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Perspectives on the evolution of reefer containers for transporting fresh produce

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ABSTRACT

Background: Refrigerated containers or 'reefers' are essential for transporting fresh fruit and vegetables in transnational supply chains. By refrigeration, they ensure that food quality is better preserved and food losses are reduced. Countries that produce fresh produce also unlock new markets for export through refrigerated container transport.

Scope and approach: The authors have worked in the research and development of reefer-facilitated supply chains for over two decades. Based on our research and engineering work with key stakeholders, we provide our perspective on how the industry will or should evolve. We also elaborate on upcoming trends and key bottlenecks the industry faces. This paper touches upon subjects relevant to the global fruit and vegetable trade. These topics involve (1) the fresh produce reefer market, (2) the climate inside the reefer, including temperature uniformity and controlled atmosphere trends, (3) sustainability aspects such as greenhouse gas emissions and potential energy savings, and (4) the move towards smart reefers and the use of digital food twins.

Key findings: We particularly encourage more research on using a controlled atmosphere to save energy and better preserve foods, the effectiveness of ethylene scrubbers in reefers, synergizing the data acquisition pipelines of different sensor systems, and integrating these data with other parts of the supply chain into one data ecosystem.

Conclusions: As future trends, we foresee a further reduction of the carbon footprint and developments in digital twins of the refrigerated container and its cargo to monitor and predict future fruit and vegetable quality during transit and beyond.

1. Introduction

Refrigerated intermodal transport containers, commonly called reefer containers, play a vital role in global food supply chains. The inception of reefer containers can be traced back to 1956, when the first porthole reefer container was introduced (Rodrigue & Notteboom, 2015). These early containers were insulated but lacked a built-in refrigeration unit. Instead, they were placed on vessels connected to air ducts that supplied cold air. However, in the 1970s, a significant advancement occurred with the introduction of integral reefer containers. These containers integrated the refrigeration unit within the insulated structure and relied on an external electricity supply for power. At present, all reefer containers are of the integral type.

As of 2019, the global reefer container fleet comprised approximately 3.2 million Twenty-foot Equivalent Units (TEU). Among these, only 5% of the fleet consisted of 20-foot containers with dimensions of 20′ × 8′ × 8′6'' (6.1 × 2.4 × 2.6 m). The remaining 95% were 40-foot High Cube (HC) containers measuring 40′ × 8′ × 9′6'' (12.1 × 2.4 × 2.9 m). This distribution translates to around 1.6 million reefer containers being globally operated. The fleet has experienced a consistent annual growth rate of approximately 5% for an extended period, and there is no evidence to suggest a significant change in this growth rate in

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the foreseeable future. Reefer containers handle 80% of seaborne reefer cargo, while specialized breakbulk ocean reefer vessels carry the remaining 20%. Reefer containers have become an indispensable part of global supply chains and instrumental to waves of globalization.

For that reason, several researchers and companies have mapped the refrigerated container industry characteristics and upcoming trends. For example, comprehensive statistics and market information on reefer trade are available (Drewry, 2019), which offers valuable insights that are updated annually. This document provides a detailed market overview encompassing various aspects such as rates, trade volumes, fleet size, and the number of new builds. Table 1 provides key parameters associated with reefer containers (Drewry, 2019; Rodrigue & Notteboom, 2015). Castelein et al. (2020) conducted a literature review on the reefer market, resulting in the identification of 132 research papers, categorized into five main clusters: monitoring and control technologies, understanding the spatial climate distribution within reefers, implementation of Radio Frequency Identification (RFID) tags for cargo temperature monitoring, investigating the relationship between transport conditions and fruit and vegetable quality, and advancements in refrigeration technology.

The current study aims to add to this knowledge by providing perspectives and opinions of researchers and engineers who have worked in the reefer industry for over two decades. We present insights into the current knowledge state and highlight potential areas for future exploration in reefer containers. We particularly tackle the fresh produce reefer market (section 2), the climate inside the reefer (section 3), sustainability (section 4), and the move towards smart reefers (section 5). We sketch the evolution of this industry with upcoming trends and key bottlenecks. Thereby, people working in this field get an update, or people starting in this field receive a practical perspective on the industry.

2. Economic and market figures

The forces of supply and demand primarily determine reefer container freight rates. Between 2017 and 2019, the global average freight rate remained relatively stable at approximately $3,000 per transport. However, during the Covid-19 pandemic, the average freight rate experienced a substantial increase, reaching over $6,000 in the third quarter of 2022 (Gray, 2022). Recent information indicates that freight rates show signs of decline in 2023.

The value of reefer cargoes varies depending on the type of goods being transported. For instance, a load of bananas may have a value after transport of around $20,000, while a load of avocados could be valued at $60,000. More delicate items, such as cut roses, may cost $100,000 per shipment. These numbers strongly depend on the product and its quality (e.g., organic produce compared to regular). They represent the value after transport, which the importer purchases, and not the higher market value.

Table 1
Characteristics of reefer containers.

Variable	Value
Global reefer fleet size (TEU)	3.2 million
Global reefer fleet size (no. of containers)	1.6 million
Share of 40ft HC reefers	95%
Share of controlled atmosphere (CA) containers	15%
Price of a newbuild 40ft High Cube (HC) reefer	$18,000
Average freight rate ($ per shipment, global)	$3,000
Reefer cargo value ($/shipment)	Typically between $20,000 and $100,000
Average power consumption	2 kW
No. of shipments (shipments per year per container)	3.2
Average cargo weight (tonnes)	20
Typical container lifespan (years)	15

The manufacturing prices of new build 40-foot HC reefers experienced stability and a downward trend, ranging between $15,000 and $18,000 from 2010 to 2018. However, since then, several major disruptions, including the Covid-19 pandemic, have likely exerted upward pressure on prices due to inflated input prices and higher demand from the market. One factor contributing to the relatively low reefer equipment prices is the highly optimized economies of scale, coupled with the majority of production concentrated in China. An initiative by Maersk Container Industries (MCI) to manufacture reefers in Chile (close to producer markets) was abandoned after only a few years. Afterward, MCI consolidated its manufacturing in one factory in China, citing proximity to suppliers and efficiency gains of consolidation as key reasons (FreshFruitPortal.com, 2018).

A reefer container consists of both a container box and a refrigeration unit. Four manufacturers are responsible for producing the reefer containers, manufacturing the insulated container box, and installing the refrigeration unit: China International Marine Containers, Dong Fang International Containers, Guangdong FUWA Engineering Group, and Maersk Container Industries. All production of these container boxes is centered in China. Four reefer manufacturers are responsible for producing refrigeration units: Carrier Transicold, Starcool by Maersk Container Industries, Daikin, and Thermo King. Their primary production facilities are in China, Singapore, and Japan. The dominance of these few companies in the market has persisted since 2000 or even earlier.

There has been significant consolidation among reefer carriers (container shipping lines) over the past decade(s). Presently, the global reefer container fleet comprises approximately 3.2 million TEU, with Maersk and MSC each having roughly 20% of the market. The top 10 carriers collectively control over 80% of the global fleet. Moreover, not all carriers are present in all trade lanes, limiting the options to shippers when selecting a carrier for their cargo. This limited choice raises concerns about the potential formation of oligopolies through alliances, posing a threat to the resilience of global food supply chains and can impact the cost of transporting goods. Nevertheless, the refrigerated transport market is still experiencing an ongoing shift towards reefer containers, indicating a flexible, cost-effective, and often more sustainable mode of transportation away from airfreight and conventional refrigerated vessels (Castelein et al., 2020).

Reefer slots on container ships, capable of accommodating operating reefers, represent only a limited share of container slots onboard vessels. The characteristics of a reefer slot include an electric power supply plug, accessibility for mechanics to the reefer unit, and a system to dissipate the heat generated by the reefer unit (Wild et al., 2005). The proportion of reefer slots varies across vessels, depending on the trade lanes they service. Reefer slots typically occupy 15%–25% of the container slots on the vessel for the top 10 container carriers (Drewry, 2019).

3. Climate inside the reefer

In reefer containers (Fig. 1), the interior climate is controlled to extend the postharvest life of the transported fruit and vegetables. When discussing the indoor climate, we mean temperature, relative humidity, and oxygen, carbon dioxide, and ethylene concentrations. The discussion below is based, among others, on expert knowledge from the team of authors.

3.1. Temperature

In cold rooms, refrigerated trailers, and refrigerated containers, the conventional practice involves regulating the temperature using a single control sensor to maintain it at the desired set point. The positioning of this control sensor is crucial. If the sensor is not placed in the coldest area of the space, there is a risk of cold-related injuries, such as chilling or freezing injuries, particularly when there is high cooling demand.

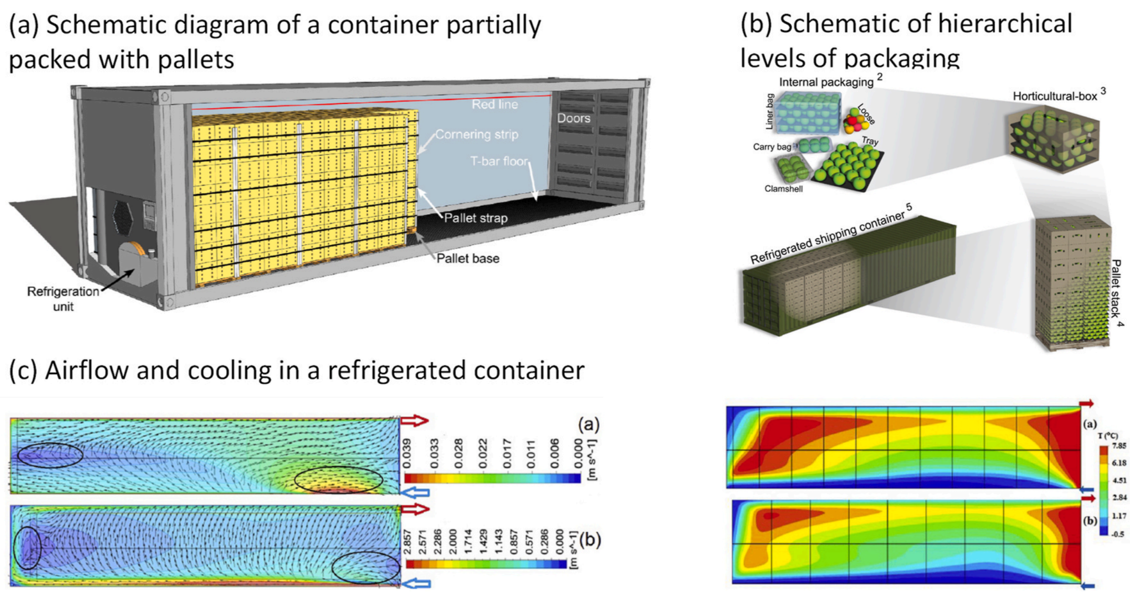

Fig. 1. Overview of refrigerated containers and the airflow conditions within. (a) Schematic diagram of a container partially packed with pallets. (b) Schematic diagram showing the various hierarchical levels of packaging in a refrigerated container. (c) Images of fluid dynamics simulations of selected studies on refrigerated containers (adjusted from (Tarl M Berry et al., 2022a; Tarl Michael Berry, Defraeye, & Ambaw, 2022b; Getahun et al., 2017)).

Typically, the refrigeration unit of a reefer has at least one sensor for the supply air and at least one sensor that senses the return air. When the setpoint is colder than −10 °C (in frozen mode), the control sensor is the return air temperature sensor.

Conversely, when the setpoint is above −10 °C (in chilled mode), the control sensor is the supply air temperature sensor. The changeover temperature varies by reefer manufacturer. As a result, in chilled mode, the coldest part of the cargo is either not colder than the setpoint or only slightly colder, which reduces the risk of chilling or freezing injuries during transportation. Nonetheless, temperature variations are inevitable within the cargo space, with the area near the doors (farthest from the refrigeration unit) being warmer than the area near the unit.

It is desirable to minimize these temperature gradients to ensure cargo quality, keeping all parts of the cargo within an acceptable temperature range for the specific product. Furthermore, the temperature gradient within the cargo space also affects humidity levels. However, mapping or monitoring the temperature heterogeneity of the air and the foods in the container remains challenging.

A key bottleneck is that access to the cargo is often hindered, so it is not easy to place and retrieve the sensors, as they are placed only after packaging. Sensors are typically placed at easy-to-access locations, such as corners of the pallets or on top of pallets. The human resources, time, and sensor costs associated with such monitoring are often high enough that stakeholders decide not to do it, despite the high value of the cargo. However, the cost of sensors is decreasing, and the sensors can be integrated even within food packaging, hence avoiding separate placement and handling. These developments in enhanced temperature monitoring can outweigh the additional expenses in the future. These developments can encourage a broader range of stakeholders to embrace the improved monitoring approach.

3.2. Humidity

As the air temperature decreases, its relative humidity increases. Therefore, in closed, cooled spaces where fresh produce is stored, the relative humidity often exceeds 90%. This high humidity can lead to condensation or frosting in the coldest areas and on the food product, whereas transpiration (water loss) will occur in the warmer or low humidity zones. Transpiration is undesirable as it causes shrinkage and weight loss in the fruit and vegetables.

Unlike cold rooms, reefer containers are not optimized to minimize transpiration as they serve multiple purposes, transporting various goods, including frozen meat, chilled fruit and vegetables, chilled flowers, chilled pharmaceuticals, and electronics, often at room temperature. In reefer containers, the emphasis is on minimizing space and equipment weight for efficient cargo transport rather than optimizing humidity control. As a result, transpiration in reefer containers tends to be higher than in cold rooms. Such cold rooms are typically designed specifically for storage of fresh-produce for several weeks or months.

Reefer containers can only actively dehumidify, not humidify. The dehumidification capacity is limited, and the set relative humidity is often not reached (L. Lukasse & Leentfaar, 2020). For most cargoes, it is generally recommended to leave humidity uncontrolled. Humidity monitoring is advised to determine whether the targeted range for the fruit or vegetables is maintained.

3.3. Oxygen, carbon dioxide, and controlled atmosphere

Certain reefer containers may have an additional feature installed to implement Controlled Atmosphere (CA) transport to lower the respiration of fresh produce. This technology has existed since around 2000, and the proportion of CA-equipped reefers has steadily increased over the past decade, accounting for approximately 15% of the global fleet. Ensuring sufficient air tightness in CA shipments is crucial to maintaining optimal oxygen (O_2) and carbon dioxide levels (CO_2), which can differ significantly from the ambient atmosphere. The most common source of air leakage is through the door gaskets. CA containers are equipped with CA curtain rails near the doors to address this. During CA shipments, a CA curtain is fixed to the rails using a ribbon to minimize air leakage through the door gaskets.

All four major reefer unit manufacturers now offer CA solutions, categorized as active and passive CA. Active CA systems introduce nitrogen-rich air into the container to reduce oxygen. Passive CA relies solely on the respiration of the fruits to deplete oxygen. Passive CA is simpler and less expensive, but its effectiveness is highly dependent on both the product's respiration rate and the air tightness of the container, and it cannot be controlled.

In the coming years, we anticipate a shift towards more active CA containers, as achieving sufficient air tightness for passive CA is often not always possible as the equipment ages. In the past years, there also has been a push to reduce the environmental impact of airfreight-transported fruits, vegetables, and flowers. Shifting this cargo onto ships often requires CA technology to compensate for the additional transport time.

Note that a vent in non-CA containers allows fresh air exchange for perishable cargo such as fruits, vegetables, and flowers. Without adequate fresh air exchange, the respiration of fruits, vegetables, and flowers can lead to high levels of CO_2 or ethylene, affecting their quality.

3.4. Ethylene

Ethylene is a volatile compound released by climacteric fruits and vegetables associated with ripening processes (Hu et al., 2019). A general guideline is to maintain ethylene levels sufficiently low. In fruit reefer containers, measures are regularly implemented to reduce ethylene concentrations. These measures include fresh air exchange in shipments conducted under regular atmosphere conditions and the use of ethylene scrubbers. Most commercially available ethylene scrubbers use potassium or sodium permanganate. In addition, a system exists for ozone treatment in refrigerated containers which also destroys ethylene as a side effect.

Numerous commercial suppliers offer ethylene scrubbers, also known as absorbers or filters. Installing ethylene scrubbers is standard practice in controlled atmosphere shipments where no fresh-air exchange is possible. However, it is not uncommon for ethylene scrubbers to be utilized in regular atmosphere shipments. Unfortunately, measuring ethylene levels during transit poses challenges as small sensors with sufficient sensitivity and a low cost are not (yet) available. As a result, there is a lack of data on ethylene concentrations occurring during reefer transport. Due to the infrequent measurement of ethylene levels, the effectiveness of scrubbing procedures is seldom verified. This subject requires increased attention and research within the postharvest community.

4. Sustainability

The sustainability of the fleet of refrigerated containers becomes increasingly important. Sustainability encompasses multiple dimensions, including social, economic, environmental, and governance aspects. Here we limit ourselves to the environmental aspects only. Within the category of environmental aspects, we focus on food losses and greenhouse gas (GHG) emissions.

4.1. Food losses

Food losses pose a significant challenge within the global food system, with approximately one-third of all food produced for human consumption being lost or wasted globally (Gustavsson et al., 2011). This amounts to a staggering 1.9 billion tons of food lost yearly (Xuezhen Guo et al., 2020). These food losses include foods with high moisture content, such as fruit and vegetables, and foods with low moisture content, such as seeds, grains or coffee beans. Refrigerated containers are used for foods with a high-moisture content to maintain the cold chain. Low-moisture content foods typically do not need refrigeration but an appropriate hygrothermal climate and packaging, which is called the 'dry chain' (Bradford et al., 2018).

Reefer containers transport approximately 0.1 billion tons of food annually. This value is estimated based on the number of reefers, shipments per year, and average cargo weight (Table 1). Likely, the direct impact of reefer transport on food losses is less than 1% of reefer container shipments result in cargo claims (Miller, 2023), and most of these claims do not involve a complete loss of cargo. Can reefer transport still have an indirect and more substantial impact on food losses? The answer is yes. Any partial loss of quality during transport further diminishes the remaining shelf life of the transported goods along the supply chain, thereby increasing the risk of food losses and waste downstream. Quality deterioration can occur due to suboptimal temperature, humidity, and gas conditions, as well as delayed deliveries, which accelerate the rate of quality loss. The main problem is that the extent of this loss of quality is difficult to quantify for every single shipment. Fortunately, the ongoing advancements in utilizing physics-based models or data-driven machine learning models to complement traditional quality decay models help capture the variations in shipments, thereby enhancing the understanding of shipment heterogeneity (Thijs Defraeye et al., 2020).

4.2. Carbon footprint and comparison to other transport modalities

Numerous studies have been conducted to quantify the carbon footprint associated with various modes of transportation. An extensive collection of CO_2 emissions for different transport modes can be found in (gov.UK, 2023). Typically, the carbon footprint of transport is measured in kilograms of CO_2-equivalents emitted per kilometer of transport for one metric ton of goods (kg CO_2-eq per ton per km). The CO_2 emissions from refrigerated transport are attributable to transportation and refrigeration. Table 2 presents some typical values for these emissions.

In the refrigeration column, the value for Heavy Goods Vehicles (HGVs) is set at 0.01257 kg CO_2-eq per ton per km, based on the disparity between refrigerated and non-refrigerated diesel-driven HGVs as indicated in (gov.UK, 2023). This approach demonstrates that refrigeration increases the CO_2 emissions from transport by 16% for heavy goods vehicles. Other studies often assert that refrigeration accounts for approximately 20% of energy consumption in refrigerated road transport (Tassou et al., 2009). For refrigerated rail transport, we have chosen to set the greenhouse gas (GHG) conversion factor for refrigeration equal to that of HGVs, as a significant portion of rail transport (particularly in Europe) involves 45ft reefers with similar volumes to semi-trailers and equipped with the same trailer refrigeration units.

Consequently, we anticipate minimal differences between road and rail transport. The energy usage for container refrigeration is calculated based on the findings of (Fitzgerald et al., 2011), who estimated that intercontinental apple transport via reefer containers emits approximately 0.018 kg CO_2-eq per ton per km, with 19% attributed to refrigeration. The power consumption of reefer units that was reported (Fitzgerald et al., 2011) aligns reasonably well with our experimental observations (L. Lukasse et al., 2012; L. J. S. Lukasse et al., 2011).

The ratio of CO_2 emissions for air transport: road transport: rail transport: ocean transport is approximately 60 : 6: 3 : 1 (Table 2). Therefore, shifting from airfreight to container transport presents a significant opportunity to reduce the carbon footprint of global supply chains. Table 2 also indicates that refrigeration accounts for approximately 20% of the total emissions in all transport modes except air freight. Consequently, investing in more efficient transport refrigeration systems is a worthwhile endeavor. However, the main reduction in energy consumption during ocean transport lies not in refrigeration but in the transport by the ship itself.

For this reason, ships are now implementing smart steaming. Here the ship's speed is dynamically optimized to avoid waiting times at ports and ensure they meet their time window at the port. Ships can cruise at lower speeds between ports to save as much energy as possible while still

Table 2
The carbon footprint of refrigerated transport modalities per distance unit and per amount of food being transported (kg CO_2-eq per ton per km) (source (gov.UK, 2023)).

Transport mode	Transport	Refrigeration	Total
Ocean (reefer container)	0.01267	0.00342	0.01609
Rail	0.02782	0.01257	0.04039
Heavy Goods Vehicles (>33t)	0.08032	0.01257	0.09289
Long-haul flights	1.01890	0	1.01890

meeting their time window at the port. In case that time windows at the port can also be shifted, this optimization strategy will make controlling food quality upon arrival even more challenging since ships will all start to cruise 'smart'. However, smart steaming and newer, more sustainable ship technology developments are essential to contribute to reducing the carbon footprint of food transport.

4.3. Refrigerants

Refrigerants with an ozone depletion potential (ODP) greater than zero have long been prohibited, but the focus has now shifted to global warming potential (GWP) as a significant concern. Table 3 lists ODP and GWP values for refrigerants used in container refrigeration units. For example, R134a has a GWP of 1430 CO_2-eq, meaning that a leak of 1 kg of R134a contributes to global warming as much as 1,430 kg of CO_2 does.

Container refrigeration units typically contain approximately 5 kg of refrigerant. Different refrigerants have been used chronologically, including R12, R22, R404A, R134a, R452A, R744 (CO_2), and R513A. When refrigerants are released into the atmosphere, they evaporate and contribute to environmental issues as potent greenhouse gases. Additionally, early refrigerants such as R12 and R22 were found to deplete the ozone layer (Bolaji & Huan, 2013). Consequently, there has been a growing focus on enacting stringent legislation, primarily by the EU, to promote the adoption of more environmentally-friendly refrigerants (Mota-Babiloni et al., 2015). This drive for sustainability extends beyond container refrigeration to the wider refrigeration industry.

Currently, the dominant refrigerant in the reefer container industry is R134a, with an estimated 90–95% of today's reefer units charged with this refrigerant. Approximately 5% are charged with Thermo King's R404A, which R452A has replaced in recent years. Less than 1% of reefer units use R513A, which has 50% lower GWP than R134a. Carrier introduced its NaturaLine unit in 2011, running on R744 (GWP 1, CO_2) (Shaw, 2011). Since 2017, Maersk Container Industry's Star Cool has manufactured all units to run on either R134a or R513A. In 2018 and 2019, Carrier and Daikin followed suit with similar options. In 2021, Thermo King started moving away from R404A with the launch of its new Container Fresh & Frozen (CFF) model, which runs on R134a or R513A. Currently, the market share of R744 and R513A is insignificant, as their adoption is heavily influenced by future environmental legislation. Over the past few decades, there has been a clear shift towards more environmentally friendly refrigerants. They may be slightly less energy-efficient due to less favorable thermodynamic properties and potentially slightly less safe. A review on this subject is available (Vuppaladadiyam et al., 2022).

Recent EU legislation, which is currently subject to further debate, has adopted measures prohibiting hydrofluorocarbons (HFCs) refrigerants entirely in new reefer containers starting from January 2029. Meanwhile, the US Environmental Protection Agency (EPA) established a Global Warming Potential (GWP) limit of 700, effective January 2025. However, the extent of the EPA regulation remains unclear, particularly regarding its scope and applicability. Currently, the fluorinated gases (F-gas) regulation covers equipment that is "placed on the market." It is uncertain whether European companies would be permitted to purchase reefers containing HFCs manufactured in third-party countries beyond the proposed date.

5. Smart reefers

The term 'smart container' is widely used to refer to containers equipped with telematics devices that enable real-time tracking and monitoring of climate conditions recorded by the reefer unit. This technology enhances control over supply chains and equipment. Smart reefers became commercially available around 2015, and approximately 50% of the global fleet is currently equipped with these devices. It is anticipated that in a few more years, all reefers in service will be 'smart'. However, technology is still evolving, and issues like occasional transmission of erroneous data and missing data persist. We anticipate that these initial challenges will soon become rare exceptions as technology matures. All these systems are integrated within the refrigeration unit's hardware and software systems. Access to the data, therefore, needs to go through the unit manufacturer's data access dashboards (CP, 2020).

Additionally, container-independent advanced telematics systems are being developed (Jedermann, 2009; Jedermann et al., 2017; Lang et al., 2011), and several sensor companies provide solutions for remote monitoring in refrigerated containers. These systems collect data from wireless sensors placed on or in pallets and boxes, which are transmitted to the cloud. These data often are only accessible to the stakeholders commissioning the placement of the sensors, which can be importers or retailers. Refrigerated container owners do not have automatic access to these data. So, two separate systems exist that collect information on the climatic conditions in the reefer unit: one by the container operators and one by the stakeholders shipping the cargo via commercially-available sensors. We believe that integrating data gathered by the telematics system of smart reefers with information recorded by wireless sensors on pallets and boxes is essential and inevitable as a next step to better preserve fruit and vegetables during transport. Using API's (Application Programming Interfaces), this should be feasible. This principle could be extended to other unit operations of the supply chain, where data engineers can work to synergize data acquisition pipelines of different systems further. We see a large added value that can be created by gathering and streamlining data and information acquisition to improve decision-making.

The concept of advanced monitoring in smart reefers offers several advantages. It presents an opportunity to support the implementation of quality-controlled logistics using digital twins. Present-day logistics for perishables predominantly rely on the FIFO (First In, First Out) principle, but the FEFO (First Expired, First Out) approach has the potential to reduce losses and increase profits. Quality-controlled logistics, through sensors and (reliable) quality decay prediction algorithms, provides ample opportunities to enhance efficiency in the fresh food chain, reduce logistics costs, and mitigate food losses (Guo et al., 2021). Imagine having the capability to monitor relevant environmental parameters and precisely estimate the remaining quality of fruit and vegetable batches during transit, as well as predict their future quality evolution. The currently available real-time remote access to temperature readings and other climate parameters should enable stakeholders to form better-informed opinions about the quality development of fruit and vegetables during transit and make their logistics decisions accordingly.

It would be advantageous to leverage this superior information for improved decision-making processes (Tromp et al., 2012). As a result, multiple new initiatives are being observed that use the available hygrothermal data in the reefer unit and metadata on the food being transported to predict food quality development during transit. One of these activities is the development of digital twins of fruit and vegetable supply chains and food in reefers (Defraeye et al., 2020; Guo et al., 2021;

Table 3
Ozone depletion potential and global warming potential of refrigerants of container refrigeration unit (Wikipedia, 2023).

Refrigerant	R12	R22	R404A	R134a	R452A	R744 (CO_2)	R513A
ODP [kg of R11)/kg]	1	0.055	0	0	0	0	0
Net GWP over 100 years [CO_2-eq]	10,200	1,760	3,922	1,430	1,945	1	573

Jedermann et al., 2022), which aims to make full use of real-time remote access data to improve quality prediction. A digital twin is a digital representation of its physical counterpart. This counterpart can be a single fruit or vegetable (T. Defraeye et al., 2019; Shrivastava et al., 2022), a package of products, or even an entire reefer unit. Digital twins are fed with (preferably) real-time data from the reefer unit and predict quality development in transit. The digital twin calculates actionable metrics on food quality, such as remaining shelf life, firmness, color, mass loss, risk of thermal damage, and pest mortality rates. These metrics are then employed for decision support in handling the fruit and vegetables during subsequent stages of the supply chain. Digital twins can also simulate the impact of controls and decisions before implementing them on their physical counterparts, i.e., the reefer unit.

Very simple digital twins can be created. These models can be physics-based or data-driven. Data-driven models can use classical generalized linear regression or AI models, such as machine learning. At a minimum, it consists of a food quality prediction model that is continuously fed with measurements of environmental conditions during transport. The ease with which 'digital twins' of a fruit or all fruits in the cargo can be generated induces a danger, namely that less accurate or representative digital twins populate the reefer industry. This can severely damage trust in this technology in the coming years. When deploying digital twins, rigorous verification and validation must be performed. Food quality should be addressed together with ethical and societal values such as the autonomy of the twins in decision-making and carbon footprint, to maintain explainability and trustworthiness of digital-twin solutions.

These 'smart' refrigerated containers will form an important building block in future smart supply chain and logistics networks (Freitag et al., 2022). Other supply chain components that will play a role are, among others: the vessel size, capacity, and type; the depth and restrictions of the canals through which the ships and logistic routes are passing (e.g., Suez, Panama); the number of available ships in operation and in transit; the number of cranes in ports and the resulting peak loading capacity; other port infrastructure such as storage capacity in the terminal's container yards; the port's hinterland logistics infrastructure; the climate and weather conditions; the maritime accessibility of growing regions. These will, in turn, determine the speed at which these containers and the goods within are transported.

Apart from the use of smart reefers and digital twins for the cold chain, similar concepts could also be deployed for low-moisture content foods. These technologies could help to minimize mycotoxin accumulation and insect infestations, and improve food quality and safety. As a result, food losses are reduced and public health is protected better (Bradford et al., 2018).

6. Conclusions & outlook

We have synthesized several key findings, developments, and perspectives in the reefer container shipping industry:

- The industry has experienced significant consolidation among carriers in recent decades. The three largest reefer carriers now operate the majority of the fleet, resulting in limited choices for shippers in many trade lanes.
- The measured gate-to-gate food losses during reefer container transport are relatively small compared to global food losses in supply chains. However, the indirect quality loss and its impact on the final food loss at the end of the chain is not measured. Any quality loss during transport reduces the remaining shelf life downstream, increasing the risk of food losses and waste.
- The carbon footprint of fresh food transport by reefer stays significantly lower compared to air transport, with a ratio of 60:1, depending on the supply chain. This drives a continuous trend away from airfreight when transporting perishables.
- Considering the large and growing size of the fleet, there is a strong motivation to further reduce the carbon footprint by optimizing refrigeration and reducing fuel consumption during transport.
- Controlled atmosphere (CA) containers comprise 15% of the reefer fleet.
- The transition to low-Global Warming Potential refrigerants is already underway, but its implementation needs a continuous drive by legislation.
- More research and measurements are needed to assess the effectiveness of ethylene scrubbers in reefers, which can help manage the ripening process of certain fruits and vegetables.

The trend indicates that all reefers will eventually become 'smart reefers', where the cargo is monitored in real-time. Several research and R&D teams are exploring the potential of this concept to develop digital twins of fruit and vegetables in reefers, which can be utilized in quality-controlled logistics. Implementing certain aspects of these initiatives, such as real-time information and quality prediction models, is expected to occur rapidly, leading to significant opportunities for optimizing quality and reducing losses in reefer shipments. This rapid evolution should, however, be monitored carefully to ensure the verification, reliability, explainability, and trustworthiness of these new technologies.

Author contributions

L.L. conceptualized the study and acquired funding; L.L. did the project administration; L.L. performed the investigation and developed the methodology with key input of all other authors; L.L. developed the paper concept; L.L. wrote the original draft of the paper together with T. D. and R.S.; T.D. did the visualization; all coauthors performed critical review and editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and ChatGPT in order to improve the spelling, grammar, and style of the text. No additional original content was generated using these AI-assisted technologies. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data availability

Data will be made available on request.

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