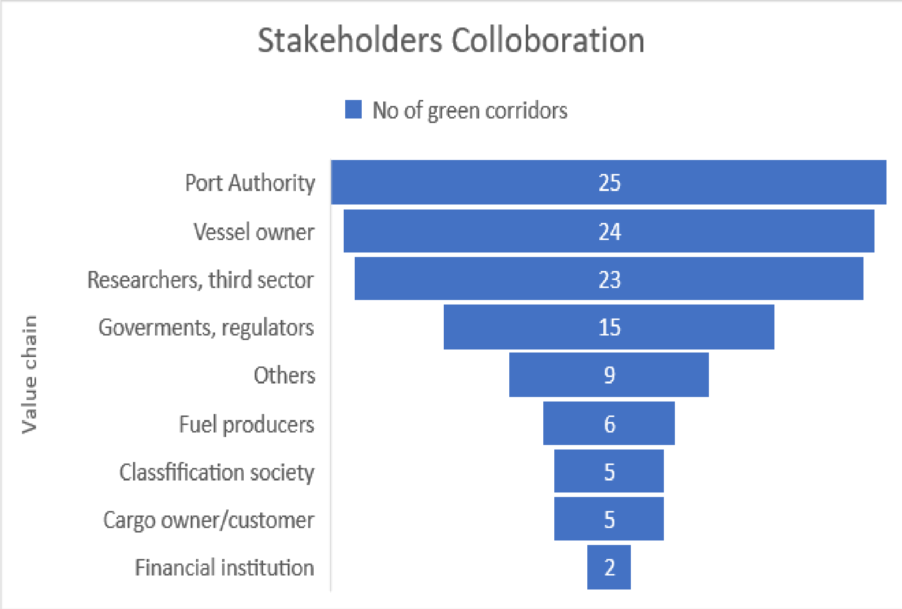


Figure 7 Stakeholder collaboration
Source: Adopted by author from (Elena, 2022)

2.3.2 Viable fuel pathway

Quantifying the corridor's energy needs will be a crucial consideration in decision-making for green corridors. Fuel manufacturers should assess the alternative fuels market by considering the unique characteristics and requirements of their potential customers. The shipping industry must evaluate the fuel accessibility, given the scale of the green corridor project. The green corridor partnership should assure fuel producers of ongoing demand in order to speed up this process. The sector is currently engaged in period of experimentation and exploration to determine the effects of adopting these green fuels(ABS, 2022). Ship owners and operators, ports, fuel suppliers, engine makers, shipyards, and other players are looking to one another for hints about where the industry is headed because adoption at scale will require entire value chains to cohere. Alternative fuels are anticipated to be used in green corridors to significantly reduce emissions. As global decarbonization progresses, a variety of fuels, such as biofuels, methane, hydrogen, methanol, and ammonia, are expected to play a part in shipping. Many alternative fuels can be produced in various ways (methane, for instance, can be produced through bio- or e-methane production), which results in different well-to-wake emissions for the same fuel.

Table 1 Well to wake emissions

Fuels	Well to wake emission (kg CO2eq/GJ)			Emission reduction potential compared to LSFO		
	2025	2030	2035	2025	2030	2035
LSFO	96	96	96	0	0	0
e-methane	11.6	11.4	11.3	88	88	88
Bio-methane	21	16.9	13.9	78	82	86
e-hydrogen	1.5	1.1	0.7	98	99	99
Blue hydrogen	17.4	16	14.7	82	83	85
e-methanol	0.8	0.5	0.4	99	99	99
Bio-methanol	10.4	8.4	6.6	89	91	93
e-ammonia	1	0.7	0.5	99	99	99
Blue ammonia	19.3	17.8	16.5	80	81	83

Source: Author adopted from (Maersk Mc-kinney Moller centre, 2022)

Methane can be via bio-methane or e-methane resulting in various well-to-wake emissions for the same fuel as seen in table 1. Selecting alternative fuels can significantly contribute to emission reduction compared to Low-Sulphur Fuel Oil (LSFO). From table 1, the highest potential for decarbonization is found in electrified fuels like e-methanol and e-ammonia where its well to wake emission is so low (less than 1) when compared to others. Their emission reduction potential when compared to LSFO is the highest at 99. But reaching that level of technology readiness for these green fuels require innovation.

Innovation in green fuel technologies have been making steady progress already. However, the ***challenges*** faced for the innovation of these new technologies are significant. Below are the main challenges and the gaps found in the innovation to produce & scale up new fuel technologies to meet the market demand as explained in (Petersen et al., 2021): -

1. *Green fuel technology not market ready* – The technology needed across value chain is relatively high, but the commercial readiness or the market acceptance is very low. Table 2 explains that Technological readiness level (TRL) which has been used to access the technological readiness of fuel technology scaling from 1-9 and Commercial readiness level (CRL) to access the commercial readiness ranging from 1-6. The TRL for fuel production, bunkering infra and vessel operations are very high compared to CRL. Biodiesel and biogas have the overall highest TRL by fuel production, bunker infrastructure and vessel operations. Innovation is needed to improve the productivity and energy efficiency to support the uptake of these fuels commercially. Table 3 shows the interlink between them.

Table 2 Technology readiness measured by TRL & CRL

	Fuel production		Bunkering infrastructure		Vessel Operations		Avergae by fuel	
	TRL(1-9)	CRL(1-6)	TRL(1-9)	CRL(1-6)	TRL(1-9)	CRL(1-6)	TRL(1-9)	CRL(1-6)
Green hydrogen	9	2	6	1.5	6.4	1.5	6.8	1.6
Green ammonia	8.2	2.8	8	2	5.7	1.3	7	1.9
E-methanol	9	2	9	2.5	7.1	2	7.6	2.1
Biodiesel	9	2	9	3	9	3.2	9	2.9
Biogas	9	2	9	3	9	2.8	9	2.8
DME	5.8	1.8	8.5	1.5	7.4	1.5	7.1	1.6
Average by value chain	7.9	2.4	8.2	2.2	7.1	1.9		

Table 3 Interlink between TRL and CRL

(TRL) Technology readiness level	(CRL) Commerical Readiness Level
	6 - Bankable asset class
	5 - Market competition and widespread development
	4 - Multiple commerical applications
	3 - Commerical scale up
9 - Vessel call or bunkering service readily available	
8 - Vessel call or bunkering system complete and qualified	2 - Commerical trial, small scale
7 - Vessel call or bunkering established on project in operating environm	
6 - Vessel call or bunkering framework demonstrated in a controlled environment	
5 - Vessel call or bunkering framework designed	
4 - Vessel call or bunkering approach decided	
3 - Sufficient information gathered	
2 - Intrest of port stakeholders determinded	1 - Hypothetical commerical proposition
1 - Fuel relevance assessed	

Source: Created by author with reference to (Petersen et al., 2021)

The six-fuel options overall readiness is determined by averaging the results for each technology. Table 2 clearly shows that average technology readiness scores are very high, ranging from 7.1 (for vessel operations) to 8.2 (for bunkering). The range of the commercial readiness is lower, ranging from 1.9 to 2.4. This shows that in order to encourage commercial deployment and acceptance, the competitiveness of the fuels has to be enhanced through innovation and additional market-supporting measures.

2. *No single choice of zero emission fuel as yet* – Each fuel has its limitations and challenges. Different types of fuel technologies are adopted by different part of the shipping sector. All fuel technologies have the need to further develop, expand and to scale up. Table 3 shows the study comprises of two pathways, one with electricity-based fuels and other with bio-based fuels. The limitations of all fuels have been explained below in table 4 along with feedstock requirements, storage and emission challenges.

Table 4 Limitations of fuels

Type	Fuel	Risk to users	Feedstock	Storage	Emissions
Electricity based fuels	Green hydrogen	Very high - highly flammable	Demand can only be met with electricity producing facilities.	High storage volume & low temperature	Nox and other particle emissions
	Green ammonia	Very high - toxic & corrosive		High vloume	Nitrous oxide, Nox emissions
	E-methanol	High - toxic, corrosive & poisonous		More storage due to low energy density.	Low CO2 and low suplur,nitrous oxide emissions
Bio based fuels	Biodiesel	Moderate	Demand for supply of bio-materials at appropreiate scale	Can use exisiting storage though low energy density	Nox and other particle emissions
	Biogas	High - highly flammable		Can use LNG storage though low energy density than LNG	Nitrous oxide, Nox emissions

Source: Author adopted from reference to (Petersen et al., 2021)

Table 4 shows that green fuels like green hydrogen and green ammonia don't produce CO2, electricity-based fuels appear to be advantageous. However, e-methanol emits CO2, but in considerably smaller amounts than marine fossil fuels because it employs waste CO2 as a feedstock input (Petersen et al., 2021). Despite green hydrogen's obvious potential in other industries, its low energy density makes it difficult to use in the marine industry, particularly for long-haul international shipping. Green hydrogen must be kept in cryogenic storage, which consumes a lot of energy and onboard volume and significantly reduces the amount of cargo that can be transported (Moradi and Groth, 2019). Even though green ammonia has a higher energy density than other alternatives, it is poisonous and corrosive, posing a serious risk to both human and environmental health. Green ammonia also releases nitrous oxide when burned, hence a good method of managing this must be developed (Al-Aboosi et al., 2021).

With respect to fuels based on bio, CO2 emissions from biofuels make them less desirable. Additionally, technologies for producing biofuel, bunkering, and operating vessels already exist and are in use commercially. But their uncertainty about the supply of feedstock to produce the biofuels. Overall, the industry is yet to choose one fuel in the idea of transitioning the fuel.

3. *Cross-cutting gaps & innovations* – The study of technology across the whole value chain for each of these green fuels by specialists has uncovered important gaps. These gaps span either a section of the value chain or the full value chain, and they apply to all or select categories of fuels. The (Petersen et al., 2021) has identified cross cutting gaps as an hinderance to innovation: -
    - Knowledge gap - Inadequate knowledge about how effectively green fuels operate and how practically they perform in the full value chain. There are information gaps regarding the fuel's ability to be competitive on price and practical operational problems. Such as, how it will affect cargo capacity, bunker storage, lack of safe standards. Issues pertaining to bunkering the ship, and how well engines will operate. This applies to all fuel value chains.
    - Safety standards - The lack of standardized procedures for fuels and clearly defined safety management strategies highlights the need for additional actions. The advancement of fuel technology development could be aided by these initiatives, which could involve updating current international standards or developing new ones.
    - Scaling up the supply - Inadequate supply of feedstock, particularly the biomass and renewable energy sources required to produce enough green fuels. To close this gap, a combination of innovative techniques and market research is to be focused to reduce the material costs, improve the performance of renewable energies and eventually reducing the price of these fuels.

2.3.3 Market demand

A green corridor can be transformed from a theoretically viable idea to an economically viable solution by establishing a solid business case. While each corridor's business case may have different details, the emission reductions along the value chain and wanting a cost-effective solution remain at the core of it. Beyond its geographical location, a corridor can serve as a platform for the facilitation of innovative business strategies and regulations intended to aid stakeholders in achieving low or zero carbon emissions (ABS, 2022). Market demand for a corridor must be based on pre-feasibility assessment that answers the following: -

- What is the business case?
- What are the available green fuel options and ease of developing a new infrastructure?
- What are the policies and government initiatives that enable the development of a green corridor?

Different implementation of fuel options like methanol, LNG, ammonia, or hydrogen have varying levels of economic feasibility depending on the location. Therefore, when choosing a fuel option, it's important to assess its overall cost throughout its lifecycle. This analysis should cover emissions reduction, initial setup costs (CAPEX), and ongoing operational expenses (OPEX). Additionally, it's worth considering how prices for alternative fuels may decrease as their availability increases over time.

The shipping industry will experience a rapid phase of energy and technological change that will have a greater impact on costs, asset values, and earning potential. As per (DNV,2022), since the beginning of 2022, alternative fuel ships have received almost 60% of all new orders in gross tonnage (GT), with orders for LNG dual-fuel vessels and increasingly for methanol accounting for 5% of the fleet's GT and 47% of the orderbook. Figure 8 shows in 2022, 98.8 % of conventional fuels are being used in world fleet, out of which 923 vessels are LNG, 396 which are hybrid, 19 which are LPG and 11 ships of methanol. The demand for green fuel is increasing as order book for 2022 reveals the ships being ordered with alternative fuel such as 417 of battery/hybrid ships, 57 LPG, 35 methanol, 3 hydrogen ships. Steady rise in order of LNG is also visible.

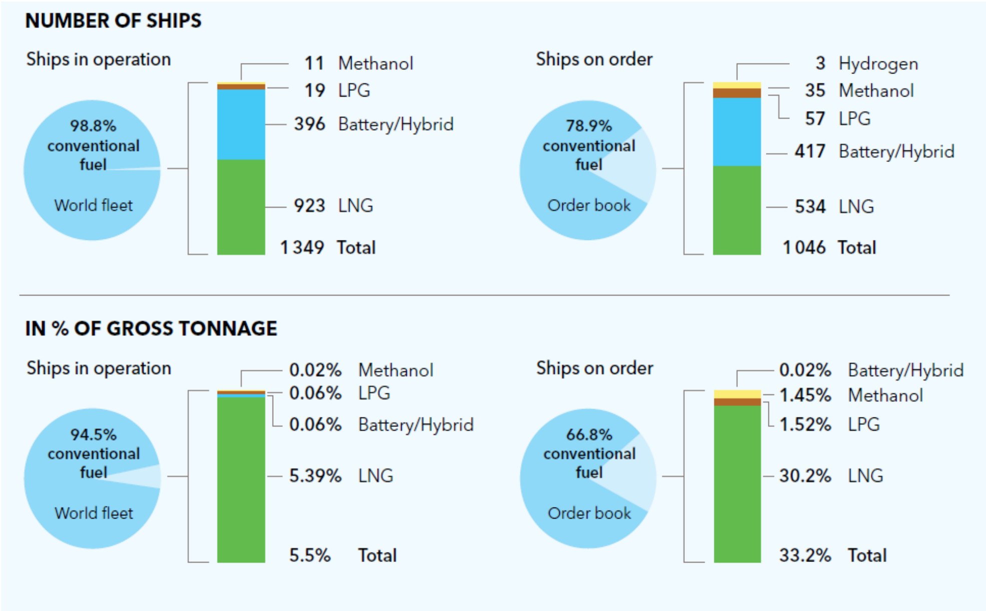


Figure 8 Alternate fuel uptake in world fleet by number of ships in 2022
Source: (DNV,2022)

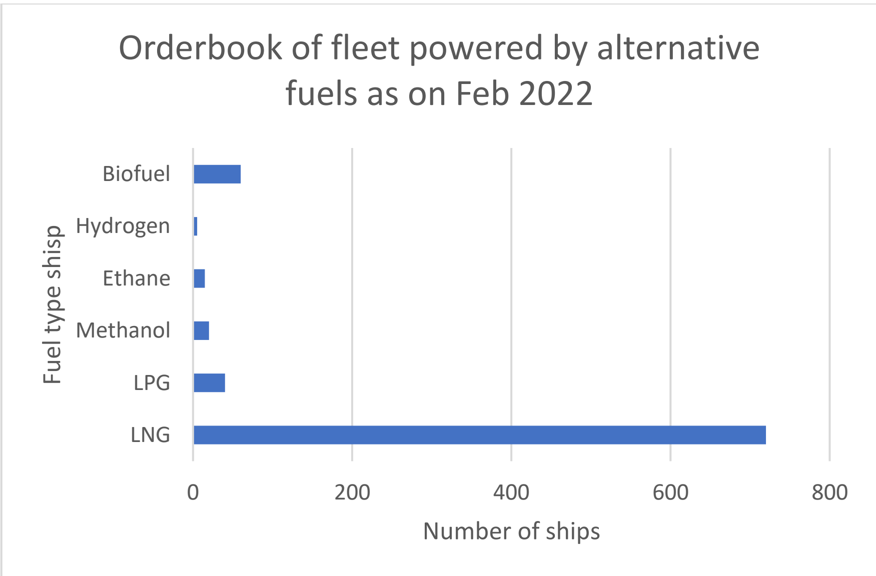


Figure 9 Orderbook fleet powered by alternative fuel as of February 2022
Source: (Adopted from ABS,2022)

Around 1.4 percent of the world's fleet was propelled by alternative fuels as of February 2022 (DNV,2022). As seen in figure 9, ships than run on LNG, methanol, and LPG have experienced significant growth in order book in recent years. Ammonia as a marine fuel has also made strides. It is expected that the orderbook of methanol, ammonia and hydrogen will start to make steady progress from 2030. From figure 10, LNG has been the most preferred and reliable option in 2022. The 1.4 % of existing fleet of alternative fuels are seen in the form of methanol to be most number of ships in the fleet, and hydrogen being the least preferred as on Feb 2022.

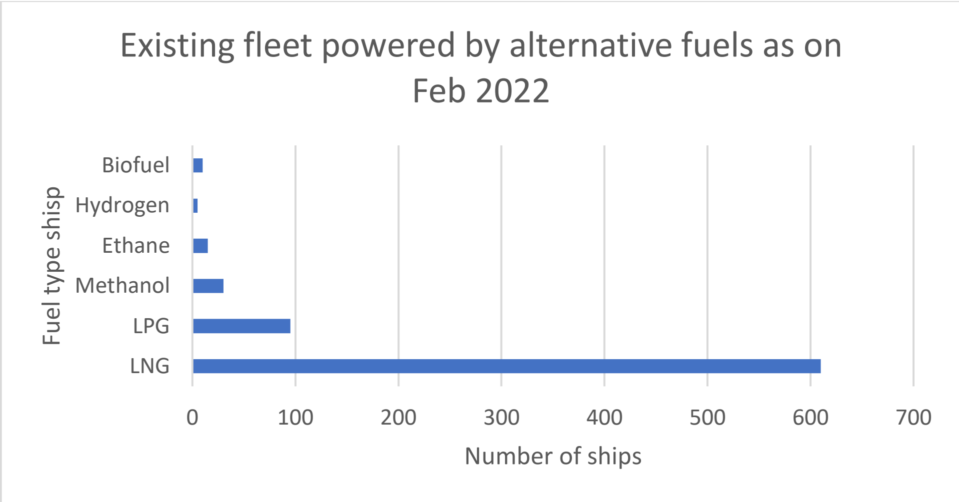


Figure 10 Existing fleet powered by alternative fuel as of February 2022
Source: (Adopted from ABS,2022)

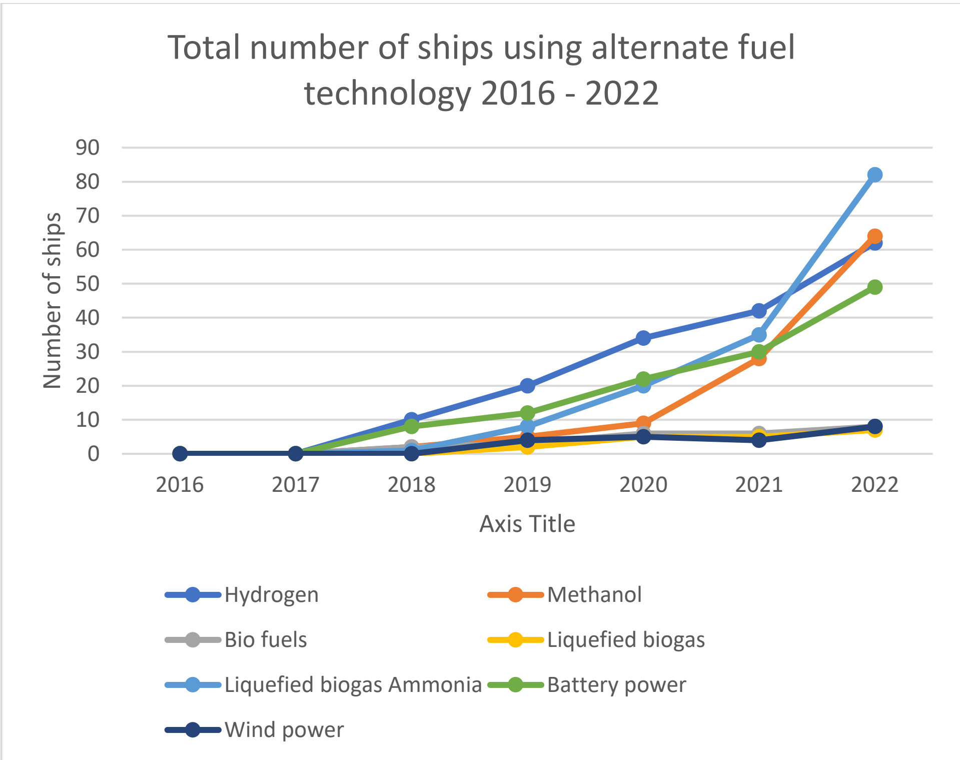


Figure 11 Total no of ship using alternate fuel technology 2016-2022
Source: (Adopted from Dr Domagoj and Katharine, 2022)

The development of pilot projects of alternate fuels has advanced significantly over the past few years, is shown in figure 11 in terms of a sharp rise in the number of projects in terms of fuel type. Pilot projects of alternate fuels attract interest of stakeholders and can be crucial in persuading financial institutions, lawmakers, a variety of key industry stakeholders, and the general public of the proposed fuel's long-term sustainability. Such projects help in cutting down cost and closing the gap between alternate and fossil fuels.

2.3.4 Policy and regulations

Policies and regulations are crucial in facilitating large-scale initiatives that include numerous stakeholders from various economic sectors. Although the green shipping corridor at first glance seems to be focused on maritime activity, its potential effects could be felt in a number of different economic sectors. As a result, it is essential to create a top-down regulatory and policy structure that is supportive of these activities. According to (DNV, 2022), innovations that are on the verge of becoming commercially viable can be powerfully accelerated by a combination of economic policies that remove financial barriers and regulatory policies that reduce non-financial hurdles.

These helpful regulatory and policy support tools, which heavily engage in emissions reduction and sustainable development are crucial. One such example is EU Fit for 55 (Maritime Industry Focused Provisions). These policies include things like producing green hydrogen, electrifying ports, and capturing emissions from oceangoing vessels while they are berthed. These regulations serve as an illustration of how governments might encourage the construction of green corridors for the good of society(Balcombe et al., 2019). Regulations can assist propel the industry, much like incentive-based policy draws in new ideas. Another such example is the IMO's technical and operational rules for Carbon Intensity Indicator (CII), Energy efficiency design index (EEDI), and Energy efficiency existing index (EEXI). From 1st January 2023, it is mandatory for all ships to calculate their attained EEXI to measure their energy efficiency. Ship owners are required to take steps toward decarbonizing their ships as a result of the implementation of these requirements. When it comes to successfully integrating alternative fuels on a large scale, there are problems that must be overcome. In this situation, green corridors give ship owners and operators a way to reduce their vessels EEXI or CII ratings.

According to a qualitative assessment, three types of policies that can accelerate the development of a green corridor of their impact and viability:

1. Policies to lower cost of zero emission fuel production – Important policies and regulations can reduce the cost of zero-emission fuels inside the green corridor by supporting both its supply and demand sides. These regulatory actions include facilitating the use of natural salt caverns for affordable hydrogen storage and compensating electrolysers for potential grid stabilization contributions. They also include speeding up the permit application process for green fuel projects, providing loan assurances, subsidizing capital investments, and providing loan guarantees.
2. Policies to create an enabling ecosystem - Supportive ecosystems can be built by allocating financial resources to expand the bunkering capacity at port facilities. Building the necessary infrastructure to provide ships with greener fuels like liquefied natural gas (LNG), hydrogen, or other low-carbon options is part of expanding bunkering infrastructure. Refuelling ships is referred to as bunkering. By making additional bunkering facilities at ports along green shipping lanes, stakeholders may ensure a steady supply of ecologically friendly fuels for ships traveling along these routes. This investment not only meets the ships' immediate fuel demands, but it also paves the way for the widespread use of environmentally friendly fuels, increasing the viability and success of green shipping initiatives.
3. An incentivisation scheme for zero emission fuels - Zero-emission fuel incentives, such as a Contract-for-Difference (CFD), a sort of regulatory mechanism, can considerably help green shipping routes. In the context of policies and legislation, a CFD is a financial arrangement wherein a

government or relevant authority and a fuel supplier agree that the government will pay the difference between a predetermined "strike price" for zero-emission fuel and the going market price. This approach has a number of benefits when it comes to shipping routes that are environmentally beneficial.

2.4 Technology Adoption

Technology adoption means a successful integration of a new technology (innovation) adoption or acceptance into the system. Shipping industry transports most of the world's goods and is responsible for 3% of global GHG emissions, potentially increasing by half by 2050 on its current trajectory. To set international shipping on an ambitious zero emission trajectory, we need commercially viable, zero-emission ocean-going vessels and alternate fuels and infrastructure in the global fleet by 2030. The adoption of new technology and innovation is crucial for the successful implementation and effectiveness of green corridors in the shipping industry. Green corridors aim to reduce emissions, enhance energy efficiency, and promote sustainability, and advancements in technology play a pivotal role in achieving these goals.

The concept of "diffusion of innovations" refers to the theory that explains how a new technology, idea or products spread and are adopted within a social network or a community over time. Diffusion of Innovation (DOI) theory, developed by E.M. Rogers in 1962, is one of the oldest social science theories (Meade and Islam, 2006). The idea of diffusion of innovations, which was originated in communication theory, describes how an idea or product gradually gets acceptance and spreads throughout a community or society. This process encourages members of the social system to adopt novel concepts, practices, or goods. The word "adoption" describes how people change their behaviour, for as when they adopt a new product or practice a new activity. The perception of the concept, action, or product as fresh and innovative is crucial to its adoption. The diffusion process is made possible by this perspective.

The adoption of an "innovation," or a new idea, behaviour, or product, doesn't take place in a society all at once. Instead, it's a progressive process where certain people are more likely than others to accept the innovation. According to (Li and Sui, 2011), those that absorb innovations sooner than others have different characteristics. Understanding the characteristics that either encourage or discourage the acceptance of an innovation within a certain group is essential for successfully introducing that innovation to that group. Although the majority of the public falls into one of the five known groups of adopters (as shown in figure 12), it is still crucial to comprehend the traits of the intended audience. The five groups are explained below (Meade and Islam, 2006).

Innovators: Innovators are those, that are eager to test out new ideas first. They are bold and curious about new ideas. They tend to be the first to come up with novel ideas and are very willing to take risks. Very little, if anything, needs to be done to appeal to this population.

Early Adopters: Individuals who are considered leaders in their fields. They like taking on leadership responsibilities and embracing change. They are quite comfortable implementing novel ideas because they are already conscious of the need for change.

Early Majority: Although the "Early Majority" group is not typically at the forefront of innovation, they do accept novel concepts before they gain on. However, before they are willing to adopt an innovation, they typically demand solid proof of its effectiveness.

Late Majority: They are resistant to change and won't adopt a new idea until the majority have given it a chance. Information on how many other individuals have tried the innovation and successfully adopted it serves as an approach to appeal to these people.

Laggards: These are extremely conventional and tradition-bound. They are the hardest group to convince to accept change since they are so resistant to it. Statistics, fear appeals, and peer pressure from other adopter groups are all methods for influencing this population.

The adoption of new fuel technology in shipping sector, will eventually follow an S-curve (as seen in figure 12) like it has always been the case with all past industrial technological transformations. The S-curve has three phases (Sawaguchi, 2011), it begins with a slow emerging phase, and then it suddenly peaks after it crosses the tipping point, during which learning happens quickly and costs start to decrease. The diffusion phase then begins with the quick uptake of the new technology, with positive feedback loops among various players boosting confidence and spurring demand and investment along the entire value chain. In the reconfiguration phase, as new technology is adopted and then new technology is diffused into the entire network.

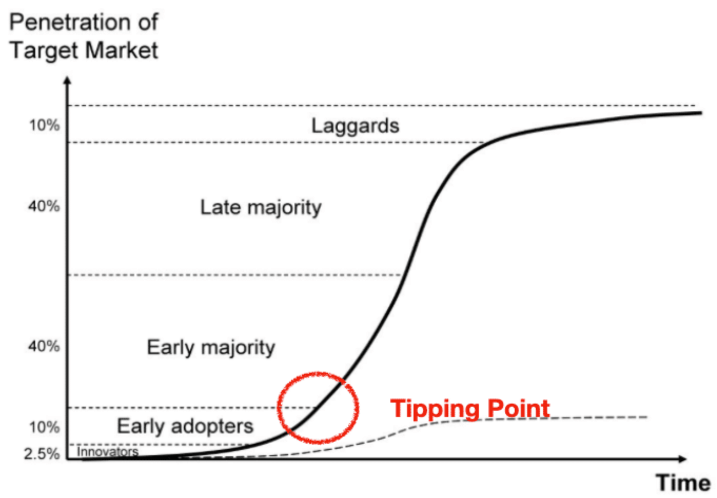


Figure 12 Law of diffusion in innovation
Source: (Stephen, 2020)

Based on the (Randall et al., 2020), the shipping sector is expected to reach the tipping for the zero-emission fuel technology to be diffused into the network by 2030. In order to achieve decarbonization by the year 2050, zero emission fuels must account for 93 percent of all energy by 2046 and 27 percent by 2036, and 5 percent adoption rate by 2030.

2.4.1 Network diffusion models

Network diffusion models are computational frameworks used to study how behaviors, information, innovations, or influences spread through interconnected networks of individuals, entities, or nodes over time. The concept of diffusion are used in various fields like social networks, epidemiology, innovation adoption, transportation and infrastructure etc. (Ryan and Gross, n.d.) says that social contacts, social interaction, and interpersonal communication were significant influences for the adoption of new behaviors. When companies spend million dollars on building new products or technologies, the investments increase as the process advances. Hence, they look for tools and models that accurately forecast the diffusion process of the new technologies. There is very little information about the influence of policy, network effects, cost adjustments, expectations and complementary innovation on choices of green corridors. The ***reason*** for choosing network diffusion model for this research was to understand the extent to which ideas like green corridors could be adopted in a network. It is important to understand how the dynamics of adoption are likely to unfold within a network of ports. The extent to which ports are likely to be adopted with a new technology is affected by decisions from their neighboring ports. The various parameters of the network as mentioned in section 3.4 (initial R&D, rate of increase and threshold value of the port) affects the dynamics of the diffusion of a technology to a large extend (David et al., 2003) .

These models take into account the structure of the network, the relationships between nodes, and the dynamics of adoption. Estimating the influence spread is the initial step to determine an optimal set of initial users to reach a given goal. There are several types of network models within the category of network diffusion models, each with its own assumptions and characteristics. These models are used to study how behaviors, innovations, information, or influences spread through interconnected networks. Here are some common types of models in network diffusion: -

1. **Bass Model**

The concept of Bass model was introduced by Frank Bass which depicts, the diffusion of innovation through influences such as internal influences (e.g. Word of mouth) and external influences (e.g. advertising). The model mainly specifies an individual probability of adopting a new technology over time (t) by interaction between consumers and potential users and how the new products get adopted as an interaction between them. This model is especially helpful for researching innovations that spread through word-of-mouth, where early adopters (**innovators-P**) and later adopters (**imitators-Q**) play different roles in influencing acceptance (Goldenberg et al., 2000). Model is widely used in forecasting, especially product forecasting and technology forecasting.

The Bass Model uses two parameters to describe the adoption process: *Innovators & imitators*.

- Coefficient of Innovation (p): This parameter represents the rate at which innovators adopt the technology. It captures the inherent interest of individuals in trying new things and reflects the self-driven adoption.
- Coefficient of Imitation (q): This parameter represents the rate at which imitators adopt the technology. It captures the influence of social interactions and the number of people who have already adopted the technology.

By estimating only two parameters, a coefficient of innovation and a coefficient of imitation, the model yields the widely observed 'S-shaped' curve of market penetration that shows a slow initial uptake as 'initial adopters' are persuaded to enter the market, succeeded by a rapid growth phase while many imitators decide to follow their lead, and finally a slowing down phase as the market reaches saturation. Different forms of this model have been used to understand and, to varying extents, forecast the innovation process in a wide variety of industrial and consumer settings.

This model however has ***some shortcomings***, as per (Chatterjee and Eliashberg, 1990) the model has certain simplifying assumptions such as ***fixed population size, constant parameters over time and homogenous adoption behaviours***. They say the parameters of the model assumes constant value of p & q and **does not have measurable definition**, while in reality these values could change due to the evolving market conditions. The model does not incorporate external shocks such as economic conditions or cultural shifts which could significantly impact the adoption process. Moreover, the model usually fits the observed diffusion curve well, but it is not as useful for predicting the diffusion of an innovation before or shortly after its launch (Van Den Bulte and Lilien, 1997).

2.4.2 Choice of network diffusion model

To study of diffusion in a network, a mathematical framework is required which best represents these networks as operational models. A model to represent the network of ports and the routes or links connecting them to neighbouring ports to study how independent preferences interact and aggregate within the network. The spread of diffusion of innovation of a new technology is represented when a port becomes an active node or inactive node in a network. The strength of influence between the neighbouring ports decides, whether or not a port gets active or not (Kumar et al., 2020).

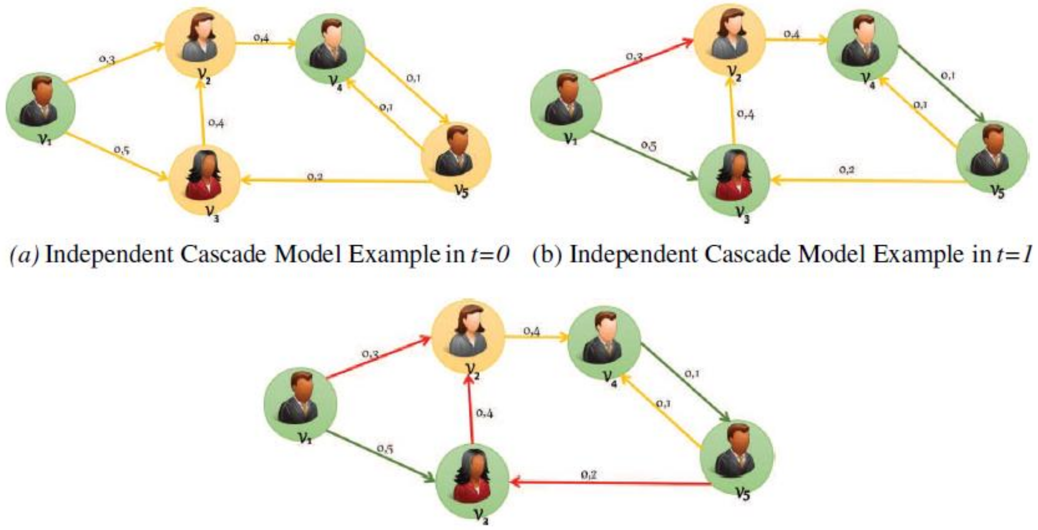
The ports in the networks are assumed to be rational (i.e.) they have their own business strategy, goals and preferences. Their perception of their situations is acted upon to reach their maximum utility of the port. Hence, individual preferences of each port in the network are the main focus of the model. Each port has a specific pre-requisite for establishing a green corridor. The crucial concept of describing these pre-requisites among the ports in the network is studied under the concept of **"threshold"** (Granovetter, 1978). This type of study on threshold is best represented by Independent Cascade model and Linear threshold model. These two models are the most basic and well-studied diffusion models. To study the maximizing influence in a network, one needs to infer the influence function from the observed data. But if the data is not available, the most common approach is to estimate the parameters of that particular diffusion model that is in use. However, it remains difficult to decide the choice of diffusion model which fits best for the research (He and Kempe, 2016)

After considering the above shortcoming of the bass model, ***the concept of threshold model was the preferred model which best fits this study.*** This research is based on a probability study which uses certain assumptions (based on initial R&D, rate of increase and threshold values) and scenarios (one without an active node, and another with an active node) to study the relation between the ports and the routes connecting them for a faster adoption of a new technology which would diffuse the entire network. The concept of IC is explained next.

2. Independent Cascade Model (IC)

The Independent Cascade model is used to simulate the diffusion of influence, information or a behaviour within a network. In this model, nodes represent entities or individuals and edges represent the relationship between them. The process starts with a subset of nodes being initially active (ie) it refers to a predefined group of nodes within a network that are set to be in an active state of beginning of the influence propagation process (Kumar et al., 2020).

The progression occurs in distinct stages. At the outset of the IC process, a few nodes are designated as starting points, referred to as seed nodes. Once these nodes receive the information, they become active. In each discrete stage, an active node attempts to influence one of its inactive neighbors. If successful, that particular node won't have another opportunity to activate the same inactive neighbor. The outcome is determined by the propagation probability of the connection between them. Propagation Probability signifies the likelihood of one node influencing another. In practical scenarios, this probability varies based on the relationship, meaning each connection could have a distinct value. Nonetheless, for experimental purposes, it's often assumed to be uniform across all connections.



(*a*) Independent Cascade Model Example in *t=0* (b) Independent Cascade Model Example in *t=1*

Figure 13 Example of independent case model over time period
Source: (Vianna, 2019)

Figure 13 illustrates an example from (Vianna, 2019) on how the IC (Influence Cascade) model functions using a network as an example. This network consists of nodes labeled as v1, v2, v3, v4, and v5. Activated nodes are depicted as green circles, while inactivated ones are shown as yellow circles. Pending activation attempts are represented by yellow edges, successful activations are depicted in green, and unsuccessful attempts are in red. The numbers displayed above the edges indicate the probability needed to activate the receiving node.

To begin, a group of active nodes is chosen to kickstart the spreading process. In the provided illustration, this includes nodes v1 and v4 (depicted in Figure). Moving forward in time t2, every active link gets a distinct opportunity to activate its neighboring nodes through a Bernoulli test. V1 was successful in activation v3 but fails to activate v2, while v4 successes in activating v5. At the end of each process, the nodes v1, v2, v4 and v5 will be active, so that v3 and v4 have been activated by diffusion of influence.

In both IC & Linear Threshold (LT) models, the information diffusion occurs by the activation of nodes in discrete steps, with the difference that in ***IC model, the activation is done in a single chance***. Whereas in LT model, the activation is done according to the degree of influence that a certain node receives from its neighbours (Kundu, 2013). Hence, considering the influence of all the ports in a network for the adoption of new technology, **the linear threshold model was chosen to be ideal**. It is explained briefly in chapter 3.3.

3 Chapter - Research Methodology

In this chapter, the methodology used to develop a simple network model for studying the technology diffusion process within a network using a probability function will be discussed. Firstly, a simple network that replicates shipping ports was constructed. The model was used to study, how the technology diffuses through the network. The initial parameters and assumptions used in building the network model will be explained. Followed by the measures of those parameters which could influence the network to diffuse faster. Finally, a simple methodology to validate the network model dynamics was outlined.

3.1 Setting up the network model

A network is a collection of interconnected elements, nodes, or other entities that communicate and interact with one another. The idea of a network revolves on the links that exist between different parts, allowing the flow of data or information.

A network is a collection of connected nodes or vertices and they are drawn as points. The connection between the nodes is called edges, and they are drawn as lines between these nodes. Each node can be interpreted as a person, company or any component in a system. Each edge can be interpreted as a relation that connects two nodes together as shown in the figure 14.

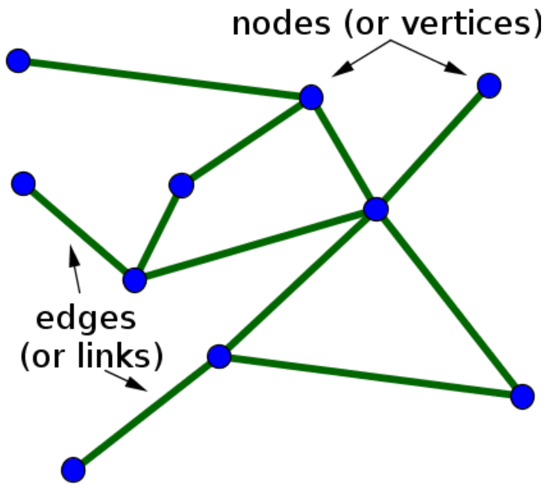


Figure 14 Diagram of a network
Source: (Nykamp, n.d.)

A network can be represented in any systems in the world. It could be presented in business case studies, social study, corporate study, relationship study, etc. An example could be internet is a network, the nodes are the mobile phones, laptops or the computers, and the edges are the wireless connection between the devices which enables the internet. In business case studies, it could enable companies to take measured decisions and strategies that can tackle different issues (Landherr, 2010).

An edge of an ordered pair of nodes represents a possible direction of flow. If the flow through an edge is allowed in only one direction, that edge has a directed arc, if not undirected arc. A network that has only directed arcs is called *directed network*. If all is arcs are undirected, it is an *undirected network* as shown in the figure 15.

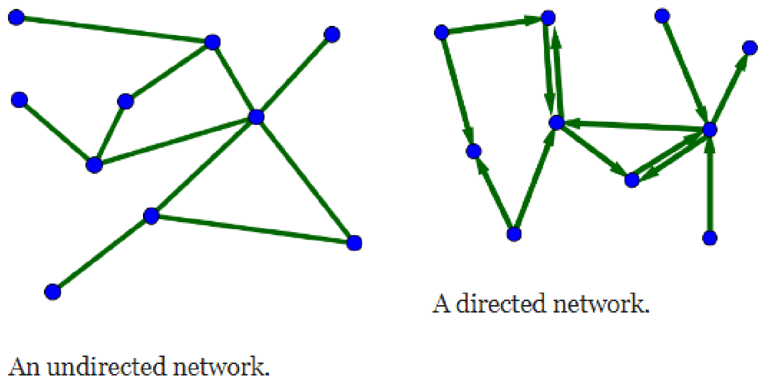


Figure 15 Types of networks
Source: (Nykamp, n.d.)

According to the network theory in (Das et al., 2018), a flow of information in a network would follow *a path, a walk, a trail or a geodesic*. A path is a flow of information from node A to B through a set of nodes without repeating any node, which means a path will not have repeated edges. A trail is a flow of information from node A to B through a set of nodes that may contain repeated nodes but no edges repeated. A walk is a set of nodes that may contain repeated nodes and edges. Finally, geodesic refers to the shortest path (Borgatti, 2005)

A network can be classified as a random or a scale free network. The feature of a ***random network*** is, connection between nodes is formed randomly. This means, each potential edge between pair of nodes has equal probability of being present or absent. Despite the random placement of the edges, most nodes have approximately same number of edges (Barabasi and Bonabeau, 2003), the edges of the nodes in the network would follow a poison distribution with a bell shape like shown in the figure 16. Whereas in the case of scale free network, the degree of the nodes follow a power law distribution (ie) few node will have high degree presence, while few others will have low degree presence. In summary, the key difference between both the network lies in their degree distribution. The degree measure of a node is an important factor which influences the diffusion process to a great extent. Random networks have relatively uniform degree distribution, and scale free networks have a highly skewed degree distribution.

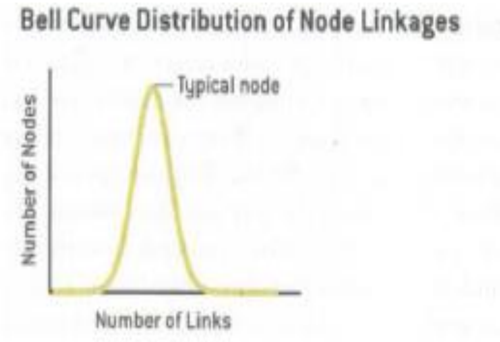


Figure 16 Bell curve distribution of node linkages
Source: (Luo et al., 2018)

To develop a simple network model, certain reasonable estimations of the network involving the number of nodes. In this case, these nodes are a representation of the ports in the world. There are so many ports and it's impossible to simulate the model for every port. Hence, this network model has **5 nodes** that represents those ports. Figure 17 shows the diagram of the simple network model which was constructed for this research. This model was developed to represent the reality of green corridors between ports. The model will be used to analyze, how an activation of certain nodes having a green corridor with a preferential link which will accelerate the diffusion process within a network. Another estimation of choosing a parameter to study the network. As seen from Chapter 2, there are many parameters required for a port to reach a level of technology adoption of green fuel to establish a green corridor for that port. However, the model will get complex if multiple parameters are used which would make it difficult to analyze the study pattern. Hence, this model considered a parameter - Research & Development (R&D) of a port to study the diffusion process within a network.

Task: How quickly would a network with a given probability of P1(R&D) converge to activate each node over a time interval?

Assumptions taken: A single node can extend an arc only to adjacent nodes. The arcs cannot intersect, they can only be parallel lines as shown in the figure 17.

Parameters considered: (R&D)

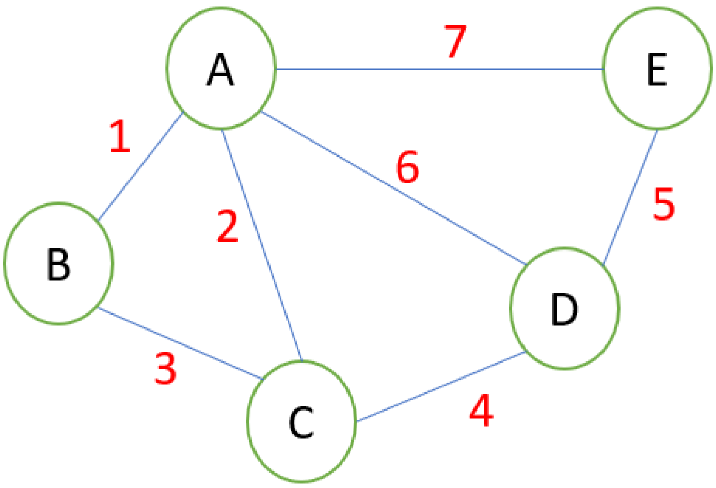


Figure 17 Simple network diagram made by author

Table 5 Simplified network model

Simplified network model	
Size	5 Nodes + 7 edges
Model	Linear threshold model
Type of network	Directed network
Structure of network	Random network

3.2 Centrality Measures

A centrality measure is a quantitative metric which is used in the network theory to ascertain the importance of a nodes within a network. The measure provides information about the relative influence, connectivity, control based on the position and interactions within a network (Bloch et al., 2023). It's a measure to help identify nodes that play a vital role in the information flow to understand the dynamics of the network. A centrality can be calculated in numerous ways which depends on the objectives of the research.

3.2.1 Degree centrality

It is one of the simplest and highly effective measures of centrality based on the number of connections attached to a node. A node with a high degree centrality is more connected with other nodes. From the table 6, the degree centrality is calculated for this network.

Table 6 Connection of nodes

Nodes	Number of arcs attached to node
A	4
B	2
C	3
D	3
E	2

To calculate the degree centrality = $\frac{Number\ of\ arcs\ attached\ to\ a\ node}{(n-1)}$

Where, 'n' is the total number of nodes (n=5)

Table 7 Degree centrality of the nodes

Nodes	Degree centrality
A	1
B	0.5
C	0.75
D	0.75
E	0.5

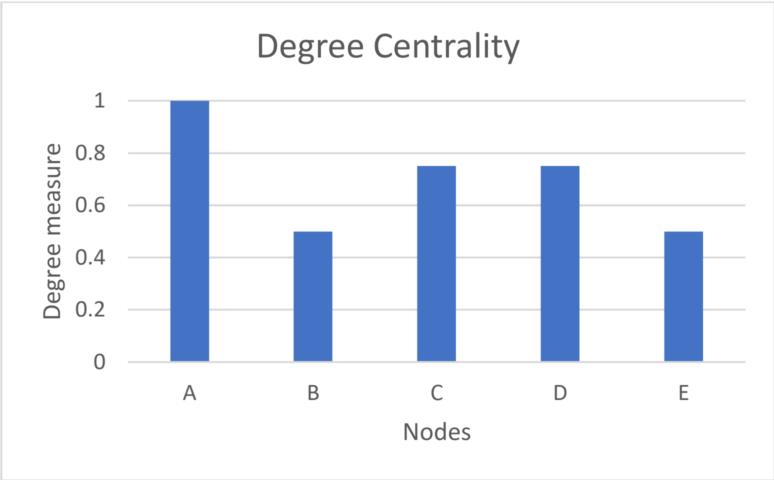


Figure 18 Degree centrality of the nodes by author

From figure 18, node A has the higher degree measure such as 1, it's because it has the highest number of arcs (4 arcs) connected to it. Likewise, nodes B & D has least arcs (2 arcs) connected to them, with a degree centrality measure of 0.5

3.2.2 Closeness centrality

Closeness centrality measures how fast a node can reach all other nodes in the network. The nodes with high closeness centrality are more central in terms of communication efficiency and can spread rapidly with the network. To work this out, we need a measure distance between the nodes to calculate the closeness. Figure 18 shows the simple network diagram used to study closeness centrality.

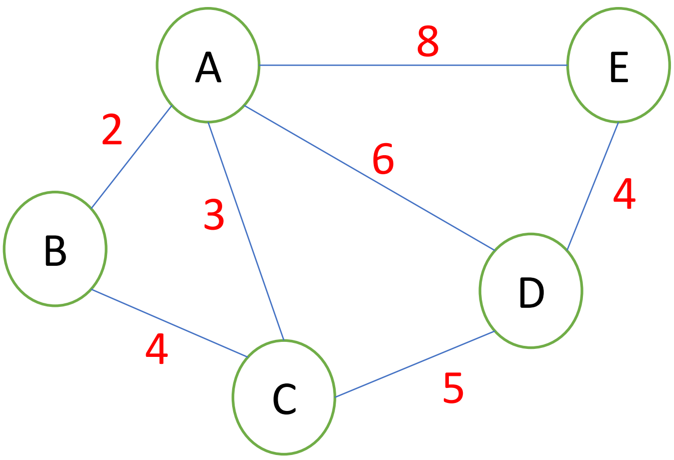


Figure 19 Network of closeness centrality by Author

For transfer from Node A to B, the following options are possible: -

1. A – B [=2]
2. A – C – B [3 + 4 = 7]
3. A – D – C – B [6 + 5 + 4 = 15]
4. A – E – D – C – B [8 + 4 + 5 + 4 = 21]

However, the fastest route is option 1.

For transfer from Node B to D, the following options are possible: -

1. B-C-D [4+5 = 9]
2. B-A-D [2 + 6 = 8]
3. B-A-C-D [2+3+5 = 10]
4. B-A-E-D [2+8+4 = 14]

In this case, option 2 is the fastest.

To calculate the closeness centrality, closeness (v) = $\frac{1}{\sum_{i=1,i\neq v}^{n} d(v,i)}$

The equation sums up all the distances of node v, $d(v,i)$ refers to the number of distance of 1 from the node v to the node i. Centrality must be standardized by diving the maximum possible value of 1 / (n-1). Using these formulae, the closeness centrality for this network was calculated with the assumed distances between the nodes.

Table 8 Closeness centrality measure for the network

Measure of closeness between the nodes						Closeness centrality (CC)
	A	**B**	**C**	**D**	**E**	
A	0	2	5	3	5	0.26
B	2	0	4	5	9	0.20
C	5	4	0	3	5	0.23
D	3	5	3	0	2	0.30
E	5	9	5	2	0	0.19

From the table 8, node D has the highest measure, which means it is on average closest to all other nodes followed by node A. Node E and node B is averaged farthest from all other nodes based on the input distance values given between the nodes. An important inference to make for closeness centrality is that, the number of edges connected to a node does not matter influence the closeness unlike the degree centrality.

3.2.3 Entropy measures

Entropy is a measure to quantify the amount of randomness, uncertainty or complexity of a networks structure. It provides insights into the level of disorder or diversity within a system. The basic idea is to find those nodes that produce the largest changes in the connectivity and or centrality when removed from the network. The two derived entropy equations are *centrality entropy* and *connectivity entropy* measure.

(Daniel, 2008) has developed a method to calculate the measure of connectivity entropy of node v.

$$X(v) = \frac{\deg(vi)}{2N}$$

Where, deg (vi) refers to the number of edges attached to node vi and 'N' refers to the total number of nodes in the network. An example to calculate the measure of connectivity for node A, $X(A) = \frac{4}{2*5} = 0.40$

Table 9 Entropy measure of the network

Nodes	Arcs attached to a node	2N	X(N)
X(A)	4	10	0.40
X(B)	2	10	0.20
X(C)	3	10	0.30
X(D)	3	10	0.30
X(E)	2	10	0.20

Table 9 shows the calculation of the measure of connectivity of each node. Below equation explains the measure of connectivity measure of node v.

$$H_{co}(G) = -\sum_{i=0}^{n} X(v_i) * Log_2 X(v_i)$$

Where, paths(vi) are number of edges from vi to all other nodes and 'N' refers to total number of nodes in the network. Table 9 shows the connectivity entropy as mentioned below.

Table 10 Connectivity entropy

	X(vi)	Base	Log2 X(vi)	H Co(G)
X(A)	0.40	2	-1.3219	0.53
X(B)	0.20	2	-2.3219	0.46
X(C)	0.30	2	-1.737	0.52
X(D)	0.30	2	-1.737	0.52
X(E)	0.20	2	-2.3219	0.46
			Total	2.50

Table 10 shows entropy measure H Co(G) determines the degree of connection of a node within the network. In other words, removal of a single node will decrease in the total entropy of the network. Node A is the highest and hence the most influential node, followed by nodes C & D with 0.52

(Daniel, 2008) has developed a method to calculate the measure of centrality entropy of node v.

The formula to measure the centrality probability of node v is stated below :-

$$Y(v) = \frac{paths(v_i)}{paths(v_1, v_2, v_3 \dots v_m)}$$

Where paths(vi) is number of edges from vi to all other nodes, and paths (v1,v2,v3.. vn) refers to the all paths exist in the network.

Table 11 Entropy measure 2 of the network

Nodes	Paths(vi)	Paths (v1..vn)	Y(vi)
X(A)	4	7	0.57
X(B)	2	7	0.28
X(C)	3	7	0.42
X(D)	3	7	0.42
X(E)	2	7	0.28

Table 11 shows the calculation of the measure of centrality entropy of each node. Below equation explains the measure of connectivity measure of node v.

$$H_{ce}(G) = -\sum_{i=0}^{n} Y(v_i) * Log_2 Y(v_i)$$

Table 12 Centrality entropy

	Y(vi)	Base	Log2 Y(vi)	H Ce(G)
X(A)	0.57	2	-0.81	0.46
X(B)	0.28	2	-1.81	0.52
X(C)	0.42	2	-1.22	0.52
X(D)	0.42	2	-1.22	0.52
X(E)	0.28	2	-1.81	0.52
			Total average	2.54

Table 12 shows entropy measure H Ce(G) determines the degree of centrality of a node within the network. In other words, removal of a single node will decrease in the total entropy of the network. Node A is the lowest and hence the least affected node, followed by other nodes at 0.52. The node that drastically reduces the number of viable paths to reach other nodes when removed will have a higher impact on the total centrality entropy within the network.

From calculating the entropy measures, it is easy to identify the redundant nodes in the network. The following inferences was made based on the measures of centrality in the network mode.

Table 13 Result of parameters of centrality

Parameters of centrality	Results
Degree	Node A
Closeness	Node D (Based on distances in the network).
Entropy	Node A

3.3 Concept of linear threshold model

The Linear Threshold Model (LTM) - LT focuses on the concept of thresholds, where each node (in this case, ports, shipping companies or stakeholders) has a certain threshold value that represents the minimum level of influence required from its neighbours to adopt a specific behaviour or idea. Each node can be in one 2 stages: either the node is *activated or not activated*. Every activated node can influence its neighbours and help in their activation too, formally called as cascade effect.

Each node will have a threshold value for it to get activated, which is represented by Ɵ. For a node to achieve its threshold, it will happen when the *sum of the incoming neighbouring weights is greater than or equal to the defined threshold value.* To formulate it in the form of function, it is $\theta_i <= \alpha_{ij} + \alpha_{ik}$, where node i will get activated if the incoming weight from its neighbouring nodes of j and k are higher than the threshold value of Ɵi.

Consider an example from (Vianna, 2019) a network of 5 nodes namely v1, v2, v3, v4 and v5. If the node is green, it means the node is activated and if its yellow, it means it is not activated. For the edges, yellow edge means it is still pending activation attempts, green edge represents its successful in activation and red edge means failure. The figure 20 below starts with node V1 and V5 activated at time t=0.

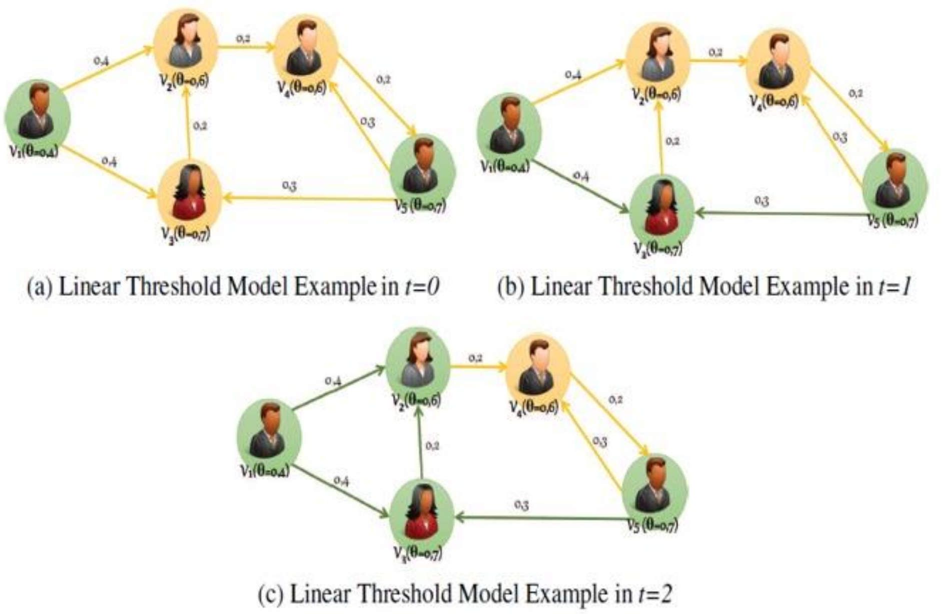


Figure 20 Example of a Linear threshold model
Source: (Vianna, 2019)

At t=0, node v1, v5 is already activated. When t=1, we see that the threshold value of node v3 is 0.7 and the incoming weights from its neighbours is 0.4 and 0.3 respectively from nodes 1 and 5, which is equal to the threshold value and thereby activating node 3. As we can see, the arcs from 1 and 5 going to v3 is yellow and changed to green in t=2, which is exactly where the transmission has happened. At t=2, we can see that node v2 is also activated as the sum of incoming weights of its neighbour nodes from 1 and 3 are equal to its threshold which is enough for its activation and thereby the network is getting diffused.

3.4 Model validation algorithm

The construction of the model has been explained from section 3.1 – 3.4. In this section, we present how to simulate the model to get inferences and see how long it takes for the technology to get diffused. By using this model, we aim to understand the concepts explained in chapter 2, and how a technology diffusion happens through a network based on the parameters set up in the model.

LTM with 5 nodes and 7 edges are constructed within this network. The condition for each of the nodes to get activated are based on their connections with the neighbouring nodes are discussed in the table 14. Figure 21 shows the simple model of a network.

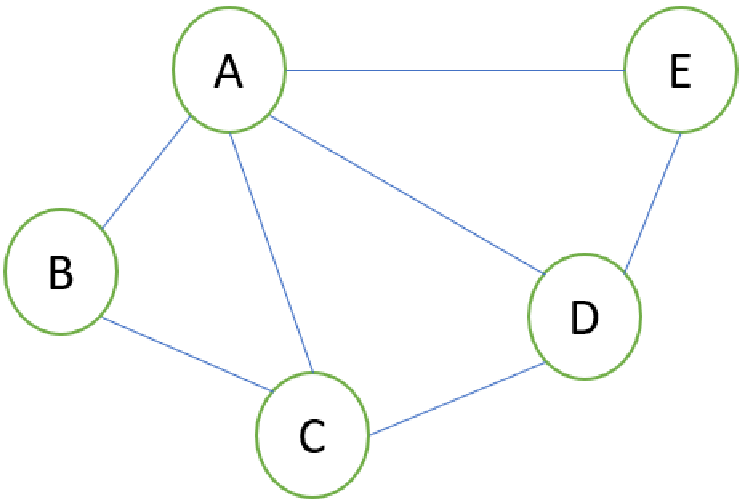


Figure 21 Simple network model by author

Table 14 Model validation algorithm by author

Nodes	Adjacent nodes	Incoming arcs from the adjacent nodes	Threshold value for the node
ϴA	B&C	ba+ca	ϴA < α ba+ α ca
	B&E	ba+ea	ϴA < α ba+ α ea
	B&D	ba+da	ϴA < α ba+ α da
	C&E	ca+ea	ϴA < α ca+ α ea
	C&D	ca+da	ϴA < α ca+ α da

	D&E	da+ea	ϴA > α da+ α ea
ϴB	A&C	ab+cb	ϴA < α ab+ α cb
ϴC	B&A	bc+ac	ϴA < α bc+ α ac
	A&D	ac+dc	ϴA < α ac+ α dc
	B&D	bc+dc	ϴA < α bc+ α dc
ϴD	C&E	cd+ed	ϴA < α cd+ α ed
	C&A	cd+ad	ϴA < α cd+ α ad
	A&E	ad+ed	ϴA < α ad+ α ed
ϴE	A&D	ae+de	ϴA < α ae+ α de

3.4.1 Assigning the base probability

Next step is to establish a probability (P1) in Research & Development (R&D) for all the nodes at a time interval in the network. The base probability values (P1) of R&D of the all the nodes are taken proportional to the number of arcs it is connected. However, 2 small changes in the assumptions were taken to have some dynamics in the network. The P1(C)=0.2, though it has 3 arcs connecting to it. And P1(E) = 0.1, though it has 2 arcs connecting to it. Table 15 shows the base probability of all the nodes.

Table 15 Base probability of the network

Node	**P1**(R&D)
A	0.4
B	0.2
C	0.2
D	0.3
E	0.1

3.4.2 Assigning the rate of change of probability over a time t.

After setting up the initial base probabilities of R & D for each node over time t period. P1 of R&D will be increased by 20% (0.20) over the next time t period.

These values increase proportionally based on their initial base probabilities are shown in the table 16.

Table 16 Rate of change of probability over a time t

	t1	t2	t3	t4	t5
Nodes	**P1**	**P1**	**P1**	**P1**	**P1**
P1(A)	0.4	0.48	0.57	0.69	0.82
P1(B)	0.2	0.24	0.28	0.34	0.41
P1(C)	0.2	0.24	0.28	0.34	0.41
P1(D)	0.3	0.36	0.43	0.51	0.62
P1(E)	0.1	0.12	0.14	0.17	0.20

3.4.3 Assigning the base probabilities for all the arcs in the network

After completing both the steps, the probabilities for the arcs are calculated. The probabilities of these arcs are an important measure to identify the weight of the incoming arcs from the adjacent nodes. These values determines if a node gets activated or not. Table 17 shows all the arcs with the base probabilities over a time t.

Table 17 Base probabilities for all the arcs in the network

Arcs	t1	t2	t3	t4	t5
P(AB/BA)	0.08	0.12	0.17	0.24	0.34
P(AC/CA)	0.08	0.12	0.17	0.24	0.34
P(AD/DA)	0.12	0.17	0.25	0.36	0.52
P(AE/EA)	0.04	0.06	0.08	0.12	0.17
P(BC/CB)	0.04	0.06	0.08	0.12	0.17
P(CD/DC)	0.06	0.09	0.12	0.18	0.26
P(DE/ED)	0.03	0.04	0.06	0.09	0.13

3.4.4 Probability of the network

Next step is to find the base probabilities for each node with respect to every incoming weight from their neighbour nodes. The probability of each node was considered to be mutually exclusive. These values are then checked if they reached the threshold value. Table 18 shows the probability for all the nodes and their arcs from the neighbour nodes from time t1 to t4.

Table 18 Probability of the network

Nodes	Adjacent nodes	Incoming arcs	P1(t1)	P1(t2)	P1(t3)	P1(t4)
ϴA	B&C	ba+ca	0.16	0.23	0.33	0.48
	B&E	ba+ea	0.12	0.17	0.25	0.36
	B&D	ba+da	0.2	0.29	0.41	0.60
	C&E	ca+ea	0.12	0.17	0.25	0.36
	C&D	ca+da	0.2	0.29	0.41	0.60
	D&E	da+ea	0.16	0.23	0.33	0.48
ϴB	A&C	ab+cb	0.12	0.17	0.25	0.36
ϴC	B&A	bc+ac	0.12	0.17	0.25	0.36
	A&D	ac+dc	0.14	0.20	0.29	0.42
	B&D	bc+dc	0.1	0.14	0.21	0.30
ϴD	C&E	cd+ed	0.09	0.13	0.19	0.27
	C&A	cd+ad	0.18	0.26	0.37	0.54
	A&E	ad+ed	0.15	0.22	0.31	0.45
ϴE	A&D	ae+de	0.07	0.10	0.15	0.21

3.4.5 Validation of the threshold condition in the network

The final stage of the model is to check if the condition of the threshold model is satisfied. The probability of the network from section 3.4.4 was computed for all the arcs present in the network. If the threshold value is achieved between an arc, then a green corridor can be established between the 2 nodes in that arc.

For example, node A has 3 arcs with respect to node B (B&C, B&E & B&D), likewise node B has only 1 arc with respect to node A (A&C). At least one condition of threshold value should be achieved with respect to both the nodes. Even ***if one of the conditions*** (that is one arc from A & one arc from B should achieve the threshold value) for a green corridor to be established between them. Table 19 shows the threshold values to activate the node.

Table 19 Threshold values of the nodes to activate

Nodes	Threshold values to activate
ΘA, ΘB, ΘC, ΘD, ΘE	0.5

Table 20 Validation of the threshold condition in the network

Nodes	Adjacent nodes	Incoming arcs from the nodes	Condition for threshold value	Weight of incoming arcs at t=1	Arcs (A-B), (A-C), (A-D), (A-E), (B-C), (C-D), (D-E)
ΘA	B&C	ba+ca	$\Theta A < \alpha ba + \alpha ca$	0.16	Node A with respect to other nodes are not activated as the threshold value is not met.
	B&E	ba+ea	$\Theta A < \alpha ba + \alpha ea$	0.12	
	B&D	ba+da	$\Theta A < \alpha ba + \alpha da$	0.2	
	C&E	ca+ea	$\Theta A < \alpha ca + \alpha ea$	0.12	
	C&D	ca+da	$\Theta A < \alpha ca + \alpha da$	0.2	
	D&E	da+ea	$\Theta A > \alpha da + \alpha ea$	0.16	
ΘB	A&C	ab+cb	$\Theta A < \alpha ab + \alpha cb$	0.12	B Not activated.
ΘC	B&A	bc+ac	$\Theta A < \alpha bc + \alpha ac$	0.12	C Not activated.
	A&D	ac+dc	$\Theta A < \alpha ac + \alpha dc$	0.14	
	B&D	bc+dc	$\Theta A < \alpha bc + \alpha dc$	0.1	
ΘD	C&E	cd+ed	$\Theta A < \alpha cd + \alpha ed$	0.09	D Not activated.
	C&A	cd+ad	$\Theta A < \alpha cd + \alpha ad$	0.18	
	A&E	ad+ed	$\Theta A < \alpha ad + \alpha ed$	0.15	
ΘE	A&D	ae+de	$\Theta A < \alpha ae + \alpha de$	0.07	E Not activated.

From table 20, the condition is not satisfied as per the LT Model and none of the arcs got activated at t1. Hence, for time t=2, the base P1(t2) will increase by 20%

in base probabilities for of all the nodes as shown in the section 3.4.2. The P1 of nodes will be proportionally increasing with time t until all the arcs get adopted.

Here is an example (figure 22) of how the network propagation happens at t1 interval. As none of the arcs is activated, the P1(t2) increases by 20% and checks for the same condition if the arcs are adopted.

Index				P1(t1)	A-B	A-C	A-D	A-E	B-C	C-D	D-E
A	ΘA	B&C	ba+ca	0.16							
A		B&E	ba+ea	0.12							
A		B&D	ba+da	0.2							
A		C&E	ca+ea	0.12							
A		C&D	ca+da	0.2							
A		D&E	da+ea	0.16	NOT ACTIVE	NOT ACTIVE	NOT ACTIVE	NOT ACTIVE	NOT ACTIVE	NOT ACTIVE	NOT ACTIVE
B	ΘB	A&C	ab+cb	0.12							
C	ΘC	B&A	bc+ac	0.12							
C		A&D	ac+dc	0.14							
C		B&D	bc+dc	0.1							
D	ΘD	C&E	cd+ed	0.09							
D		C&A	cd+ad	0.18							
D		A&E	ad+ed	0.15							
E	ΘE	A&D	ae+de	0.07							

Figure 22 Example of the result of the model validation

Formula

=IF(AND(OR(E40>=$D$32;E41>=$D$32;E42>=$D$32);E46>=$D$33);"ACTIVE";" NOT ACTIVE")

4 Chapter - Results and Analysis

In this chapter, the results of the model simulation which were used to study the dynamics between the nodes (ports), arcs (green corridor routes) and the influence they have on each other was analysed. The agenda of the model was to check whether, how having a green corridor through a preferential link would accelerate the adoption of new technology throughout the network.

To integrate alternative fuels effectively into green corridors, several crucial factors must align. This includes not only increasing the availability of these fuels but also ensuring that ships are equipped and prepared to utilize them onboard. Moreover, ports need to be adequately equipped to manage, supply, and accommodate ships operating on alternative fuels. In section 2.3.2, the importance of fuel specific innovation across value chain was broadly classified into three parts; innovation of fuel production, technology readiness of a port, innovation for ship design, storage, propulsion & emissions.

The network diffusion model was employed to investigate whether a port's readiness for green corridor technologies has the potential to accelerate and facilitate the readiness of other ports within the network. To accelerate the energy transition, it is important for ports to handle/ supply new fuel technology. Since the focus is on ports in this research, one important driver such as R&D with respect to port was used in the network model to study the dynamics of the diffusion process. Different ports will have, different readiness level for different fuels across a region. Figure 23 shows the port readiness level at different stages from 1-9.

A probability network model was constructed with three parameters which influences the driver such as R&D to study the diffusion process of ports readiness level for green corridor. The parameters are as follows: -

1. Initial R&D – The initial R&D talks about the current port readiness level with respect to a fuel technology. Specific readiness level varies with individual port and fuel. If Node A will only plan to be a

port of call for hydrogen, which means it can receive ships sailing on hydrogen and will supply the fuel for bunkering purposes. Hence, it is the existing technological readiness of a port to handle green ships and green fuel. Since it is probability study, the score of the node (port) of TRL refers as the initial R&D.

2. Rate of change of R&D over time t - The rate of change of R&D should be assumed as the increase in investments or specific fuel innovation to handle the supply and demand of a green fuel in the port. The investments can be made on specific fuel production of a green fuel which is in demand in the region, improve the bunker infrastructure to handle ships of specific fuel technology when calling ports. The investments could be increased by 10 or 20% which helps the port to move ahead on the port readiness level rating of a specific fuel technology.
3. Threshold value – The threshold value is the minimum required port readiness level by a port to establish a green corridor with another port. This means, the port has reached its deployment stage of the new fuel technology in the rating which can handle ships for operating in the port, transport the fuel to port efficiently at scale and provide safe bunkering assistance.

To attain a more comprehensive understanding of port readiness within the region. It is advisable for all ports in the area to gauge their current readiness levels and what they anticipate in the future. By elevating this assessment process to a regional level, it would offer an insightful overview of the entire region's preparedness to handle and supply various alternative fuels. This, in turn, could serve as a catalyst for the initiation and acceleration of green corridor projects. Moreover, it would enable other stakeholders to gain clarity regarding the timelines for the adoption of alternative fuels, potentially fostering a sense of urgency in their own decarbonization endeavors.

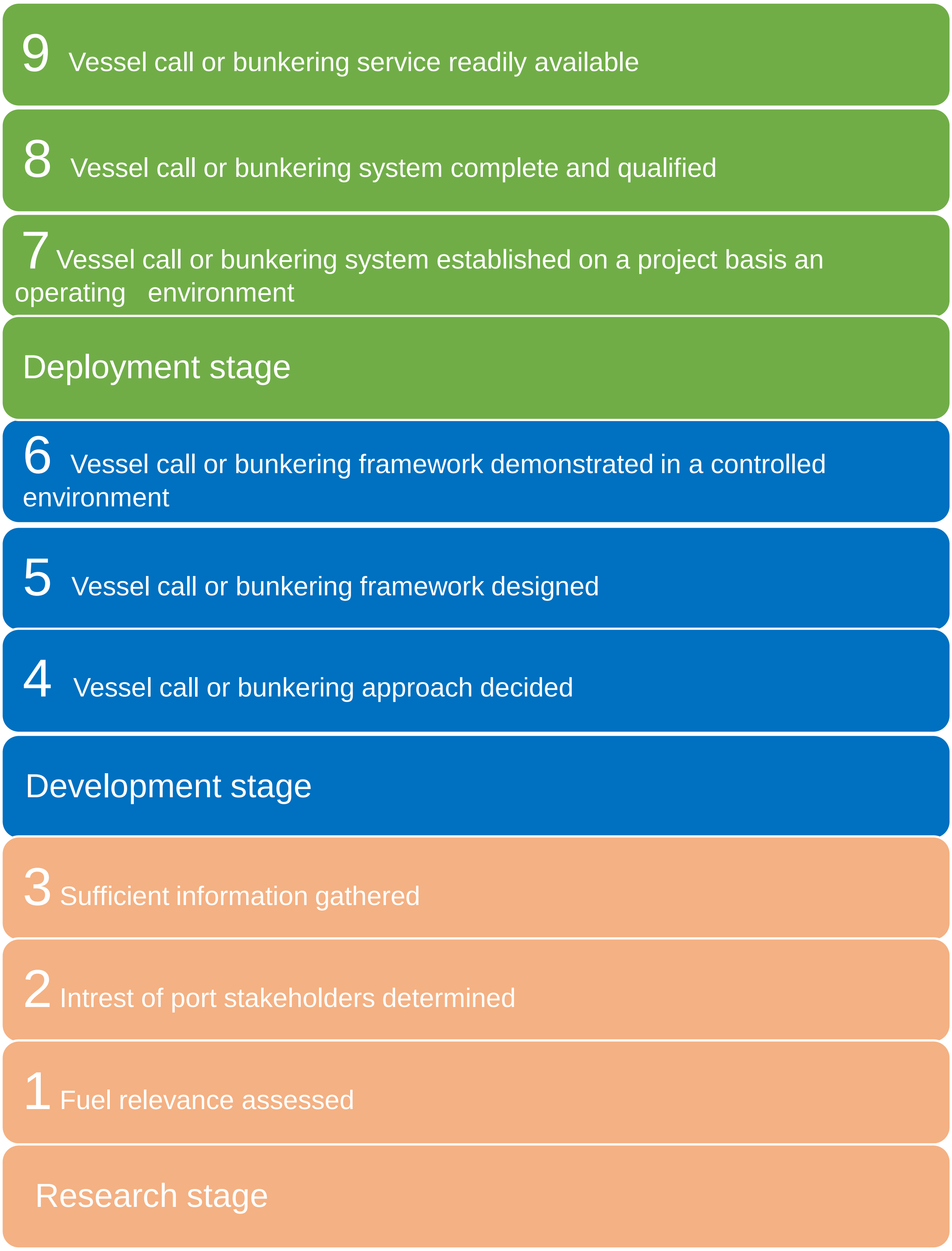


Figure 23 Port readiness level

Source: Adopted from (Maersk - Mc-kinney, 2023)

The model was run in two scenarios in the network and further sensitivity analysis was carried out to check the robustness of the model.

In the first scenario, all the ports in the network were considered to have insufficient TRL for a port to establish a green corridor (i.e.) each port was assigned an initial R&D (current TRL level) lesser than the TV of the port. The rate of change of investment was increased by 20% for every time interval t. The exercise was used to identify, when does all the ports (nodes) in the network will have sufficient TRL (TV) to adopt the green corridor (arcs) at a certain time interval.

4.1 Scenario 1 - Network propagation with inactive nodes at time t1.

In this scenario, we consider the probability P1 - R&D parameter of all the nodes are of the set values, based on their connections with other nodes as explained in chapter 3.5.2 at each time t interval. The rate of adoption of P1 increases by 20% (0.2) for all the base probabilities of each of the nodes over time period 't' until all the arcs get activated. The threshold value for the all nodes is set at 0.5.

Input values

Node	Base (P1)
A	0.4
B	0.2
C	0.2
D	0.3
E	0.1

Figure 24 Input values for scenario 1 by author

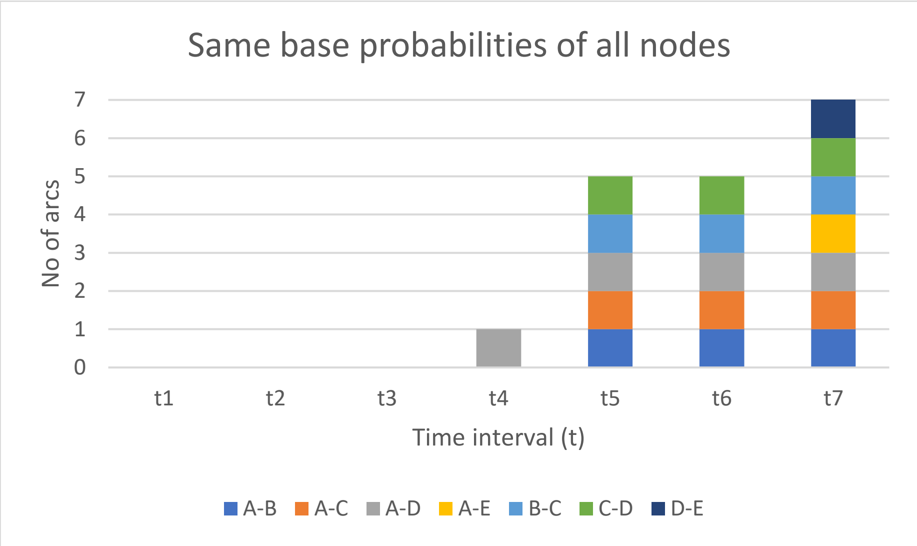


Figure 25 Result for scenario 1 by author

Analysis

From the figure 25, no arcs are adopted until t3, but the first arc to get adopted is A-D. As per the centrality measures in the section 3.2, nodes A & D were proved to be central nodes which are a key parameter for arc A-D to get adopted first. Incidentally, both nodes A & D has the highest base probability such as 0.4 & 0.3 respectively. These 2 reasons led to the arc A-D getting activated first.

At5, 3 out of 4 arcs are connected to node A, and 2 out of 3 arcs are connected to node D which got activated. This proves that central nodes are more effective in helping non central nodes for faster adoption. The arcs which are connected to node E, which is A-E & D-E is the last to get activated at t7. Though node E is connected to central node (A&D), the base probability of node E is the lowest (0.1) which led it to get activated the last at t7.

In other words, the first green corridor to get adopted in the network was between two central ports such as A and D. Incidentally, they have the highest TRL within the network, but still less than the TV of the port. The last green corridors to get adopted are the routes which are connected to port E. They happened to be the last to get adopted as they have the lowest TRL within the network. Even when none of the ports in the network has a TRL above than the TV, it took t7 for the entire network to get adopted with green corridors.

4.2 Scenario 2 - Network propagation with one active node at time t1

In the second scenario, at least one port in the network is assumed to have initial R&D more than the TV of the port. In other words, that one port (node) is considered to be active node, (i.e. port reached the TRL and given highest level of P1(R&D) base probability of 1). The rate of change of investment was increased by 20% for every time interval t. Same exercise is used to identify when does all the ports (nodes) in the network will have sufficient TRL (TV) to adopt the green corridor (arcs) at a certain time interval. The threshold value for the all nodes is set at 0.5. Each node was given a chance to be a source node to study the adoption process of the green corridor and how fast it takes for the entire network to get diffused.

4.2.1 When Node A is source node when base probability of node P1(A)=1

Input values

Node	Base(P1)
A	1
B	0.2
C	0.2
D	0.3
E	0.1

Figure 26 Input value when Node A (source)

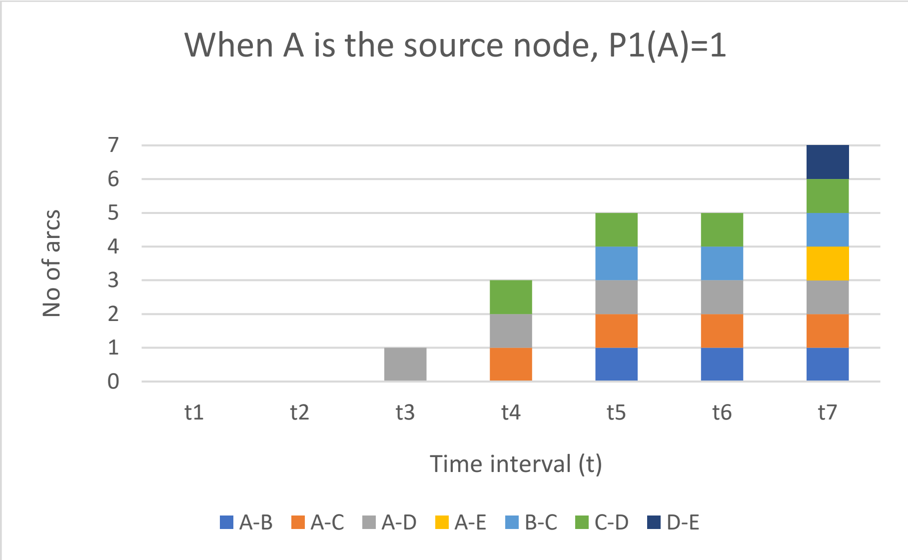


Figure 27 Result when Node A (source) by Author

From figure 27, it was observed that no arcs are adopted until t2, and the first arc to get adopted is A-D at t3. Nodes A & D were proved to be central nodes which are a key parameter to get adopted. At t4, 2 arcs connected to node C such as A-C & C-D gets adopted. Though node B & C had the same base probability, arcs connected to node C has adopted faster. This proves that, having a high base probability alone is not enough, number of arcs connected with a node equally influences the time of adoption. The arcs which are connected to node E, which is A-E & D-E is the last to get activated at t7. Though node E is connected to central node (A&D), the base probability of node E is the lowest (0.1) which led it to get activated the last. The most central node A in this case, has the highest probability of 1, yet there was not adoption of arcs until t3 and it took t7 to activate all the arcs in the network.

4.2.2 When Node B is source node when base probability of node P1(B)=1

Input values

Node	Base(P1)
A	0.4
B	1
C	0.2
D	0.3
E	0.1

Figure 28 Input value when Node B (source)

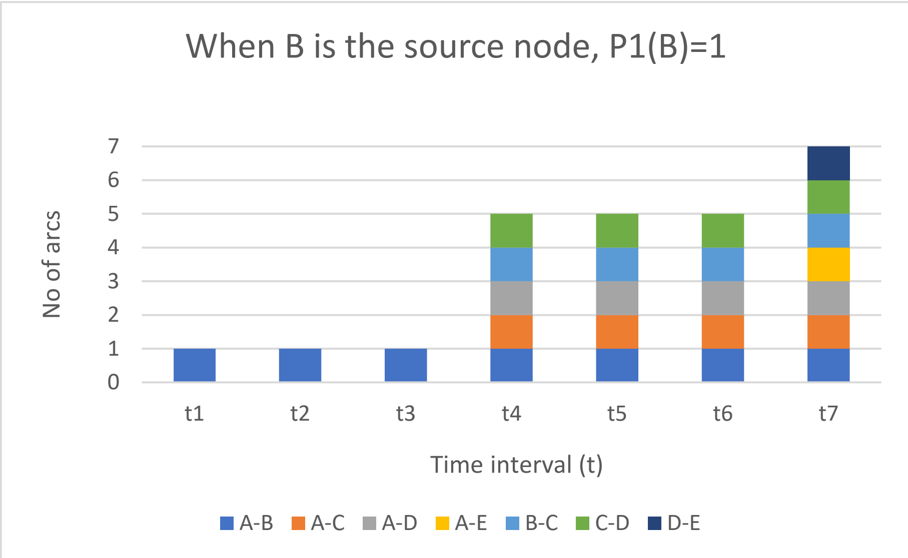


Figure 29 Result when Node B (source)

From the figure 29, it was observed that arc A-B is the only arc adopted at t1, this is because A is a central node & arc that connects to central node has a faster adoption. Except all arcs which are connected to node E, rest gets activated at t4 such as arcs A-C, A-D, B-C, C-D. These arcs remain to be same from time interval t4 to t6. Only at t7, arcs A-E & D-E got activated. It shows the base probability of node E was so low that it had to wait from t4 to get activated at t7. It would have been a faster adoption of all the arcs at t4, provided the node E had a higher base probability.

4.2.3 When Node C is source node when base probability of node P1(C)=1

Input values

Node	Base P1
A	0.4
B	0.2
C	1
D	0.3
E	0.1

Figure 30 Input value when Node C (source)

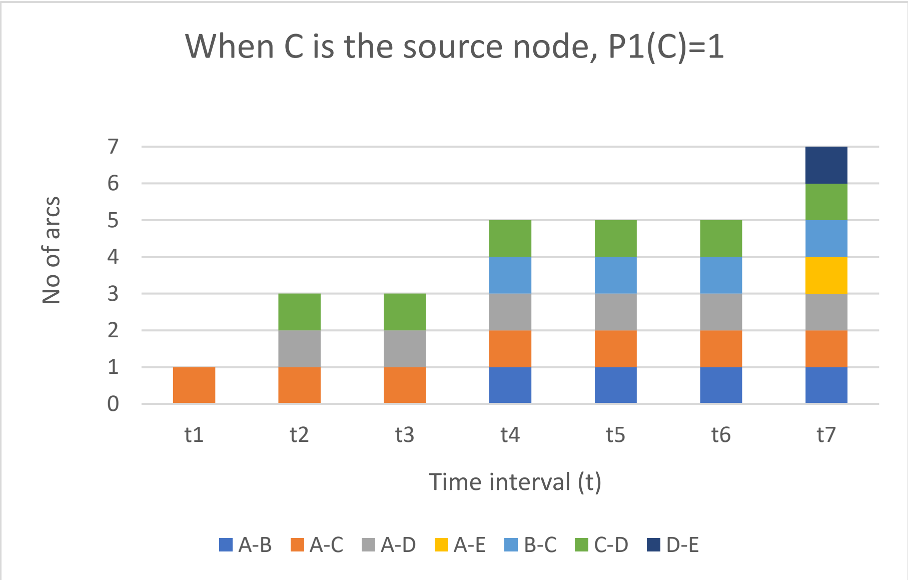


Figure 31 Result when Node C (source)

From figure 31, it was observed that arcs A-C is the only arc adopted at t1, which proved to be arcs connected to central nodes are a key parameter to get faster adoption. At t2, arcs A-D & C-D are adopted, which has 2 arcs from node D (which proves the importance of arcs connected to central nodes). At t4, the arcs connected to node B was activated such as A-B & B-C, this happened to be adopted later than A & D because its base probability is the lowest after node E. These arcs remain to be same for the time interval t4 to t6. Only at t7, arcs A-E & D-E got activated. It shows the base probability of node E was so low that it had to wait from t4 to get it activated. It would have been a faster adoption of all the arcs at t4, provided the node E had a higher base probability.

4.2.4 When Node D is source node when base probability of P1(D)=1

Input values

Node	Base P1
A	0.4
B	0.2
C	0.2
D	1
E	0.1

Figure 32 Input value when Node D (source)

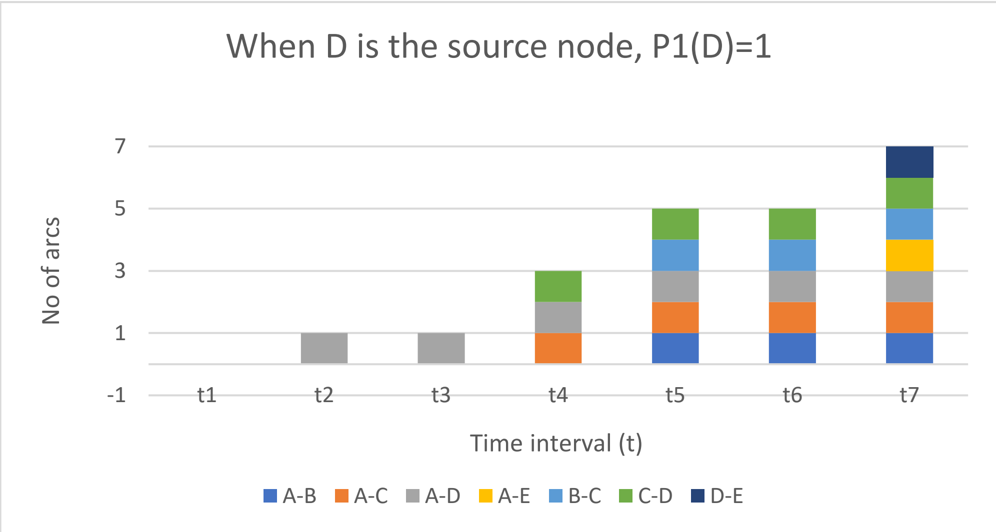


Figure 33 Result when Node D (source)

From figure 33, it was observed that arc A-D is the only arc to get adopted at t2. There are no arcs activated in t1, unlike in the cases of source node when B, C & E respectively were having P1=1. The reason, why it took arc A-D to get adopted only at t2 is because the base probability for other nodes connected was low which deferred its adoption to t2. At t4, the next arcs adopted are from node C such as A-C & C-D which has the next highest base probability after nodes D & A along with more number arcs connected to node C. At t5, the arcs connected to node B was activated such as A-B & B-C, this happened after C as it is the next in line with the base probability. These arcs remain to be same for the time interval t5 to t6. Only at t7, arcs A-E & D-E got activated. It shows the base probability of node E was so low that it had to wait from t4 to get it activated.

4.2.5 When Node E is source node when base probability of P1(E) =1

Input values

Node	Base P1
A	0.4
B	0.2
C	0.2
D	0.3
E	1

Figure 34 Input value when Node E (source)

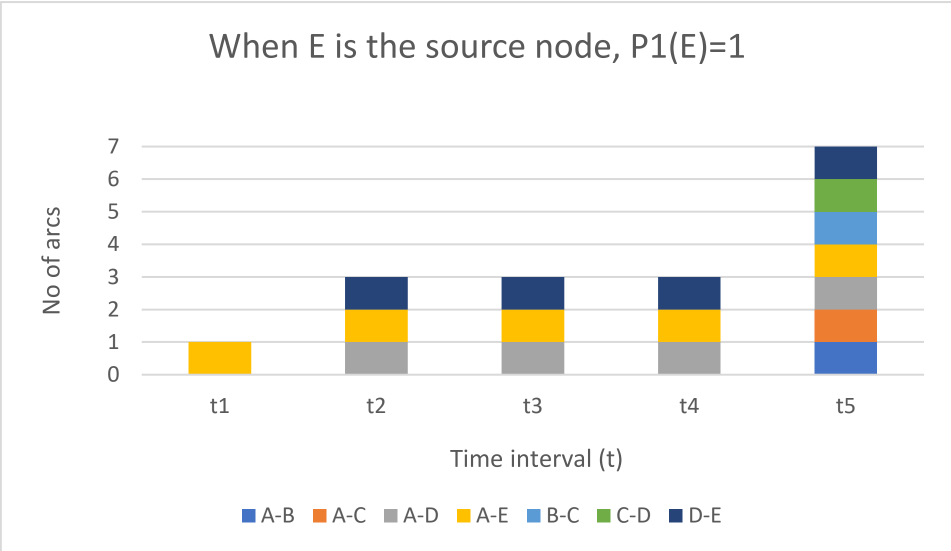


Figure 35 Result when Node E (source)

From figure 35, it was observed that arcs A-E is the only arc adopted at t1, which proved to be arcs connected to central nodes are a key parameter to get faster adoption. In all other cases, arc A-E was the last to get adopted. At t2, the arcs A-D & D-E is adopted, where 2 arcs are coming from node D, this happened due to high base probability after source node E. In all other cases, arc D-E was the last to get adopted. At t5, the pending arcs from node A, node B and node C such as A-B, A-C, B-C, C-D gets adopted at t5. This case happens to be the fastest adoption of all the arcs at time interval t5, whereas in all other cases, it took t7 until all arcs to get adopted. This was due to the fact that, the average base probabilities of all other nodes in this case were the highest, which led to faster adoption, whereas in other cases the base P1 of node E was 0.1 which was the lowest and hence it was the last to get adoption. An important inference from this case is, the diffusion of the entire network happens faster when invested in ports with low R&D when compared to investing in central ports with higher R&D.

In other words, scenario two when the port E was a source node provided a unique finding unlike other four cases. The green corridor routes in the entire network were adopted the fastest at time interval t5 when Port E was the source node. In all other cases, the adoption of entire network happened at time interval t7. The reason being, the TRL of port E was the lowest and least ready to have a green corridor. When it was given a minimum TRL to establish a corridor, the average combined TRL of all other ports in the network were enhanced. Hence the adoption was much faster in this case.

4.3 Sensitivity Analysis

In this section, certain parameters will be changed to check how those inputs affect the results and thereby testing the robustness of the model. The three most important parameters for this network model are the *initial base probabilities* (P1) that are given to the nodes, *the rate of increase for the base probabilities over time interval t* and finally *the threshold value* for the activation of all the nodes. The change in initial base probabilities was executed in scenario 2 under the section 4.2, where each node was a source node and assumed the highest base probability of 1. We will be performing the sensitivity analysis for change in rate of increase in P1, followed by change in threshold values.

4.3.1 Sensitivity with change in Rate of increase of base probability

The base probabilities will be the same as scenario 1 as mentioned in table 14. But the rate of increase for base probabilities will be changed in 3 cases, having the same threshold value of 0.5 for all the nodes. These 3 cases will be analyzed to check the dynamics of the model and infer some important results.

Case 1 – When P1 for node A & D are increased by 20% while other nodes B, C & E are increased by 10%

In case 1, the base probabilities of nodes A & D were made to increase by 20% in each time interval t, and only 10% increased for the rest of the nodes B, C & E. The reason for this is, nodes A & D were proved to be more central nodes with most number of arcs connected to it in the entire network. Hence, it was assumed to be a bigger port with more availability of P1 R&D. Whereas, the non-central nodes were made to increase their base probabilities by 10%.

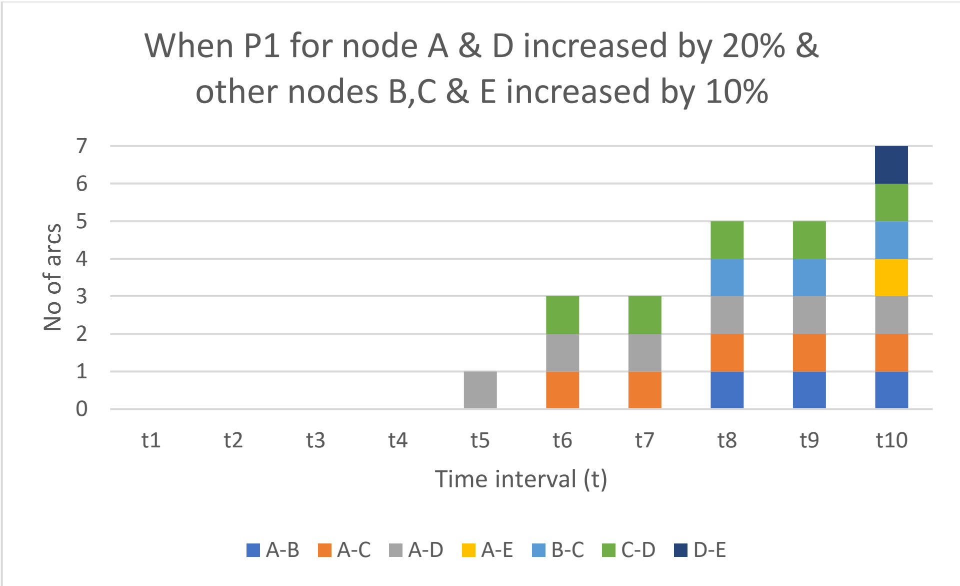


Figure 36 When P1 for node A & D increased by 20% & other node by 10%

Analysis

In figure 36, Arc A-D gets adopted first at t5, as both nodes A & D are central nodes and also the rate of increase of P1 is by 20% when compared to other nodes. This led it to faster adoption of arc A-D. Then, arc A-C gets adopted next at t6, whereas A-B gets adopted only at t8, though both nodes B & C have the same base probability of 0.2. This is because, node C is connected to two central nodes A & D, whereas node B is connected to nodes A & C. The adoption of node B is influenced by node C. Hence, only when node C gets adopted first, it helps in the faster adoption of node B. Though nodes A & D bas increased their P1 by

20%, the adoption of arcs A-E, D-E got adopted only at t10. This is because the base probability of node E is the lowest with lesser connections.

Case 2 – When P1 for node A & D are increased by 10% while other nodes B, C & E are increased by 20%

In case 2, the base probabilities of nodes A & D were made to increase by 10% in each time interval t, and 20% increased for the rest of the nodes B, C & E. This means the non-central nodes are investing more in their R&D when compared to the central nodes over the time interval t.

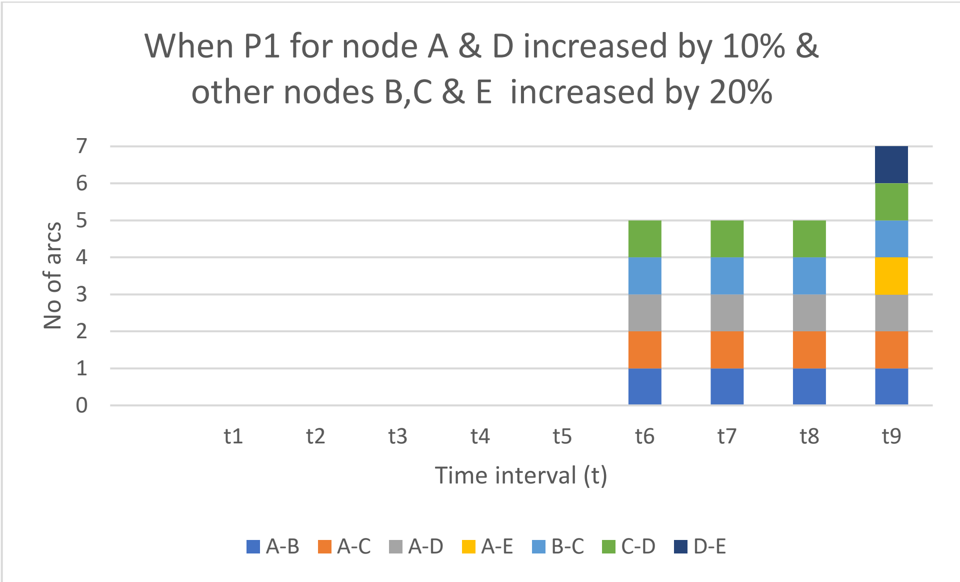


Figure 37 When P1 for node A & D increased by 10% & other nodes by 20%

Analysis

In figure 37, the five arcs such as A-B, A-C, A-D, B-C & C-D get adopted only at t6. Whereas, all these 5 arcs got adopted together at t8 in case 1. 3 out of 4 arcs connected to node A got activated in t6 except arc A-E. Only 2 arcs that are connected to node E such as A-E & D-E are not adopted throughout the time interval t6 to t8. At t9, all the 7 arcs get adopted a time interval earlier than Case 1.

Case 3 – When P1 for node B & E are increased by 20% while other nodes A, C & D are increased by 10%

In case 3, the base probabilities of nodes B & E were made to increase by 20% in each time interval t, and only 10% increased for the rest of the nodes A, C & D. Nodes B & E are the most non central nodes with less arcs connected to them and also happens to have the lowest base probabilities. Whereas, the central nodes were made to increase their base probabilities by 10%.

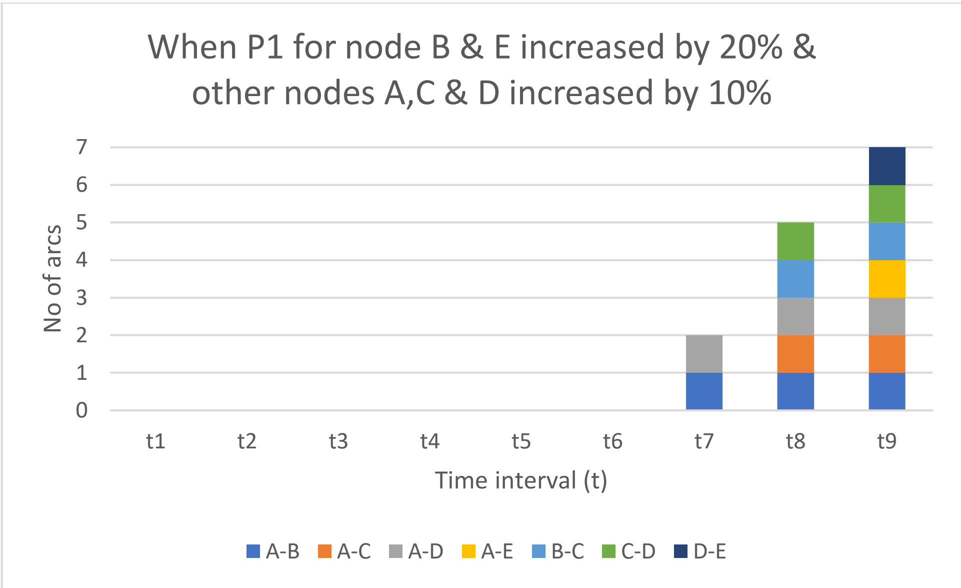


Figure 38 When P1 for node B & E increased by 20% & other node by 10%

Analysis

In figure 38, arcs A-B & A-D gets adopted first at t7. Both these arcs are connected to central node A which helps in faster adoption. Arcs A-B, A-C, A-D, B-C & C-D get adopted only at t8, the adoption has happened late because though they have increased their P1 each year, their initial base probability for node B is 0.2 and E has 0.1. Only 2 arcs that are connected to node E such as A-E & D-E are not adopted throughout the time interval until t8. All the 7 arcs got adopted at t9.

4.3.2 Sensitivity with change in Threshold value.

The base probabilities will be the same as scenario 1 as mentioned in the table 14. The rate of increase for base probabilities will be increased by 20% for all the nodes at every time t interval. But the threshold values (TV) will be changed in 2 cases. The result will be compared and analyzed to study the network.

Case 1-When Threshold value Changes for nodes A & D by '± 20%'

In this case, the TV is changed for the nodes A & D, (ie) the TV will be increased by 20% only for nodes A & D, and subsequently it will be decreased by 20% for the nodes A & D. The result of both the graphs will be analyzed to study the propagation. Nodes A & D were chosen for this case, as they are the most central nodes based on our research in section 3.2.

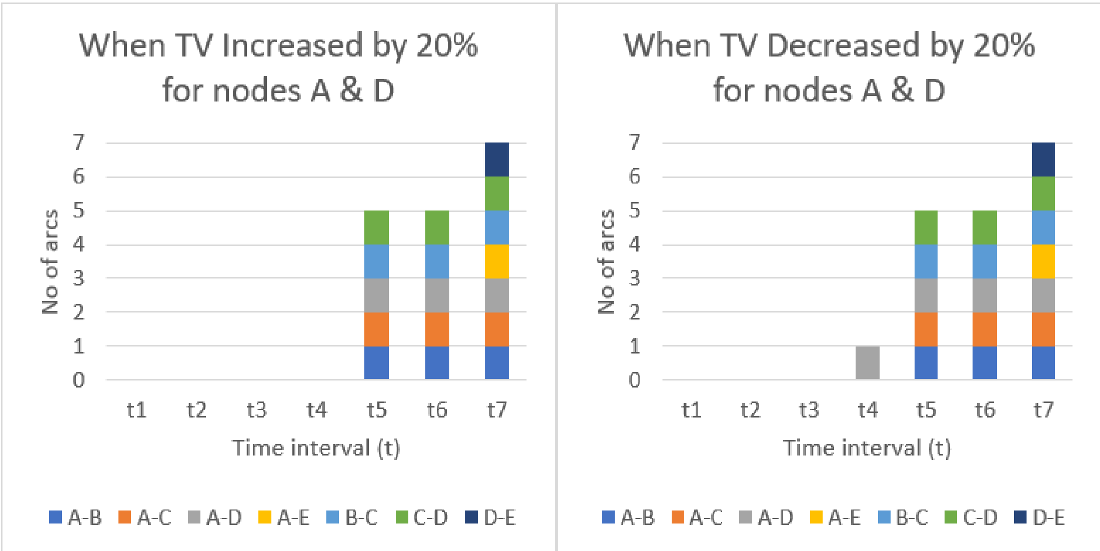


Figure 39 When Threshold value changed by ± 20% for nodes A & D

Figure 39 represents the adoption of arcs when TV is increased or decreased by 20%. In theory, the arcs should get adopted faster when the threshold level for activation is reduced. However, even with the net difference of 40% in threshold values, the adoption rate of all the arcs is similar. The only significant inference is that Arc A-D gets adopted at t4 with TV decreased by 20%. In spite of increasing the TV by 20% on the central nodes A & D, all the arcs gets adopted at t7, which is the same in case of decreasing the TV by 20% on nodes A & D. To conclude, the base probability considered for node A & D was sufficient to compensate for an increase in the TV of those nodes by 40% as no significant changes in the adoption of arcs were observed.

Case2-When Threshold value Changes for nodes B & E by '+ or – 20%'

In this case, the threshold value (TV) was changed for the nodes B & E, (ie) the TV will be increased by 20% only for nodes B & E, and subsequently it will be decreased by 20% for the nodes B & E. The result of both the graphs will be analyzed to study the propagation. Nodes B & E were chosen for this case, as they are the most non central nodes with the lowest base probability which could bring in dynamics into the study. Also, after considering the section 4.2.5 when node E was the source node, the propagation of all the arcs were the fastest at time interval t5.

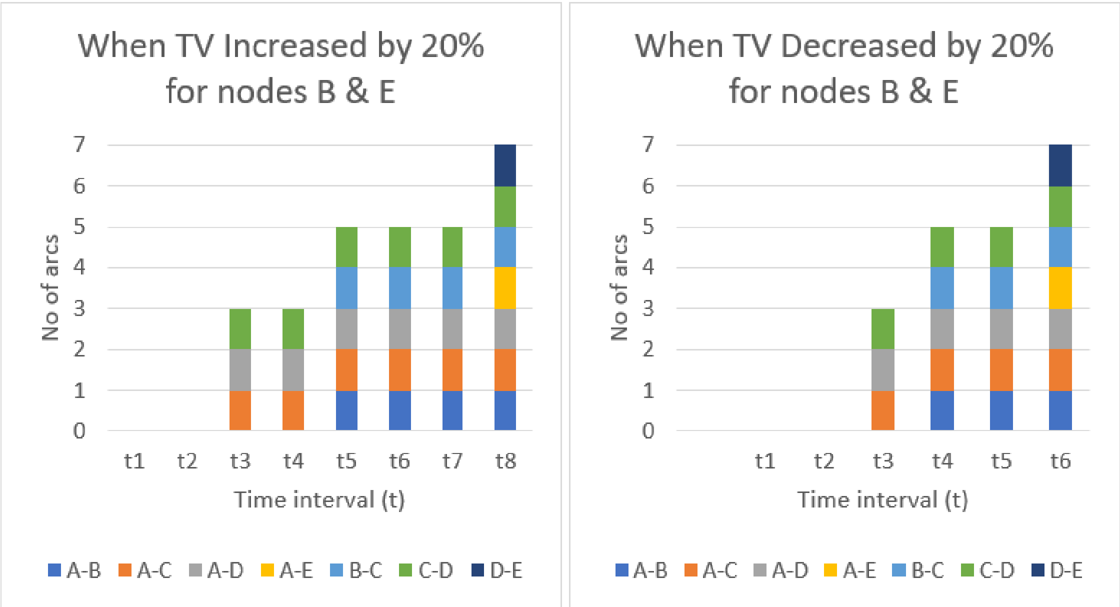


Figure 40 When Threshold value changed by ± 20% for nodes B & E

In figure 40, when TV decreases by 20% the arcs get adopted faster as the threshold level for activation is reduced. But arcs A-C, A-D, C-D gets adopted at t3 in both the cases. The next set of arcs such as A-B, A-C gets adopted at t5 & t4 respectively. The arcs which are adopted are similar with the same time interval in both cases. Arc A-E, D-E are the last ones to get adopted as the base probability of node E is the lowest. Hence, if propagation needs to be faster when TV increased by 20% in nodes B & E, it would be effective to increase the base probability of node E, which will trigger a faster adoption of all the arcs in the network.

5 Chapter - Conclusion

We examined the literature about the climate change and the need to reduce the GHG emissions on a global level. The IMO strategy includes net-zero GHG emissions from international shipping close to 2050, additionally to ensure an uptake of alternative zero and near-zero GHG fuels by 2030. This has encouraged shipping companies to investigate and invest in cutting-edge technology and adopt cleaner and net zero GHG fuels.

The primary aim of this study was to realize the IMO strategical requirements using the uptake of a new technology. The technological uptake was assessed using a threshold network model. The network under study consisted of five nodes (ports) and seven interconnected arcs (green corridor routes). The network propagation was analyzed in terms of the probabilities of R&D assigned to each port (TRL of the port). Furthermore, the potential to establish a green corridor between two ports were understood by the adoption rates of the paths connecting them. Finally, the evolution of technology adoption was understood by varying different parameters such as the base probabilities (TRL of the port), rate of increment (rate of increase in investment) and threshold values of the nodes (minimum TV of TRL to establish a green corridor).

The key findings from the model will be discussed below and be used to formulate policy recommendations to achieve faster adoption of new fuel technology.

5.1 Key Findings

The adoption of a green corridor was studied by utilizing a linear threshold model. One of the main reasons to choose this model was due to the lack of historical data which was required in other models. Our research was based on a probability study with numerous interpretations and assumptions to understand the uptake of green corridors and to forecast how long it takes for the entire network to adopt green corridors.

Firstly, the centrality measures were calculated specific to this network model. The most central ports (nodes) were identified to be port A followed by port D and port C respectively. Degree centrality was an important indicator in identifying the most central port with respect to the number of green corridor routes (arcs) linked to it. After establishing the most central port in the network, the model was evaluated in two scenarios as per section 4.1 and 4.2. In the first scenario, all the ports in the network were having insufficient TRL to establish a green corridor with other ports. In the second scenario, one port has sufficient TRL (more than TV) to establish a green corridor. The major finding in this exercise was, the green corridor routes which were connected to central port A were the first ones to get adopted in all the cases. In other words, *centrality of a port accelerates the adoption of green corridor routes within the network.*

In scenario two when the port E was a source node, all the green corridor routes in the entire network was adopted the fastest at time interval t5. In all other cases in the scenario 2, the adoption of entire network happened at time interval t7. The reason being, the TRL of port E was the lowest and least ready to have a green corridor. When the TRL of port E was greater than the TV, the average combined TRL of all other ports in the network were accelerated. Hence the adoption was much faster in this case. *To sum up, the adoption of green corridor must prioritize in investing with ports which has low initial TRL than ports which have higher TRL to diffuse the entire network faster.*

Furthermore, a sensitivity analysis on the network was performed to understand the changes in adoption as a function of different network parameters. For instance, with a change in TV by ± 20 % on central ports, all the green corridor routes were adopted by t7. Moreover, with a change in TV by ± 20 % on non-central ports, there was no significant changes in the adoption as compared to TV changes on central ports. As a result, even with a net difference of 40% in the TV, the adoption rate of all the green corridor routes was similar. *In essence, the initial R&D (TRL) considered for all the ports were sufficient to compensate for an increase in the TV by 40% on both central and non-central ports.*

Policy recommendations

Policy measures should direct towards ports with lower level of TRL to attain a faster adoption of a technology diffusion in the network. The best practical way to achieve this could be in the form of providing subsidies. Subsidies schemes to support fuels, vessels, technology transformation, and R&D for enabling green technologies must be enabled. These policies should help in tapping the demand side for green fuels to use these fuels in shipping. By doing so, it will encourage all the ports to upgrade the supply side of green fuels and being technology ready to have the necessary storage, infrastructure, expertise and feedstock to meet the market demand. The combined demand and supply policies will eventually help in closing the total cost gap of green fuel associated with scalable zero emission technologies.

Another policy recommendation to bridge the R&D levels is to create a dedicated joint R&D fund between developed and developing ports in the network. This fund should be established as a shared financial resource, includes contributions from both ports and perhaps further funding from outside grants or donations. This financial commitment serves as a tangible representation of the ports commitment to enhancing their R&D capabilities in, along with ensuring a steady resource base for future research projects. It enables the ports to invest in cutting-edge technologies, hire research talent, and undertake projects that might otherwise be financially challenging. Additional cost efficiency strategies can be considered, such as splitting the funding between the countries along the corridor and encouraging broad value chain action. Strengthening collaboration between policy makers and government bodies across countries can lead to proactive approach in designing and implementing polices, ultimately leading to more rapid and impactful innovation adoption.

Different stakeholders in the value chain can support the green transition in the region :-

1. Policies can develop support mechanism for funding the first movers and support green corridor projects to push for regulatory change to encourage net zero GHG fuels for adoption. Regulations should provide financial incentives to decarbonize the value chain and reward first movers.
2. Fuel producers must coordinate with shipping companies and ports to identify the alternative fuel demand and provide discounts and incentives for using green fuels. They should clearly communicate the feedstock supply, production outlook and delivery of green fuels.
3. Shipping companies must build a strong bond with their customers who are committed towards the sustainability goals. They have to convince the customers to pay for green transport. Companies have to research and identify strategies and technological solutions for specific routes in the green corridors.
4. Customers must be willing to pay for the green transportation which decarbonizes their value chain.
5. Government bodies must develop social awareness to initiate public to prepare social readiness and acceptance of different kind of fuels and how to handle them. They should initiate projects which attract stakeholders to invest in new green fuels to ports. Recognize that being prepared for new fuels in advance can be a competitive advantage that can lead to opportunities for growth in the local region.

5.2 Areas of further research

The result of this study profoundly suggests that centrality of a port was an important measure that helps in adoption of the network. However, the study was limited by historical data and assumptions.

The size of the network model was limited to five nodes. Further studies must consider the presence of higher number of nodes and interconnecting arcs in the network. Assumptions such as, a node can only extend an arc to its neighbors and that arcs in the network can only be parallel lines and not intersect were made. Further study must consider more dynamics with arcs intersecting each other while connecting with their nodes. In addition, the study must consider a node where it can extend its arc beyond its neighboring nodes.

The model was based on a single parameter (probability of R&D) for all the nodes. However, further study must consider multiple parameters (as seen in section 2.3) for all the nodes within a network which allows for a detailed exploration of the complexities involved in understanding the adoption of green corridors. In future, sufficient historical data of the new technology can provide valuable inputs and more robust model validation. Simulations should be carried out with wide range of scenarios that allows to explore potential impacts and gain insights into adoption of new technology, which might accelerate the adoption process.

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