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The carbon footprint of citrus exports via the Port of Durban: A container barge system analysis

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Background: The Port of Durban in South Africa has faced significant road congestion for many years. To address this, the fresh-produce industry proposed a cross-harbour container-handling barge system. The citrus industry requested this study to evaluate the potential carbon footprint impact of such a system on citrus exports transported in reefer containers around the port.

Objectives: This study aimed to assess whether a barge system could reduce the carbon footprint of citrus exports and alleviate road congestion to improve the export supply chain's efficiency.

Method: Using an exploratory case study with primary and secondary data, the research applied a deductive approach to theory development. Carbon emissions were calculated for three scenarios: the current system, the proposed barge system and a combined system.

Results: The carbon emissions for the three scenarios are as follows: current system: 25.20 kg CO_2e per reefer; proposed system: 17.43 kg CO_2e per reefer; and combined system: 20.61 kg CO_2e per reefer. However, the proposed system does not have sufficient capacity to handle all the reefer containers in a given citrus season.

Conclusion: The combined system is the logical choice. The combined system shows a CO_2e emissions saving of approximately 18% per reefer compared to the current system.

Contribution: This study explores the carbon reduction and congestion alleviation benefits of a cross-harbour barge system at the Port of Durban. Unlike existing literature on inland waterway barge systems, it provides a port-specific analysis and is among the first to quantify CO_2e emissions for citrus exports using a barge system.

Keywords: barge transportation; barge CO_2 equivalent emissions; carbon footprint; citrus industry; port congestion; road congestion.

Introduction

According to Ports Regulator of South Africa (2023), the Port of Durban is the largest container port in sub-Saharan Africa and the second largest in the southern hemisphere. The congestion experienced at the Port of Durban has grown significantly over several years (Darley-Waddilove, Goedhals-Gerber & Engelmohr Thiart 2023). This congestion has led a group of port stakeholders including citrus exporters, the Citrus Gowers Association and a terminal that handles fruit exports within the Port of Durban to propose a cross-harbour container barge system. This barge system would operate in the Port of Durban and would supplement the transport of approximately 27% of all citrus reefer[1] containers (reefers) that are currently transported via road between the port terminals during the citrus export season, which starts with grapefruit and lemons in late March, and continues for approximately 28 weeks until October when the last oranges are harvested (Eager 2023). To relieve congestion and speed up the loading of vessels, the barge would transport reefers between four terminals in the Port of Durban, namely the Maydon Wharf Fruit Terminal (MFT), the Fresh Produce Terminal (FPT) and the Durban Container Terminal (DCT). Pier 1 Container Terminal and Pier 2 Container Terminal make up the DCT.

A container barge is a flat-bottomed vessel that is used to carry containers on waterways, such as inland rivers, or across harbours at different points for loading and discharging (American Association of Port Authorities 2024). Currently, nearly all container movements from cold stores in and around the Port of Durban to the DCT take place via road transport.

1. Refrigerated containers, also referred to as reefer containers or simply as reefers, are specialised containers that are used for goods that need to be transported under temperature-controlled conditions. Reefers are equipped with their own, individual refrigeration unit that is connected to the power supply on board a ship (Kuehne & Nagel 2024).

The citrus industry requested research to determine the impact of the proposed barge system on the carbon footprint of citrus exports via the Port of Durban, the leading commercial port in South Africa. In the current global environment, where governments and businesses are striving to lower carbon emissions and ensure the longevity of the earth's natural resources, evidence that the proposed barge system would have a positive impact on the environment would increase the likelihood of its implementation. Customers of the South African citrus industry have also increased their focus on sustainability in their supply chains, elevating the need to promote initiatives of this nature.

This article compares the carbon footprint of three scenarios for citrus reefers handled at the Port of Durban: the current, proposed and combined systems.

The next section summarises the citrus industry and describes factors that lead to congestion in the Port of Durban. A brief description of the use of barge systems internationally is provided, and fuel emission factors specific to South Africa are discussed. This is followed by an overview of the research methodology that was followed. The results of the study are then presented. The article concludes by emphasising the key contributions of the study to the current body of knowledge and identifies potential areas for future research.

Theoretical perspective

Citrus contributes 62% to South Africa's fruit export volumes (FPEF 2021; FruitSA 2020). Revenue earnings of approximately R20 billion per annum make the citrus industry an important sector for the South African economy (FPEF 2021). More than half (52%) of citrus exports pass through the Port of Durban (Khumalo et al. 2023). The high export volumes during a short export season result in challenges such as congestion, reefer container shortages and port delays. In addition, there is growing pressure on organisations and stakeholders worldwide to lower their carbon footprint and reduce the emission of greenhouse gases (GHGs) (Du Plessis, Van Eeden & Goedhals-Gerber 2022a).

The aim of this study is therefore twofold: to determine whether the introduction of a container barge system at the Port of Durban would reduce the carbon footprint of citrus exports, and to establish whether it would simultaneously reduce road congestion at the port and therefore make the export supply chain more efficient.

The citrus industry

South Africa is the leading exporter of citrus in the southern hemisphere, accounting for 60% of citrus exports from this region (Brodie 2024). It is also the second-largest citrus exporter globally, after Spain (South African Government News Agency 2024). South Africa's diverse climatic regions enable the production of various citrus varieties. The production season spans from March until November (FPEF 2021; FruitSA 2020). The main citrus production regions in South Africa are in the Northern Cape along the Orange River, the Western Cape, Eastern Cape, the North West province, the KwaZulu-Natal Midlands, Eastern Mpumalanga and Limpopo (Brodie 2024b).

South Africa's citrus industry is export oriented: approximately 71% of the citrus produced during the 2023 season was exported (CGA 2023). While the export-oriented nature of the citrus industry offers opportunities for global market access, the rigorous standards that need to be adhered to and the impacts of climate change pose significant challenges for the industry (Chisoro-Dube, Landani & Roberts 2020).

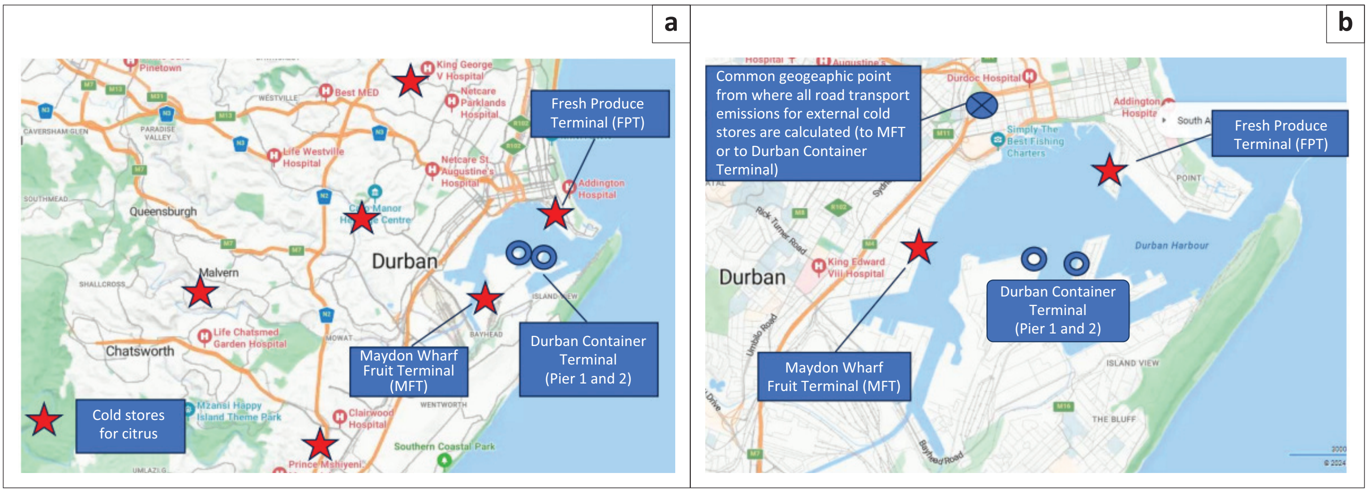
The Port of Durban

The Port of Durban is located along the east coast of South Africa, approximately 680 nautical miles northwest of Cape Agulhas and 625 nautical miles south-southwest from the Port of Maputo in Mozambique (KZN DoT 2021). The DCT is South Africa's leading container terminal, accounting for approximately 60% of the nation's container volumes (Transnet National Ports Authority 2022). It services the provinces of KwaZulu-Natal and Gauteng in South Africa, along with a significant portion of southern Africa's hinterland (Transnet Port Terminals [TPT] 2021). The port is an important enabler of international trade.

Transnet Port Terminals is responsible for managing various business units at the Port of Durban, including the DCT. Operations at this terminal started in 1977. Currently, the DCT operates as two terminals, on Pier 1 and Pier 2. According to Zangwa (2018), these two terminals have a combined capacity of 3.6 million 20-foot equivalent units (TEUs) per annum, with a design capacity of 0.7 million TEUs at Pier 1 and 2.9 million TEUs at Pier 2. Pier 2 at the DCT handles approximately 75% of all container traffic at the Port of Durban.

Two cold-storage terminals, namely the MFT and the FPT, play a prominent role in the storage, packing and export of citrus, mainly in reefers via the DCT. Figure 1a and Figure 1b show maps of the Port of Durban area, including the location of the cold stores in the port and at Piers 1 and 2. The maps also give a random indication of four cold stores outside the Port of Durban area that play a significant role in the citrus export supply chains via the Port of Durban. The location of these cold stores has not been indicated accurately because their involvement and the volumes handled in the citrus industry are confidential. Later in this article, their identity is also handled via coding instead of giving their names.

Currently, nearly all container movements from cold stores located in the vicinity of the Port of Durban to the DCT take place via road transport. Severe road congestion inside and around the Port of Durban often affects these road movements, and trucks often require over 12 h to perform a round trip of 15 km instead of the acceptable industry standard of less than 4 h (Paulo Franco [Managing Director: FPTs] pers. comm., May 2022).



Source: Adapted from Google Maps, 2024, *Durban, South Africa*, viewed n.d., from https://www.google.co.za/maps/place/Durban/@-29.8684479,30.9085502,12z/data=!3m1!4b1!4m6!3m5!1s0x1ef7aa0001bc61b7:0xcca75546c4aa6e81!8m2!3d-29.8586804!4d31.0218404!16zL20vMDF0anZ2?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D

FIGURE 1: (a) The greater Durban area, showing the Port of Durban and role players in the citrus export supply chain. (b) The location of the two key cold stores inside the port limits (the Maydon Wharf Fruit Terminal and the FPT), the two container terminals (Pier 1 and Pier 2) and a random indication of four outside cold-store locations (not accurate because of confidentiality).

Congestion at the port of Durban

Congestion at the port of Durban affects the city of Durban and its infrastructure, with the city losing close to R1 billion annually because of port congestion (Comins 2022). This is because shipping delays can disrupt supply chains, resulting in goods shortages and higher costs for businesses. In addition, the deficient condition of rail facilities linking the Port of Durban to the hinterland and the growing shift of cargo from rail to road over the last decade has further resulted in high levels of port congestion (Burgstahler 2023). Industries dependent on timely imports and exports may suffer financial losses, and there could be far-reaching effects for economic growth and employment. The congestion might also strain the infrastructure and logistics systems, requiring a coordinated approach to overcome the challenges and mitigate the economic consequences (eThekwini Maritime Cluster 2023).

In 2022, the Port of Durban received a ranking of 398 out of 405 in the World Bank Container Terminal Performance Index, indicating problems with infrastructure and efficiency. Failing and insufficient equipment and an ineffective truck-booking system (World Bank 2024) are seen as challenges at the port, which directly result in lower container throughput and congestion at the DCT. According to Kriel (2017), cold-storage facilities and container depots at the Port of Durban are situated near the port terminals, causing further bottlenecks in the citrus export supply chain. In addition, container terminals used by modern supply chains are forced to operate under conditions of increased uncertainty. These conditions are driven by a range of factors, including socioeconomic issues and changing supply chain strategies in response to market dynamics (Russell, Ruamsook & Roso 2022).

Various external factors have had a negative impact on congestion at the Port of Durban in recent years. These include the coronavirus disease 2019 (COVID-19) pandemic, the global container shortage, riots in 2021 and floods in 2022. Throughout the COVID-19 lockdown, it is delineated that South Africa's ports were operating at only 60% capacity (The Maritime Executive 2020). This led to increased delays from March to September 2020, also at the Port of Durban, negatively affecting citrus exports and resulting in added pressure for the citrus industry.

To export fruit internationally, including citrus from South Africa, it is critical to have enough reefer containers (reefers). Nearly 95% of all fruit exports from South Africa take place in reefers, with the balance moving by conventional reefer vessels or air freight (Du Plessis 2023). During and after the COVID-19 pandemic, international trade was affected by a global shortage of containers. The scarcity of reefers significantly affected South Africa (Connor 2021). Because of the imbalance between the imports and exports of perishable products to and from South Africa, a 'very high percentage' of reefers return to South Africa empty (Du Plessis, Van Eeden & Goedhals-Gerber 2022b; Jansen 2021), which makes it necessary to reposition empty reefers (Sun 2011). However, during and after the pandemic, when shipping rates rose steeply (Etter & Murray 2022), repositioning empty containers to countries off the main east–west shipping route, such as South Africa, was considered disadvantageous for shipping lines. This situation has persisted: for shipping lines to efficiently serve the citrus industry, they must supply a sufficient number of reefer containers to the South African fruit export industry (which includes citrus). When they do not, it has a negative impact on congestion at the DCT, among others. Increased flows of empty reefers from this terminal to depots and cold stores during the citrus season further contribute to congestion in and around the port.

The Port of Durban also faced two significant unplanned shocks in recent years that have negatively affected congestion levels. In July 2021, the KwaZulu-Natal and

Gauteng provinces experienced violent protests and sociopolitical unrest. These events involved the widespread looting of businesses and the destruction and burning of public facilities and private property (Vhumbunu 2021). During the unrest, operations at the Port of Durban stopped completely (Venter 2021). This unrest had a negative impact on the citrus industry, as harvests for the Valencia season had just started, and citrus farmers in the northern production regions of the country were in the peak harvesting and packing period (Meintjes 2021). Roughly 300 000 pallets of citrus were left abandoned between the land-side stages of the cold chain for more than 4 weeks, resulting in even greater pressure on port-side cold-storage facilities, which already had restricted capacity (Meintjes 2021).

Operations at the Port of Durban were affected again in April 2022 when KwaZulu-Natal was hit by floods, leading to a backlog of thousands of containers awaiting completion of import- or export handling at the Port of Durban. Because three river systems feed into the Port of Durban, debris needed to be cleared out of the port (Ndubiwa 2022). The floods also caused extensive damage to the roads leading to the port (Reid & Banya 2022).

An overview of carbon footprint

The carbon footprint is the total GHG emissions produced either directly or indirectly by an individual, product, organisation or event (The Carbon Trust 2018). It is calculated by tallying the emissions that result from each stage of the product or service's life. This includes the sourcing of raw materials, manufacturing, transportation, storage, use and recycling. Throughout a product or service's lifecycle, different GHGs may be emitted, including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Each of these gases have the potential to trap heat in the earth's atmosphere causing global warming and climate change (Denchak 2023). To make calculating emissions easier, other GHGs are converted into units of carbon dioxide equivalent (CO_2e), typically expressed in weight. This provides products and services with a carbon footprint that has a single unit for easy comparison.

Examining three scenarios at the port of Durban

This study compares the carbon footprint of three scenarios for citrus reefers handled at the Port of Durban: the current, proposed and combined systems, as shown in Table 1.

TABLE 1: Three scenarios tested in this study.

Scenario	Scenario definition
Current system	Reefers, loaded with citrus at the six different cold stores (the MFT, the FPT and four other cold stores outside the port limits), are transported by truck from the respective cold stores to the DCT during the citrus export season.
Proposed system	A barge is used instead of road transport to transport a portion of the citrus reefers destined for the DCT during the citrus export season. This system will allow a modest percentage of reefers loaded at cold stores outside the port limits access to barge transfers via the barge dock at the MFT. The proposed system includes: • Transporting citrus reefers from the four cold stores outside the port limits to the MFT by truck, where a barge-loading dock will be located. This point will be best suited for barge access from the four external cold stores. • Transporting citrus reefers to the DCT by barge from both the MFT and the FPT. Each of these terminals will have their own barge dock.
Combined system	The current and the proposed systems will be combined. Some reefers will be transported by road from the cold stores, but a portion of reefers will be transported to the DCT by barge: • Most of the reefers to be transported by barge will originate from the cold stores at the MFT and the FPT. • A small number of reefers from cold stores outside the port limits will be diverted to the MFT for transfer by barge via the barge dock.

Source: Adapted from Burgstahler, M., 2023, 'The effect of the introduction of a container barge system on the carbon footprint of the Port of Durban: A citrus industry case', Masters dissertation, Stellenbosch University, viewed 10 September 2024, from https://scholar.sun.ac.za/items/343a2b37-5de9-4e44-ae58-0862cdc256fc

DCT, Durban Container Terminal; MFT, Maydon Wharf Fruit Terminal; FPT, Fresh Produce Terminal.

Use of barge systems internationally

Barges play a role in both inland waterway transport and cross-harbour transport within a port. Inland waterway transport refers to a system of river barging where goods are transported from ports to inland destination points. In Europe, 20 out of 27 countries have inland waterways and canals (Stock Cargo 2021). Inland waterway transport is also widely used in the United States via the various navigable rivers and connected inland coastal waterways. The less common use of barge transportation is to transport cargo within a port to and from terminals. Cross-harbour barge transport was developed to avoid severely congested land-based infrastructure, such as roads, bridges and tunnels. A new cross-harbour barge system was introduced between New York and New Jersey in 2016: containers are transported between the Red Hook Container Terminal in New York and the Port Newark Container Terminal in New Jersey (Waterfront Alliance 2016).

South African fuel emission factors

Fuel emission factors provide the amount of CO_2e produced per unit of diesel consumed (Trace 2022). According to Du Plessis (2023), average fuel emission factors differ significantly from country to country. Fuel emission factors consider the lifecycle of fuel.

The lifecycle of fuel involves both well-to-tank (WTT) and tank-to-wheel (TTW), and the amalgamation of the two is classified as well-to-wheel (WTW). According to Du Plessis (2023), WTT fuel emission factors differ substantially between countries because of the feedstock (including crude oil, coal and liquefied natural gas) and the processes utilised to extract, process and distribute the fuel. Tank-to-wheel fuel emission factors do not differ substantially between countries because of the stoichiometric ratio of the combustion-to-oxidation of fuels. Table 2 shows South Africa's diesel and petrol emission factors compared to those in Europe.

Table 2 shows that South Africa has higher WTW equivalent emission factors for diesel and petrol compared to those in Europe. Although the TTW emission factors for South Africa and Europe fall within a similar range, South Africa has

TABLE 2: Fuel emission factors for South Africa compared to those of Europe.

Fuel type	Fuel emission factors for South Africa ($kg\ CO_2e/L$ fuel)			Fuel emission factors for Europe ($kg\ CO_2e/L$ fuel)		
	WTT	TTW	WTW	WTT	TTW	WTW
Diesel	1.48	2.61	4.34	0.57	2.67	3.24
Petrol	2.60	2.85	5.22	0.45	2.42	2.88

Source: Adapted from Fadiel Ahjum pers. comm., July 2022; Smart Freight Centre (2019); and Burgstahler (2023)

Note: Please see the full reference list of the article for more information: https://doi.org/10.4102/jtscm.v20i0.1112.

WTT, well-to-tank; TTW, tank-to-wheel; WTW, well-to-wheel.

higher WTT emission factors, resulting in higher WTW emission factors.

The South African WTW emission factor of 4.34 kg CO_2e/L of diesel was used to calculate the total emissions of the three transport systems covered in this article. Equation 1 was used to calculate total emissions (see Equation 1):

$$\text{Total emissions (kg } CO_2e) = \text{Total fuel (litres)} \times \text{Appropriate fuel emission factor in Table 2} \quad \text{[Eqn 1]}$$

Equation 1: Calculating total emissions

Source: Du Plessis, M.J., 2023, 'A carbon mapping framework for the international distribution of fresh fruit', PhD dissertation, Stellenbosch University.

The total emissions calculated in Equation 1 are then used to calculate the carbon footprint, as shown in Equation 2:

$$\text{Carbon footprint (kg } CO_2e/\text{t cargo}) = \frac{\text{Total emissions (kg } CO_2e)}{\text{Weight of cargo (t)}} \quad \text{[Eqn 2]}$$

Equation 2: Calculating the carbon footprint

Source: Du Plessis, M.J., 2023, 'A carbon mapping framework for the international distribution of fresh fruit', PhD dissertation, Stellenbosch University.

The weight of the cargo is the weight of the payload (t) transported.

Research design and methodology

The set objectives determined the design of this study. Both primary and secondary data were used. The research utilised a mixed-method approach. The study was conducted as an exploratory case study with a cross-sectional time horizon, examining three scenarios (the current, proposed and combined systems). A deductive approach was used for the theory development.

Cold stores included in this study

Six cold stores were included in this study. Four of them are situated outside the Port of Durban, but all within a maximum distance of 40 km from the container terminal. The two cold stores with the most relevance are the MFT and the FPT, both situated inside the port with berth access to marine transport. These six cold stores supplied over 80% of all citrus reefers to the DCT during the 2021 citrus export season (the study period). To protect confidential volume information, the cold-store names were coded. The codes used to represent the six cold stores in the current system were used for the same cold stores in the proposed system to remain consistent across all scenarios.

Current citrus supply chain system

The majority of the citrus exported through the Port of Durban originates from over 1000 km away. The three major production areas of origin in and around South Africa are:

- Eastern Cape Area;
- Northern Area including KwaZulu-Natal, Mpumalanga, North West province and Zimbabwe;
- Western Cape Area.

From the point of origin, the citrus is transported to a cold store in or around the Port of Durban. Here it is stored and maintained until a truck with an empty reefer has been scheduled to pick up the citrus at an appointed cold store. Once the empty reefer has been washed, cleaned, inspected and approved by the Perishable Products Export Control Board (PPECB) at a container depot, it is transported to the cold store. The truck makes the trip when the citrus has already been prepared for packing. The readiness of the citrus and the availability of a reefer container must be synchronised. After the truck arrives, the citrus is loaded into the empty reefer container and transported to the DCT via Bayhead Road.

At the DCT, the reefer is transported to the stack that has been assigned to a specific ship. Once the ship has berthed, the reefer container is loaded onto the ship.

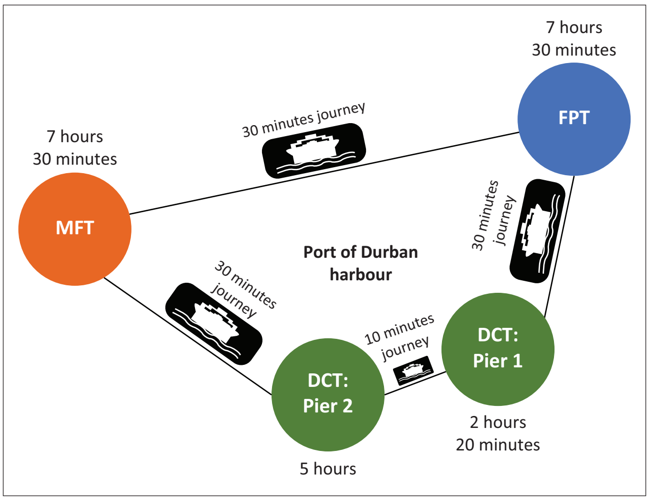
Proposed citrus supply chain system

In the proposed citrus supply chain, a barge will transport reefers to or from the following terminals (Burgstahler 2023):

- Durban Container Terminal (Pier 1 and Pier 2)
- Maydon Wharf Fruit Terminal
- Fresh Produce Terminal.

Figure 2 shows the barge operation and barge legs in the proposed system.

The barge will transport full reefer containers from the MFT and the FPT to the DCT (Pier 1 and Pier 2) in a repetitive circular pattern. During the citrus export season, the



Source: Burgstahler, M., 2023, 'The effect of the introduction of a container barge system on the carbon footprint of the Port of Durban: A citrus industry case', Masters dissertation, Stellenbosch University, viewed 10 September 2024, from https://scholar.sun.ac.za/items/343a2b37-5de9-4e44-ae58-0862cdc256fc

DCT, Durban container terminal; MFT, Maydon Wharf fruit terminal; FPT, fresh produce terminal.

FIGURE 2: One 24 h round trip showing barge legs with estimated times for all activities of the proposed system within the Port of Durban.

proposed system will operate 24 h a day for an average of 6 days a week. An assumption was made that one round trip will on average last exactly 24 h. Figure 2 indicates the estimated time that the barge would spend loading and unloading reefers at each of the four stops on the route. Outside the citrus export season, it will operate 24 h a day for an average of 5 days a week.

For emission calculation purposes, the assumption of the route in Figure 3 implies that the barge will run its main engine for 100 min per day (it will be switched off during loading and offloading). This running time is conservative, as unexpected delays could occur, such as the barge having to wait for ships to pass. Based on the current utilisation of Pier 1 and Pier 2 for citrus reefer exports, Pier 2 was assigned 70% of the allocated barge time at the DCT and Pier 1 was assigned 30%.

Figure 3 shows the supply chain of a citrus reefer being transported via the proposed system.

The citrus (from the same production areas as in the current scenario) will be kept in cold storage until an empty reefer is scheduled to be collected. In the proposed system, citrus reefers that are packed at the four cold stores outside the port will be transported to the MFT by road, where they will be loaded onto the barge. Maydon Wharf was selected as the point to load reefers from external cold stores onto the barge because it has a better geographical location. It avoids the traffic of the inner-city area, which affects transport to the FPT.

Two barge berth locations at the DCT were identified as suitable for the barge to deliver and collect citrus reefers at Pier 1 and Pier 2. As soon as the barge berths at the DCT, the crane on the barge will unload the reefers onto a shuttle truck owned and operated by the DCT. The truck will then transport these reefers to the stack.

Combined citrus supply chain system

The *proposed citrus supply chain system*, which will be utilising the barge in combination with limited road transport, will have a limited capacity. It will therefore only be able to transport about 27% of all export citrus reefers per season. This means the most effective solution would have to combine the proposed system and the *current citrus supply chain system*, which transports the balance of exports to the DCT by road. Thus, a third scenario, namely the combined system, was created. To calculate the overall emissions for the combined system, the barge and road transport for all the citrus exports in a season are combined.

Assumptions used in this study

For the current system, an assumption was made that the six cold stores included in this study represent the entire supply of citrus reefers for the 2021 citrus export season. Another assumption was that 90% of all citrus reefers transported to the DCT during 2021 were transported during the defined 2021 citrus export season used in this study.

For the proposed system, the assumed barge capacity was 240 TEUs/120 foot equivalent units (FEUs). A 40- FEU is seen as equal to 2 TEUs. The barge average payload was assumed to be 102 FEUs per round trip. The barge payload was equally allocated to the MFT (47.5%) and the FPT (47.5%). The remaining 5% was allocated to the four cold stores outside the Port of Durban. Citrus reefers from these cold stores will be transported to the MFT by road and then loaded onto the barge. This will make it possible to channel urgent export reefers from the external cold stores via the barge when there is severe road congestion at the entrance to the DCT and the terminal cannot guarantee the acceptance (via road) of such reefers for loading onto ships.

Carbon footprint calculations

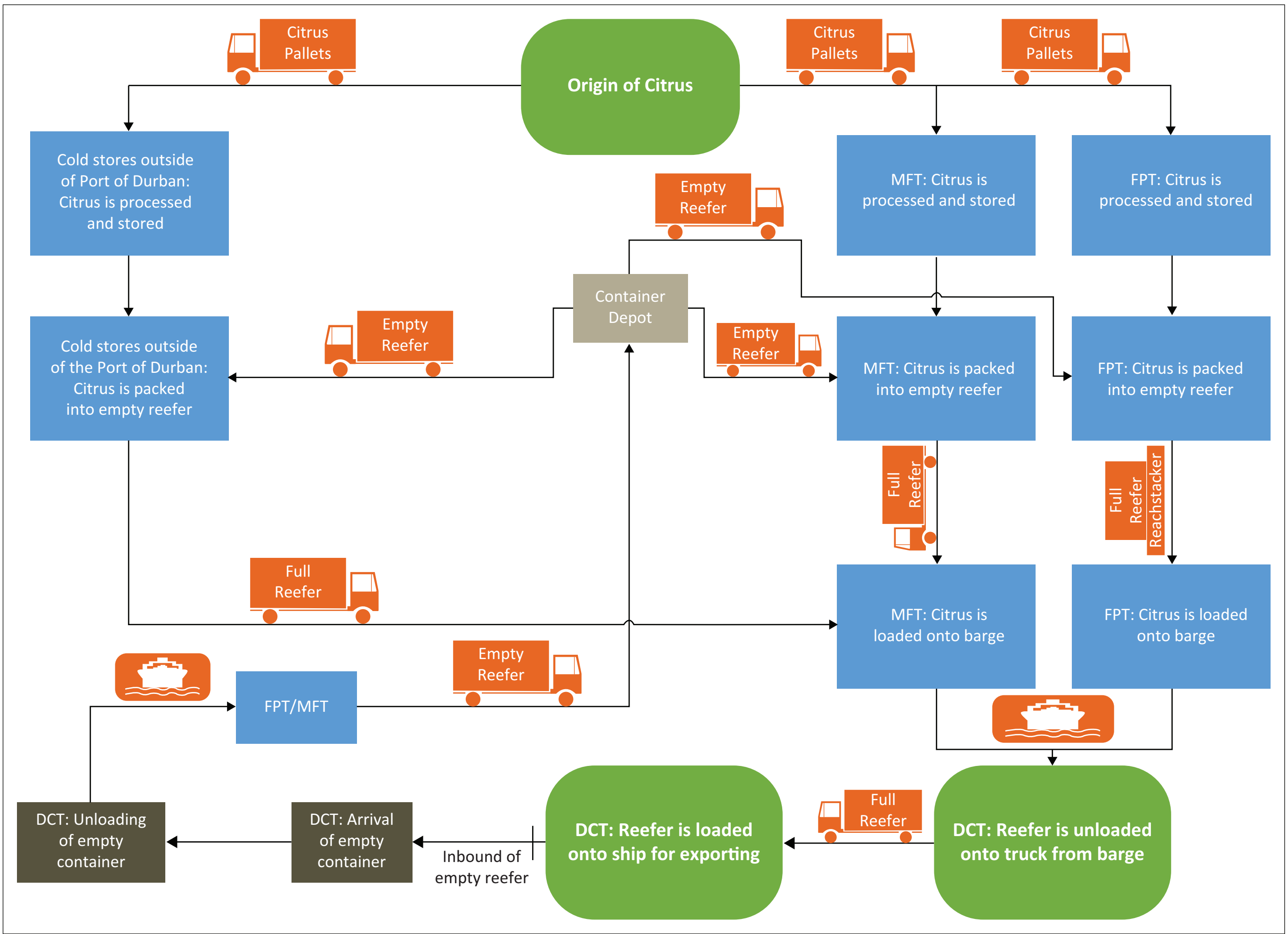
This study calculated the carbon footprint for the current, proposed and combined systems (see Table 1). To complete the carbon footprint calculations, the total fuel consumption for each system had to be determined.

Scope of carbon footprint calculations

Before calculating the carbon footprint for the three scenarios presented in this study, a scope for the carbon footprint calculations was defined for the current and the proposed systems.

Any additional transportation legs or variation in the mode of transport in the supply chain of any of the three scenarios is included in the carbon footprint calculation of that scenario. All similar transport legs with the same mode of transport (between the various scenarios) are excluded from the carbon footprint calculation.

A specific point was selected as a starting point for the carbon footprint calculation of trucks transporting citrus reefers



Source: Burgstahler, M., 2023, 'The effect of the introduction of a container barge system on the carbon footprint of the Port of Durban: A citrus industry case', Masters dissertation, Stellenbosch University, viewed 10 September 2024, from https://scholar.sun.ac.za/items/343a2b37-5de9-4e44-ae58-0862cdc256fc

DCT, Durban container terminal; MFT, Maydon Wharf fruit terminal; FPT, fresh produce terminal.

FIGURE 3: Potential supply chain of a citrus reefer using the proposed system at the Port of Durban.

from any of the four cold stores outside the Port of Durban to either the MFT or the DCT. This starting point is located just outside the port at the intersection of the R102 and Bayhead Road. From the cold stores up to this location, all citrus reefers will travel exactly the same routes. Reefers following the barge scenario will divert to the MFT just after this common point. 'Current system' reefers will continue to the DCT by truck. This was done to focus primarily on the transport section that would be changed for reefers that travel via the proposed system.

This starting point was selected because the significant distances from some cold stores to the R102/Bayhead intersection to the DCT will otherwise 'dominate' any differences in emissions between the two systems. Table 3 shows the scope for each transport leg for the current and the proposed systems.

Identifying origin-destination pairs

Origin–destination pairs (transport legs) were identified for each of the three systems tested in this study. For the current system, the origin–destination pairs were between cold stores and terminals where trucks collect and deliver citrus

TABLE 3: Scope for the current and proposed systems' carbon footprint calculations.

Transport leg	Scope of the transport leg
Cold store to the DCT	From: Packed citrus reefer on a truck moves past the selected point (R102/Bayhead Road intersection) Until: Truck arrives at the DCT at the assigned reefer stack
Cold stores outside the Port of Durban to the MFT	From: Packed citrus reefer on a truck moves past the selected point (R102/Bayhead Road intersection) Until: Truck arrives at the Maydon Wharf barge dock
Barge leg: FPT to Pier 1	From: Citrus reefer is in the FPT barge dock Until: Citrus reefer is in the Pier 1 barge dock
Barge leg: FPT to Pier 2	From: Citrus reefer is in the FPT barge dock Until: Citrus reefer is in the Pier 2 barge dock
Barge leg: Maydon Wharf to Pier 1	From: Citrus reefer is in the Maydon Wharf barge dock Until: Citrus reefer is in the Pier 1 barge dock
Barge leg: Maydon Wharf to Pier 2	From: Citrus reefer is in the Maydon Wharf barge dock Until: Citrus reefer is in the Pier 2 barge dock
Additional transport at Pier 1	From: Barge arrives at Pier 1 Until: Citrus reefer is on a shuttle truck at the assigned reefer stack at Pier 1
Additional transport at Pier 2	From: Barge arrives at Pier 2 Until: Citrus reefer is on a shuttle truck at the assigned reefer stack at Pier 2

Source: Burgstahler, M., 2023, 'The effect of the introduction of a container barge system on the carbon footprint of the Port of Durban: A citrus industry case', Masters dissertation, Stellenbosch University, viewed 10 September 2024, from https://scholar.sun.ac.za/items/343a2b37-5de9-4e44-ae58-0862cdc256fc

DCT, Durban Container Terminal; MFT, Maydon Wharf Fruit Terminal; FPT, Fresh Produce Terminal.

reefers in the vicinity of the Port of Durban. For the proposed system, the origin–destination pairs were between cold stores and terminals with barge collection points and terminals that comprise the origin and destination of the barge trip. For the combined system, the origin–destination pairs combined the origin–destination pairs of the current and the proposed systems. For all three systems, the distance (in kilometres) between each origin–destination pair, as well as the number of citrus reefers transported between each pair during the citrus export season, was determined.

Calculating fuel consumption

Representative fuel consumption figures were obtained for all the identified transport legs used to transport citrus reefers for all three systems. Using these figures, the fuel consumption for each identified transport leg was calculated, followed by the fuel consumption for each transport system. A representative average fuel consumption figure for the round-trip journey of the barge was calculated. The fuel consumption per round trip was multiplied by the number of round trips taken by the barge during a citrus export season to calculate the total fuel consumption for the barge. A stakeholder involved in the procurement and introduction of the barge provided the estimated average fuel consumption for the round-trip journey of the barge. This included assumptions on average travelling time, loading and unloading times per terminal and idling time for an average barge round trip.

Calculating total emissions

Equation 1 was used to calculate the total emissions for each transport system. The total fuel consumption (in litres) for a system was multiplied by a representative fuel emission factor. The fuel emission factor used in this study was 4.34 kg CO_2e/L of diesel.

Emissions of container handling

Container handling of reefer containers at the MFT and the FPT was not included in this study because exactly the same handling process is followed for the current and the proposed systems. The movement and loading of a reefer onto a truck at these two terminals (to be transported to the DCT) or the movement and loading onto the barge will be done with the same equipment in the same physical locations at each of these two cold-storage terminals and are estimated to use the same amount of fuel. The decision not to include these figures therefore does not affect the comparative carbon footprint between the two systems.

The handling of containers at Pier 1 and Pier 2 via the barge crane was factored into the estimated round-trip fuel consumption of the barge. The barge crane will unload reefers onto shuttle trucks (inside the terminals); hence no additional 'handling' emissions would be incurred.

Validity and reliability of results

To preserve the reliability of this study, the results were double-checked by experts in the field. All road fuel consumption information was obtained from operations managers at transport companies that support transport solutions for the DCT. Barge operation information was gathered directly from one of the main proponents of the barge system.

Ethical considerations

An application for full ethical approval was made to the Social, Behavioural and Education Research Ethics Committee (REC: SBE) at Stellenbosch University and ethics consent was received on 03 August 2022. The ethics approval number is LOG-2022-24978.

Results

This section describes the carbon footprint results for the three scenarios examined in this study, namely the current, proposed and combined systems.

Current system carbon footprint

To calculate the carbon footprint of the current system, a fuel consumption of 1.4 km/L was assumed for transporting reefer containers from the four cold stores outside the Port of Durban to the DCT. Several transport operators that operate in the vicinity of the Port of Durban were consulted to obtain this fuel consumption figure. The total numbers of citrus reefers transported from each cold store (including those at the MFT and the FPT) to the DCT in the current system during the citrus export season are (Burgstahler 2023):

- Cold Store A: 6691 FEUs
- Cold Store B: 6083 FEUs
- Cold Store C: 6083 FEUs
- Cold Store D: 7299 FEUs
- Cold Store E: 5170 FEUs
- Cold Store F: 6083 FEUs

The total fuel consumed for each cold store to the DCT road leg in the current system, as well as the total of all these road legs (for transporting reefers from the 'starting point' selected for calculations, namely the R102/Bayhead Road intersection, to the DCT) are (Burgstahler 2023):

- Cold Store A: 29 154 L of diesel
- Cold Store B: 31 718 L of diesel
- Cold Store C: 26 504 L of diesel
- Cold Store D: 80 815 L of diesel
- Cold Store E: 22 528 L of diesel
- Cold Store F: 26 504 L of diesel

The final emissions per reefer are (Burgstahler 2023):

- Total emissions for the current system: 942 750 kg CO_2e
- Carbon footprint: 0.97 kg CO_2e/tonne of citrus
- Emissions per reefer: 25.20 kg CO_2e/reefer

To calculate the total emissions per reefer, a 4.34 kg CO_2/L fuel emission factor was used. The total emissions were divided by the total cargo weight of all the citrus reefers transported via the current system (972 650 tonnes) to calculate the carbon footprint per tonne of citrus. This total was then multiplied by the weight of a packed citrus reefer container, which is 26 tonnes, to calculate the emissions per reefer.

Proposed system carbon footprint

The carbon footprint for the proposed system involves a fuel consumption of 1.8 km/L for the short road transport legs from the R102/Bayhead Road intersection to the MFT, where congestion increases. Fuel consumption for the current road deliveries of packed reefers from Maydon Wharf and the FPT, respectively, to the DCT (which will be replaced by the barge transfers) was retained at 1.4 km/L, as for the current system.

The assumed fuel consumption for a barge round trip was 385 L, while fuel consumption for the reefer handling by shuttle trucks at Pier 1 and Pier 2 was assumed to be 1.4 km/L. The numbers of citrus reefers transported from each cold store to the MFT in the proposed system during a citrus export season are (Burgstahler 2023):

- Cold Store A: 110 FEUs
- Cold Store B: 142 FEUs
- Cold Store C: 129 FEUs
- Cold Store D: 129 FEUs

The total numbers of citrus reefers that are transported on each barge transport leg during a citrus export season are (Burgstahler 2023):

- Fresh Produce Terminal to DCT (Pier 1 and Pier 2): 4845 FEUs
- Maydon Wharf to DCT (Pier 1 and Pier 2): 5355 FEUs

The total fuel consumption for the citrus reefers handled at Pier 1 and Pier 2, as well as the total number of citrus reefers handled at the two piers are (Burgstahler 2023):

- Pier 1: 3060 FEUs handled consuming 510 L of diesel
- Pier 2: 7140 FEUs handled consuming 1093 L of diesel

This is for the very short transport leg from the barge berth at each terminal to the relevant reefer stack. It was calculated at 1.4 km/L.

A barge crane is used for offloading the reefers from the trucks. The fuel consumed for this has already been included in the 385 L per round-trip estimate. The total fuel consumption for the proposed system, as well as the fuel consumption for the three major transport leg categories in the proposed system is (Burgstahler 2023):

- Road transport legs: 850 L of diesel
- Barge transport legs: 38 500 L of diesel
- Road transport of reefers inside the DCT: 1603 L of diesel

The final emissions figures for the proposed system include:

- Emissions for transporting reefers from the R102/Bayhead Road intersection to the DCT. This is for most of the reefers originating from the four cold stores outside the port that will still use truck transport to the DCT.
- Emissions for transporting a small percentage (5%) of reefers originating from the four cold stores outside the port, from the R102/Bayhead Road intersection to the MFT by road.
- Emissions for transporting all reefers from the MFT and the FPT by barge to the DCT. This includes reefers from the cold stores outside the port that have been delivered to the MFT.
- Emissions for the additional transport by shuttle truck at Pier 1 and Pier 2 for all reefers arriving by barge.

Emission figures for the proposed system are (Burgstahler 2023):

- Total emissions for the proposed system: 177 735 kg CO_2e
- Carbon footprint: 0.67 kg CO_2e/tonne of citrus
- Emissions per reefer: 17.43 kg CO_2e/reefer

The total cargo weight of all citrus reefers transported via the proposed system was 265 200 tonnes.

Carbon footprint for the combined system

With the combined system involving the current and the proposed systems, fuel consumption of both 1.4 km/L and 1.8 km/L is used for the applicable road transportation legs. The assumed barge fuel consumption of 385 L per round trip also applies. The total number of citrus reefers that will be transported to the DCT via truck in the combined system during the citrus export season, with the breakdown of reefers from each cold store that has been included in this study, are (Burgstahler 2023):

- Cold Store A: 6548 FEUs
- Cold Store B: 1238 FEUs
- Cold Store C: 5955 FEUs
- Cold Store D: 2454 FEUs
- Cold Store E: 5058 FEUs
- Cold Store F: 5955 FEUs

The total fuel consumption for the combined system, as well as the fuel consumption for the four major transport leg categories in the combined system are (Burgstahler 2023):

- Road transport legs (to the DCT): 136 708 L of diesel
- Road transport legs (to the MFT): 850 L of diesel
- Barge transport for 96 barge round trips per season: 38 500 L of diesel
- Additional reefer shuttle transport at the DCT: 1603 L of diesel

The final emission figures for the combined system are (Burgstahler 2023):

- Total emissions for the combined system: 771 050 kg CO_2e
- Carbon footprint: 0.79 kg CO_2e/tonne of citrus
- Emissions per reefer: 20.61 kg CO_2e/reefer

The total cargo weight of all citrus reefers that will be transported via the combined system is 972 650 tonnes. A total of 77% of the emissions for the combined system will originate from transporting citrus reefers in the current system (by truck only); barge transport will have no impact. The other 23% will originate from transporting citrus reefers in the proposed system, which will include a barge leg. Table 4 provides a summary of emission figures for all three systems, namely the current system, the proposed system and the future combined system.

Carbon dioxide equivalent savings

The proposed system has the lowest emissions per citrus reefer. However, this system does not have sufficient capacity to handle all the reefers in a given citrus season. Therefore, the citrus supply chains at the Port of Durban will enjoy a carbon footprint benefit if the port implements the use of the barge. When comparing the current system and the combined system, both of which transport the same number of citrus reefers, the combined system has lower emissions of 4.59 kg CO_2e per reefer. This amounts to a CO_2e savings of approximately 18%.

Contribution of the research

The study calculates the carbon emissions for three different systems: the current road-based system, the proposed barge system and a combined system. The barge system alone shows significant emission reductions, however, does not have the capacity to service all citrus containers in each season and is, therefore, not a feasible option. The proposed combined system shows a potential 18% CO_2e savings compared to the current road-only system. The research is contextually relevant because of the severe congestion issues faced at the Port of Durban, which currently ranks among the least efficient ports globally (398 out of 405). The proposed combined system is intended to relieve this congestion, making it both an environmental and logistical improvement for the citrus supply chain.

By using South African-specific fuel emission factors, the study presents a more accurate and context-specific analysis of carbon emissions, compared to studies that often use international (e.g. European or American) benchmarks. This localised approach highlights the higher WTW emission factors in South Africa, further emphasising the environmental importance of adopting the proposed system. The study underscores the increasing focus on sustainability within the South African citrus industry, which exports most of its production. As global customers and governments push for greener supply chains, this research provides concrete evidence supporting the adoption of the barge system as a sustainability initiative.

TABLE 4: Summary of emissions figures for the current, proposed and combined systems.

Emissions	Current system	Proposed system	Combined system
Total emissions (kg CO_2e)	942 750	177 735	771 050
Carbon footprint (kg CO_2e/tonne of citrus)	0.97	0.67	0.79
Emissions per reefer (kg CO_2e/reefer)	25.20	17.43	20.61

Note: Volumes for the proposed system reflect only ~27% of the total volumes for the current and the combined systems.

The findings of the research provide a framework that can be adapted for future research on the financial viability of such systems, and it provides the foundation for further investigation into carbon-mapping frameworks that account for supply chains of empty reefers – an area currently unexplored. The study also establishes a precedent for dual-mode systems (road and barge) as a balanced approach to handling high export volumes under capacity constraints.

This article contributes to the ongoing discussion on port efficiency, sustainability and carbon reduction strategies by providing real-world data and insights specifically tailored to the Port of Durban's citrus export logistics. It highlights the potential for integrating barge systems into congested port environments to achieve both environmental and operational benefits.

Conclusion and future research

The proposed system (using a barge) has the lowest emissions per citrus reefer of the three scenarios tested in this study but does not have sufficient capacity to handle all the reefer containers over a citrus season. Therefore, if the barge is introduced, the Port of Durban will need to continue using the existing road transport system along with the new barge system (the combined system). In the combined system, only 27% of the total citrus reefers will be transported by barge, from the MFT and the FPT to the DCT during the citrus export season. A small percentage of reefers, originating from the outlying cold stores, will be diverted to Maydon Wharf after the reefers have been packed. These reefers, which are assumed to make up only 5% of the barge capacity, will then also be loaded onto the barge at Maydon Wharf, together with the Maydon Wharf reefers (47.5% of the barge capacity, loaded from the cold store at Maydon Wharf).

When comparing the emissions per reefer for the current system (25.20 kg CO_2e) to those of the combined system (20.61 kg CO_2e), the difference in CO_2 emissions per TEU is 4.59 kg. A citrus reefer in the combined system saves approximately 18% CO_2 emissions compared to a citrus reefer in the current system.

Future research can investigate the financial viability of the barge system. For this system, there will be the double handling of reefers from truck to barge to container terminal, which will incur additional costs. However, the benefit to the citrus cargo owners of more reliable access to exports via the barge by avoiding congestion via the road entry option into the terminals may justify the additional costs to ensure timely exports of the sensitive reefer products. Future research can develop a carbon-mapping framework to calculate the carbon footprint of barge systems used in ports. The supply chain of empty reefers should be incorporated into the carbon footprints of that research.

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Competing interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Authors' contributions

Conceptualisation, data curation and formal analysis for the article were provided by M.B., L.L.G-G. and B.H. The investigation for this article was conducted by M.B. The methodology used in the article was developed by M.B., L.L.G-G. and B.H. The project administration for the research was supplied by L.L.G-G. Resources and supervision were provided by L.L.G-G. and B.H. Software was supplied by M.B. Validation of the article was delivered by L.L.G-G. and B.H. Visualization in the article was done by M.B. The original draft was written by M.B., L.L.G-G. and B.H, while review and editing was conducted by L.L.G-G. and B.H.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article. The raw data are not publicly available due to confidentiality reasons.

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