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Identifying trade-offs in trans-continental citrus supply chains and the resulting conflicting stakeholder's incentives via physics-based, digital fruit twins

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A R T I C L E I N F O

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A B S T R A C T

Context: Postharvest supply chains are often confronted with conflicting requirements between maximizing fruit quality and postharvest life, minimizing food loss, and minimizing energy consumption during refrigerated transportation. For example, a commonly encountered trade-off is maintaining sub-zero temperatures in a shipment to kill the larvae of fruit pests while avoiding inducing chilling injury in the fruit. In this context, the question of "what fruit attributes matter most, and to whom" comes in. Supply chains involve multiple stakeholders, including growers, exporters, regulators, distributors, retailers, and finally the consumers. Each stakeholder has different targets to meet, and therefore, the aforementioned trade-offs are assessed in different ways. This situation thereby often raises conflicting incentives for decision-making in cold chain transport.
Objective: In this study, we identify the conflicting trade-offs between respiration-driven remaining quality, transpiration-driven moisture loss, mortality of fruit fly, incidence of chilling injury, risk of condensation, and environmental impact due to the energy consumed during shipping.
Methods: To this end, we developed physics-based digital twins of citrus fruit in a refrigerated container. The digital twin utilizes measured delivery air temperature in commercial shipments as an input. In addition, it employs mechanistic simulations to mimic the hygrothermal and physiological fruit behavior in a shipment in-silico. We used the actionable metrics from this digital twin and translated these into desirability functions, which assess how well a combination of metrics satisfies the goals defined by the respective stakeholder. With this approach, we mapped to what extent different shipping scenarios meet the targets of the key stakeholders in the citrus export supply chain, namely exporters, regulators, distributors, retailers, and also consumers.
Results and conclusions: Our findings show clear differences in how the desirability curves evolve over time for different stakeholders. We found that amongst all stakeholders, only the desirability curve of the regulator remains at a satisfactory level at the end of the supply chain. We also evaluated different shipping temperature scenarios and highlighted how the temperature trade-off manifests in different metrics. Here, we highlighted that any metric cannot be optimized in isolation without adversely influencing other metrics.
Significance: Our study bridges a large gap in the quantitative estimation of stakeholder perspectives by leveraging the complementary insights provided by digital twins. This is a key step toward involving all relevant stakeholders to design the best practices and policies influencing the citrus supply chain.

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1. Introduction

Postharvest supply chains often encounter conflicting requirements between saving food, saving energy, maintaining produce quality, and increasing profits, which gives rise to trade-offs. Fig. 1a schematically depicts the trade-offs encountered in the trans-continental shipment of citrus fruit. For instance, citrus fruit can host some insect larvae, such as the Mediterranean fruit fly (*Ceratitis capitata*; MFF), which is a perceived pest in several niche markets. Therefore, these fruits are shipped at low (and often sub-zero) temperatures to kill the larvae of fruit pests and prevent their potential introduction into foreign growing regions. However, shipping the fruit at temperatures below 2 °C can induce low-temperature thermal damage or chilling injury in the fruit, which renders the fruit unmarketable due to the appearance of rind pitting or discolorations (Zacarias et al., 2020). Another instance of conflicting requirements is maintaining high relative humidity around the fruit to

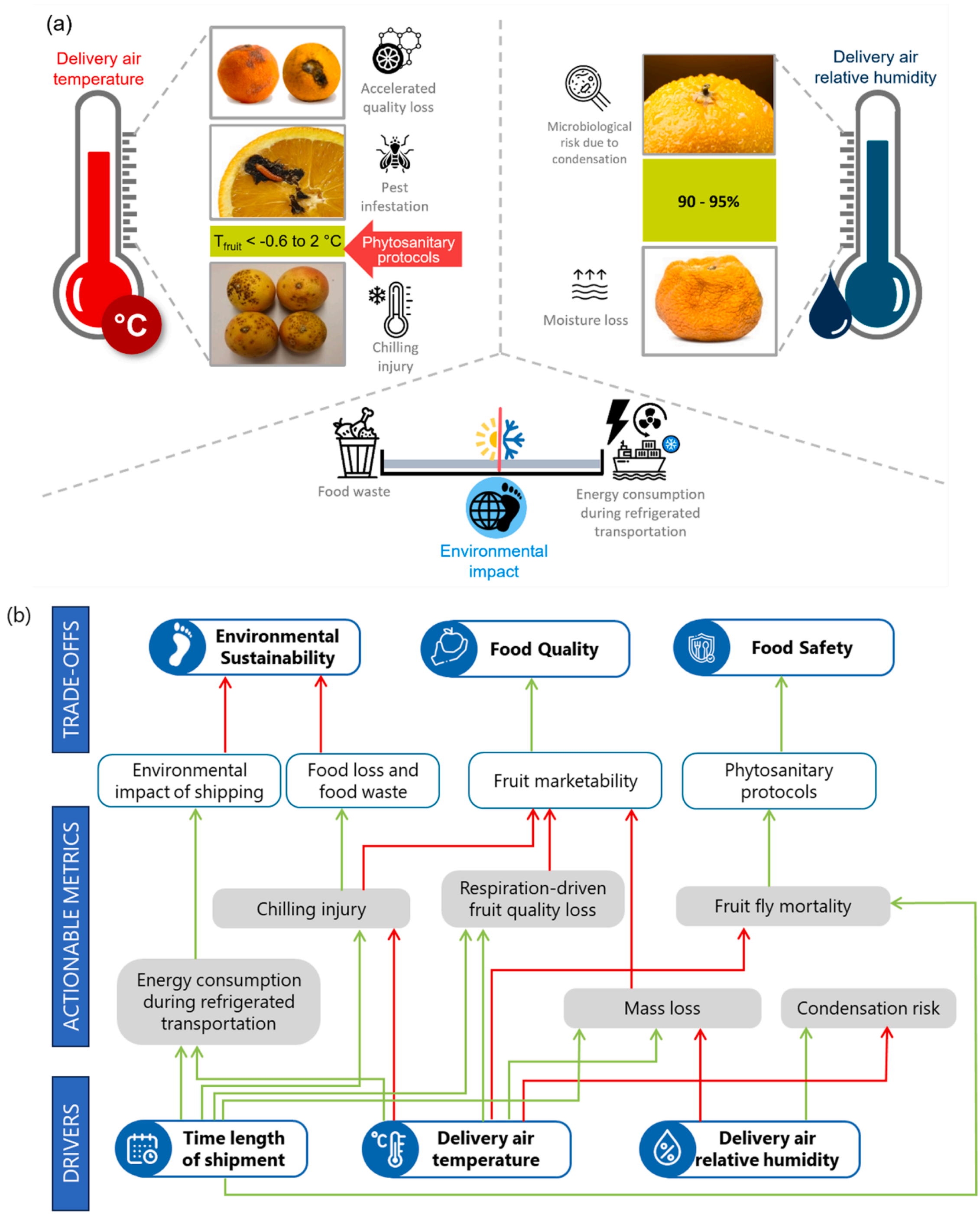

Fig. 1. Overview of the conflicting requirements encountered in the transport of citrus fruit in a refrigerated container: (a) Schematic illustration of the trade-offs for low and high delivery air temperature, relative humidity, and the environmental impact due to food loss on one hand and energy consumption due to refrigerated transportation on the other hand. (b) A map depicting how the complex trade-offs are interlinked and how the actionable metrics are intuitively linked with the controlled drivers of the supply chain, giving rise to conflicting requirements. The green arrows indicate a positive correlation (if A increases, then B increases), and the red arrows indicate a negative correlation (if A increases, then B decreases). Credit: Flaticon.com, shutterstock_1616078755, shutterstock_236770288, shutterstock_117097441, shutterstock_1929368918, shutterstock_1012970233.

reduce mass loss and wilting of the product, which could, however, stimulate condensation-linked microbial growth (Lado et al., 2019).

A fundamental trade-off also exists between the environmental impact associated with the use of energy-intensive refrigeration to prolong the shelf life of fruit as opposed to the environmental impact of food losses without it. Fig. 1b presents how these trade-offs are interlinked and lead to conflicting requirements in the transcontinental citrus export supply chain. Such maps are a starting point to make these trade-offs visible to different stakeholders. Moreover, as these factors are intricately correlated, optimizing this supply chain requires an analysis of the complete picture. Here, a singular focus or a one-metric-a-time optimization can create a different problem relating to another quality metric.

A typical agri-food supply chain involves multiple direct stakeholders, including growers, exporters, distributors, retailers, and consumers, as well as indirect stakeholders, such as regulators. Each of these stakeholders has different targets to achieve and, therefore, perceives these conflicting requirements differently. For instance, a key priority for exporters and regulators in the citrus industry is to maintain an effective cold treatment to minimize the phytosanitary risk. For citrus fruit imported from South Africa, this means that the fruit must be held between −0.6 and 3 °C for 2–3 weeks for disinfestation against the Mediterranean fruit fly, according to the protocol of the importing country (Perishable Products Exports Control Board PPECB, 2019). Additionally, distributors and exporters strive to minimize energy consumption and, therefore, the associated environmental and economic costs associated with the refrigerated transportation of fruit. This can be achieved by periodically turning off the cooling fans or running them at a lower speed, which could, however, negatively impact fruit quality preservation. Lower energy consumption also lowers the direct environmental impact associated with refrigerated transportation. The priority of retailers is to maintain fruit quality (and thereby shelf life) and marketability attributes and have a minimal mass loss in the sellable fruit weight. Fruit quality attributes are more relevant to retailers as they are directly at the receiving end of any consumer complaints for sub-quality products, irrespective of the fact that the damage may have occurred upstream in the supply chain. Mold growth and visible fruit decay are, therefore, essential to avoid. Consumers are at the far end of the supply chain and demand fruit with good quality and acceptable shelf life, irrespective of the hygrothermal history of the fruit. They have limited knowledge of and control over the supply chain but wield significant influence through purchasing power.

In recent years, there has been an increasing focus on the social, environmental, and economic sustainability of agri-food supply chains (Baba et al., 2019). This is more so relevant for global supply chains, where the food travels long distances from farm to fork, i.e., the 'food miles' are higher. The importance of stakeholder participation in decision-making has been acknowledged as a key component of the design and management of supply chains. For instance, some studies have highlighted the gap in stakeholder perceptions of the definition of sustainability (AlWaer et al., 2011; Bråhová Foltýnová et al., 2020) and information sharing in the supply chain (Minnens et al., 2019). Several studies have identified the need to adopt systems thinking approaches in agri-food supply chains to capture complex interlinked problems (Jacobi et al., 2019). However, in food systems, complex and interlinked phenomena are still often reported and analyzed independently from each other (Jacobi et al., 2018).

We aim to bridge this gap in our study by exploring the trade-offs in the trans-continental supply chain of citrus fruit and assessing how different stakeholders perceive these trade-offs. In this multi-actor multi-criteria analysis, we identify the conflicting trade-offs between respiration-driven remaining quality, mortality of fruit fly, the incidence of chilling injury, transpiration-driven moisture loss, risk of condensation, and environmental impact due to the energy consumed during refrigerated transportation. To enable the identification of these trade-offs, we need additional information on the fruit that is transported and how its quality and marketability attributes evolve over time. To this end, we developed previously physics-based digital twins of citrus fruit in a refrigerated container (Shrivastava et al., 2022). The digital twin utilizes commercially-measured delivery air temperature as an input. It employs mechanistic simulations to mimic the hygrothermal and physiological behavior of the fruit in a shipment, in silico. In this study, we utilized the actionable metrics from this digital twin and translated these into metrics of 'desirability' for different stakeholders in the citrus export supply chain, such as exporters, retailers, regulators, and consumers. 'Desirability' is the degree of preference a stakeholder has towards a certain outcome for a product or system. We evaluated the multiparameter objective function to compute the overall desirability by assigning different weighing distributions for stakeholders. Additionally, we investigated different scenarios for shipping the fruit at −1.5, 0.0, 1.5, 3.0, and 4.5 °C to pinpoint where there is scope for improvement.

2. Materials and methods

2.1. Characterization of measured commercial shipments

Commercial shipments transporting 'Valencia' orange (*Citrus sinensis* (L.) Osbeck) fruit from South Africa to markets in the Northern Hemisphere were considered in this study. For these markets, shipments from South Africa need to follow the phytosanitary regulations for export, which entail maintaining the core temperature of the fruit between −0.5 °C and 2°C for 2–3 weeks (Perishable Products Exports Control Board PPECB, 2019). In 47 commercial citrus shipments from South Africa, sensors supplying data on air temperature in the vicinity of the fruit were installed during the loading of the cargo and retrieved at the time of unloading. More details on the placement of the sensors can be found in (Shrivastava et al., 2022). These data were linked with the physics-based model described below and upcycled into actionable metrics. Additional variants were simulated at delivery air temperatures of −1.5, 0.0, 1.5, 3.0, and 4.5 °C to test different shipment scenarios.

2.2. Continuum multiphysics model for citrus fruit

2.2.1. Computational system configuration

The computational system comprised a finite element-based mechanistic model of citrus fruit ('Valencia' orange) in a refrigerated container, which is in the vicinity of the measured temperature sensor. A detailed description of the validation and calibration of the models can be found in (Shrivastava et al., 2022). The fruit was modeled as a two-dimensional axisymmetric sphere with a diameter of 73.25 mm. The computational domain was divided into two major sections of the fruit – the outer rind (or peel) and the inner fruit pulp. In the model, we solve heat transfer in the fruit pulp and rind, evaporation and condensation at the surface, fruit quality decay, the efficacy of the cold disinfestation treatment against the Mediterranean fruit fly, and thermal damage due to chilling injury (Shrivastava et al., 2022).

2.2.2. Environmental impact due to energy consumption during refrigerated transport

Refrigeration while transporting citrus fruits is key to preserving fruit quality and marketability. However, refrigerated transport has its own environmental impact, especially due to energy consumption and CO_2 emissions. In order to evaluate the environmental impact over time of the refrigerated transportation of citrus fruit, the thermal model was coupled with dynamic calculations for energy consumption and the related environmental impact. To this end, a simplified life cycle assessment (LCA) methodology was employed, standardized within the ISO 14'040 series. The scope of this gate-to-gate life cycle assessment was refrigerated transport. Therefore, the environmental impact of the transportation stage was only evaluated from the port-of-export to the port-of-import. The environmental impacts during fruit cultivation, postharvest processing, packaging, inland distribution, retail, and end-of-life were not included. The functional unit was 1 kg of citrus fruit that arrived at the destination market. The shipments were transported from South Africa to markets in the Northern Hemisphere over 18 – 28 days. The fruit was loaded at 20 °C inside 40-foot high-cube refrigerated containers (reefer). As knowledge of the cartons used for packaging was unavailable, we assumed that Supervent boxes were used in all the shipments, corresponding to 0.074 kg of packaging used per kg of fruit. Based on this assumption, one pallet of Supervent cartons holds 5120 fruits. The environmental impact in terms of kg CO_2 eq per kg citrus fruit shipped was assessed for the following:

- electricity consumed to extract heat from fruit loaded in the container;
- electricity consumed to maintain the set air temperature in the container and
- transportation of fruit in a refrigerated container by ship

2.2.2.1. Extracting heat from produce inside the reefer. After loading the fruit at an initial temperature ($T_i = 20$ °C) into the container, the fruit needs to be cooled down further (to ~2.5 °C), which is close to the set air temperature of −1.5 °C. The time required to attain this temperature (T_f) of 2.5 °C is the seven-eighths cooling time (SECT, h) for the fruit. The energy needed for this cooling was computed using Eq. (1). The fruit was assumed to be at 20 °C at the time of loading. The energy required to cool citrus fruit (of mass m) from an initial temperature ($T_i = 20$ °C) to a final temperature ($T_f = 2.5$ °C) was calculated using Eq. (1). For the scenarios of shipment at different air temperatures, the value of T_f was adjusted.

$$E_e = \frac{m \cdot c_{p,f} \cdot (T_i - T_f)}{EC} \tag{1}$$

where E_e is the energy consumed (kJ), $c_{p,f}$ is the specific heat capacity of the system (kJ•kg^{-1}•K^{-1}). *EC* (kJ heat extracted/kJ energy consumed) is the energy coefficient (Thompson et al., 2008). *EC* varies with the type of packaging, and also with the unit operation. In our study, we considered Supervent packaging, for which the value of *EC* is typically 0.41 kJ kJ^{-1} (Wu et al., 2019). The electricity is supplied from the electricity generated in the container. To estimate the environmental impact of this electricity, we considered that it was coming from a diesel generating set (eco-invent activity referred to the “market for diesel, burned in diesel-electric generating set, 18.5 kW (GLO)”) since the cooling down can also be done in the container, prior to loading on the ship.

2.2.2.2. Maintaining the set air temperature inside the reefer. Once the product in the shipment has been cooled (up to the SECT), the power consumption of the container falls down. The power consumed to maintain the set air temperature in a reefer depends on many external variables, such as ambient, outside air temperature, location of reefer within the ship, and the set air temperature. Here, we considered the average ambient temperature along the latitudinal lines intersecting the route followed by the ship from South Africa to markets in the Northern Hemisphere during October, which was 19 °C. In the chilling mode, maintaining the container at lower temperatures consumes less power as the cooling unit operates at higher efficiency (Jolly et al., 2000). For example, a container consumes about 4.88 kW or 6.89 kW to maintain a temperature of 2 °C and 21 °C, respectively (GDV, 2022). The power consumption rate (P_e, kW) was calculated by interpolating the data for power consumption as a function of the set container temperature derived for a standard refrigeration unit.

2.2.2.3. Transportation of citrus fruit. For the shipments, the transport distance by sea by a transoceanic reefer was estimated to be 13,000 km, which is the mean distance from South Africa to markets in the Northern Hemisphere (www.sea-distances.org). The environmental impact due to transportation was computed as metric ton-kilometer (tkm), computed by multiplying the weight of fruit loaded (tonne) and the distance traversed (km). The waiting times at ports were not explicitly considered, although this might also impact energy consumption (Fitzgerald et al., 2011). The indirect impact of climate change due to refrigerants causing the depletion of the ozone layer was not considered.

2.2.2.4. Environmental impact of transport of the refrigerated container. The climate change-related environmental impact due to energy consumption during transportation by ship was evaluated by means of the global warming potential indicator (GWP, kg CO_2-eq) of the impact assessment method of IPCC (2013), considering a 100-year time horizon (Table 1).

2.3. Actionable metrics and their weightage for different stakeholders

Based on the above multiphysics model, the following actionable metrics were estimated for every shipment:

- lethality of the cold treatment against the larvae of Mediterranean fruit fly (days at 2 °C)
- respiration-driven remaining shelf life (days)
- environmental impact of the energy consumed during refrigerated transportation (kg CO_2-eq)
- net transpiration-driven mass loss (%)
- chilling injury incidence in fruit (%)
- risk of condensation (wetness hours)

2.4. Desirability function

’Desirability’ refers to the degree of preference of a stakeholder towards a certain outcome for a product or system. Desirability functions are often employed to solve the optimization of a process or product quality involving various quality characteristics or antagonistic responses (Akteke-Öztürk et al., 2015). With this approach, every metric is converted into a dimensionless value between 0 and 1 using desirability functions, with a higher value implying a ’more desirable’ outcome. Essentially, the approach translates the metrics to a normalized scale in the range [0,1] and combines the metrics into one overall metric using the geometric mean.

We fitted a dynamic desirability function ($d_i(y_i)$) for each quality metric (y_i). The desirability function takes a different form depending on the goal of the optimization. For the metrics that need to be maximized (larger-the-better), such as the remaining quality and lethality of the treatment against fruit fly larvae, the desirability function is presented in Eq. (2).

Table 1
Activity processes from ecoinvent database used for compiling the life cycle inventory of the present study and corresponding characterization factors (CF) from the IPCC 2013 impact assessment method.

Life cycle inventory dataset as in ecoinvent v.3.6	Inventory unit	Characterization factor (kg CO_2-eq/inventory units)
Market for diesel, burned in diesel-electric generating set, 18.5 kW (GLO)	1 MJ	0.2546
Market for transport, freight, sea, container ship with reefer, cooling (GLO)	1 tkm	0.0200

GLO, global. MJ, Mega joule; tkm, tonne x km.

$$d_i(y_i)^{\max} = \begin{cases} 0 \text{if} y_i < A \\ \left(\dfrac{y_i - A}{B - A}\right) \text{if} A \leq y_i \leq B \\ 1 \text{if} y_i > B \end{cases} \quad (2)$$

where A is the minimum, and B is the maximum acceptable value of y_i. The underlying idea is that when one of the quality characteristics of the process or product is not within the desired limits, the overall quality is not desirable (Akteke-Öztürk et al., 2015).

For the metrics that need to be minimized (lower-the-better), such as the environmental impact of energy consumption, mass loss, chilling injury, and condensation occurrences, the desirability function takes the form presented in Eq. (3).

$$d_i(y_i)^{\min} = \begin{cases} 0 \text{if} y_i > B \\ \left(\dfrac{y_i - B}{A - B}\right) \text{if} A \leq y_i \leq B \\ 1 \text{if} y_i < A \end{cases} \quad (3)$$

The choice of desirability function and the minimum and maximum acceptable values for every critical success factor are summarized in Table S1 of the Supplementary Material.

The overall desirability (D) was computed by combining the individual desirability values (d_i) using the geometric mean (Eq. (4)). The geometric mean is used as it has the property that if any one metric is undesirable ($d_i = 0$), the overall desirability also becomes unacceptable ($D = 0$) independent of the desirability value of other metrics. When the importance of the individual desirability functions is different, a weighing strategy is employed, where w_j corresponds to the relative importance of the metric (Akteke-Öztürk et al., 2015).

$$D = \left(\prod_{i=1}^{i=6} d_i(y_i)^{w_j}\right)^{\frac{1}{\sum_{i=1}^{i=6} w_j}} \quad (4)$$

We evaluated the multiparameter objective function presented in Eq. (4) by assigning different weighing distributions for the metrics. These different scenarios of weighting were inspired by how various stakeholders would assess the different metrics, discussed in the next section. An overall desirability value below 0.4 usually indicates that the solution or outcome is reaching an unacceptable state (Marinković, 2021).

2.5. Weighting the actionable metrics for different stakeholders

In this study, we considered the stakeholders relevant to trans-continental citrus shipments. These include exporters, retailers, regulators, and consumers. Growers and/or farmer cooperatives were not included, as this is beyond the scope of this gate-to-gate study. Each of the actionable metrics detailed above was translated into six critical success factors (listed in Table 2) (Wong, 2005). A critical success factor is an element that is necessary for a stakeholder or organization to achieve its goals. The weighting for the different actionable metrics was assigned based on the Stakeholder Priority and Responsibilities Matrix for actors in the food supply chain described in (Caracciolo et al., 2011; Smith, 2008). The factors were assigned a relative importance of low (1, +), medium (2, + +), and high (3, + + +). These weights were used in the overall desirability function (Eq. (4)).

2.6. Numerical implementation

The model was implemented in the finite-element-based modeling software COMSOL Multiphysics (version 6.0). The thermophysical and thermal damage models were implemented using the 'Bioheat Transfer' interface. All other models were implemented using the 'Ordinary Differential Equation' interface. The grid used in the present study comprised 6512 finite elements. A fully-coupled direct solver was employed based on the MUltifrontal Massively Parallel sparse direct Solver (MUMPS) scheme. The time step for the simulation was determined based on the sensor's logging interval. More details can be found in (Shrivastava et al., 2022).

3. Results and discussion

3.1. What are the key trade-offs encountered in the refrigerated transport of citrus fruit?

It is widely known that shipping fruit under refrigeration conditions consumes more energy than shipping fruit under ambient conditions without refrigeration. However, the absence of refrigeration lowers fruit quality and shelf life, therefore adding to food waste. Studies have reported that increasing the shelf life of citrus fruit by one day can reduce food waste by about 42.8 % (Broekmeulen and van Donsaleer, 2015). Therefore, it is vital to identify the optimal temperature that balances these conflicting requirements throughout the shipment duration, which could be anywhere between 18 and 28 days for citrus fruit shipped from South Africa.

Fig. 2 shows how the different actionable metrics and their corresponding individual desirability evolve over time for the 47 shipments analyzed in this study. Some of these changes are desirable; for instance, desirability increases over time to reduce the surviving fraction of fruit fly larvae. However, other changes are undesirable, such as increased energy consumption and environmental impact or an increased mass loss in fruit over time. The evolution of these metrics follows different trends. For example, quality is lost exponentially, whereas mass loss increases with time almost linearly under constant environmental conditions. The environmental impact due to shipping shows an almost linear increase over time, except at the beginning when the field heat is extracted from the fruit until they are cooled to the set air temperature. The evolution of these metrics, and thus the corresponding trade-offs, are not evident from measured sensor data. Therefore, physics-based models are important to capture these metrics and their desirability over time.

A clear four-way temperature trade-off can be deduced for citrus shipments between chilling injury, respiration-driven fruit quality, fruit fly mortality, and energy consumption during refrigeration (Fig. 2). Shipping the fruit at low temperatures (0 – 5 °C) reduces the rate of enzymatic and biochemical quality-degradation reactions, thus prolonging the fruit's shelf life. Lower temperatures (-0.6 – 3 °C) are also prescribed in phytosanitary protocols for cold disinfestation treatments against fruit fly larvae. Moreover, the refrigeration unit operates at a

Table 2
Relative importance of various critical success factors for the stakeholders involved in the refrigerated transportation of citrus fruit.

Critical success factor	Exporter	Regulator	Wholesaler/distributor	Retailer	Consumer
Achieving a high fruit fly mortality	++ +	++ +	+	+	+
Maintaining respiration-driven fruit quality and shelf life	++	+	++	++ +	++ +
Minimizing energy consumption and the resulting environmental impact during transportation	++ +	+	++	+	+
Minimizing transpiration-driven mass loss	+	+	++	++ +	++ +
Minimizing low temperature-induced chilling injury incidence	++	+	++ +	++	+
Minimizing the occurrence of condensation	++	+	++	++ +	+++

+ low; ++ medium; +++ high.

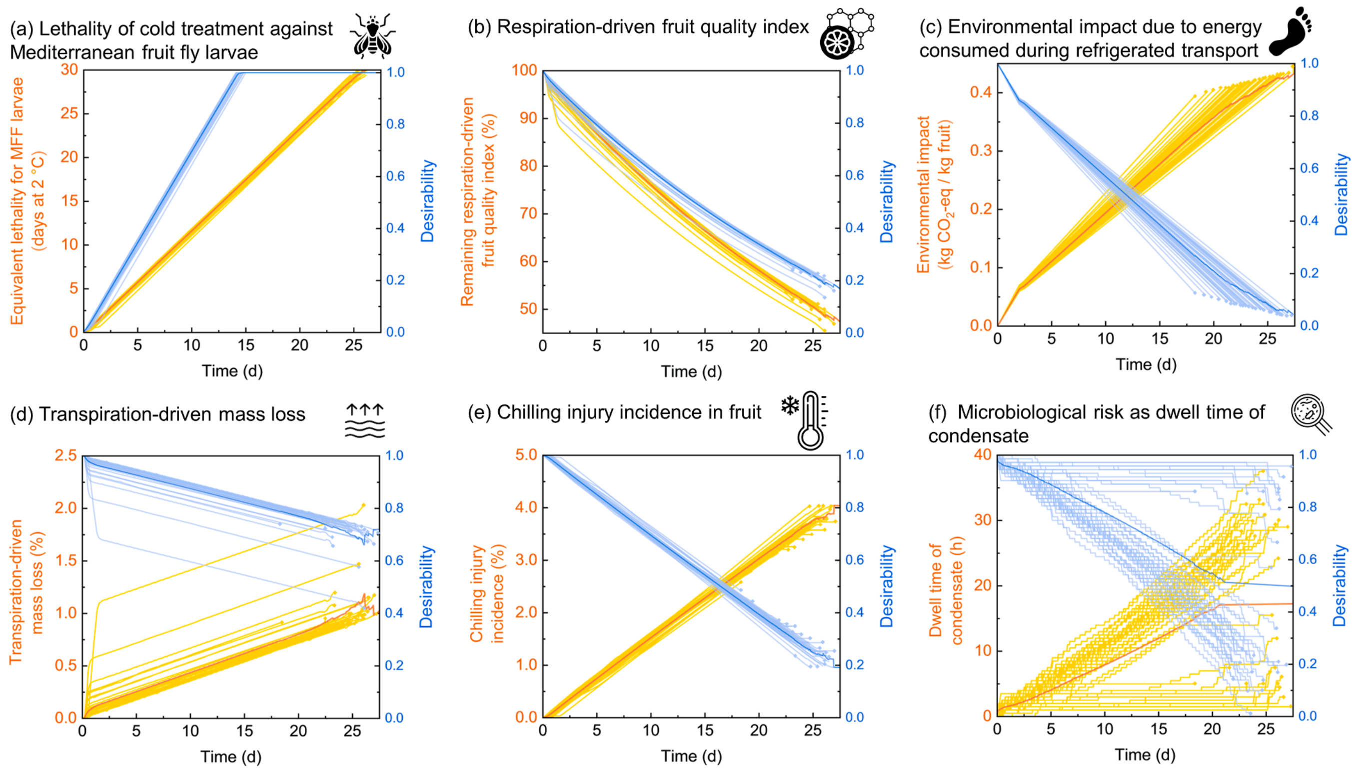

Fig. 2. Evolution of different actionable metrics (orange) and the resultant desirability (blue) over time for the 47 shipments analyzed in this study for the six metrics considered: (a) Lethality of the cold treatment against the larvae of Mediterranean fruit fly; (b) Respiration-driven fruit quality index; (c) Environmental impact of the energy consumed during refrigerated transport; (d) Transpiration-driven mass loss; (e) Chilling injury incidence in fruit; (f) Microbiological risk as dwell time of the condensate. The dark blue and orange lines in every plot correspond to the average value of the 47 curves. Credits: Flaticon.com.

higher efficiency at lower temperatures, thus consuming less energy (GDV, 2022; Jolly et al., 2000). However, low temperatures also cause considerable chilling injury to the fruit rind, lowering the fruit's marketability. Additionally, temperature also impacts moisture loss and the risk of condensation. Moisture loss is aggravated at high temperatures, whereas at low temperatures, even minor fluctuations in temperature can give rise to condensation. The implications of any deviations from the optimal temperature can be stark. For instance, if a shipment shows more than 5 % chilling injury, the shipment may be redirected to another market, thus increasing the associated food miles and likelihood of food waste. On the other hand, if the required phytosanitary protocol is not met, an entire consignment could get rejected and would need to be destroyed. Therefore, stakeholders are treading a fine line when navigating between these trade-offs.

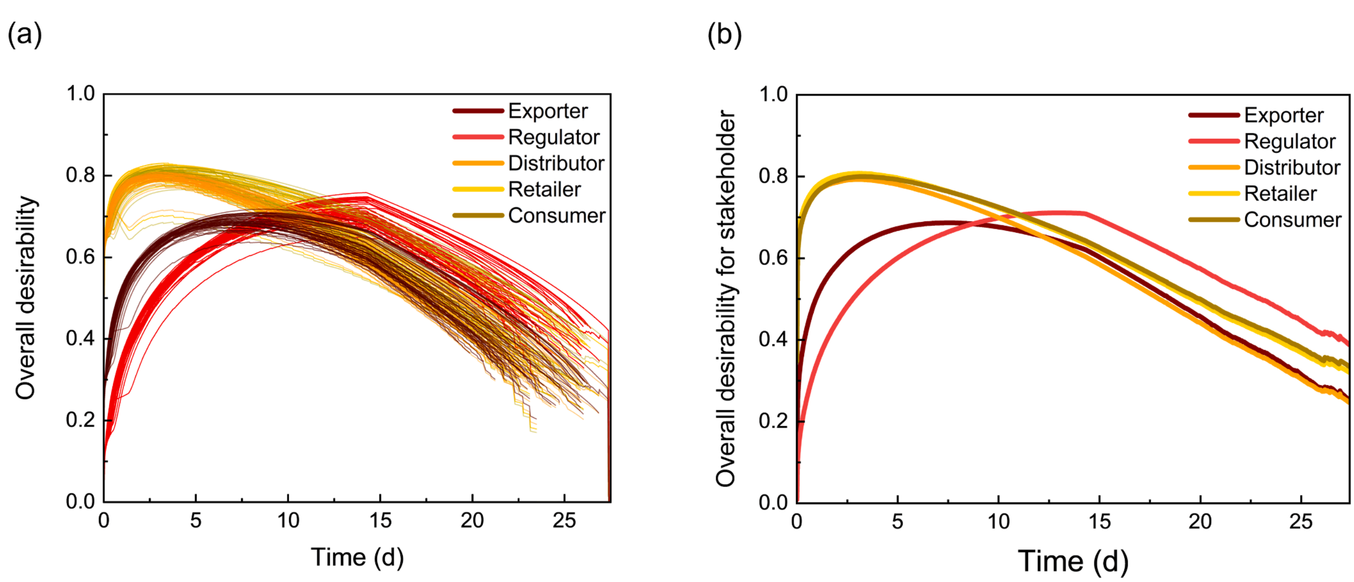

Fig. 3. Dynamic profiles of how desirability evolves for different stakeholders (exporters, regulators, distributors, retailers, and consumers) for the 47 shipments analyzed in this study. The set air temperature for these shipments was around −1.5 °C, and the shipping time was 18 – 27 days. In this figure, (b) represents the average of all the curves presented in (a).

3.2. Why is it difficult to reach a consensus among the supply chain stakeholders?

We evaluated the overall desirability as a function of time for different stakeholders, namely exporters, regulators, distributors, retailers, and consumers, based on the weighting assigned in Table 2. These desirability curves are presented in Fig. 3, where Fig. 3a shows the curves for all the 47 analyzed shipments, and Fig. 3b shows the averaged value of the 47 curves for each stakeholder. We observe a different curve trend for every stakeholder. The overall desirability of retailers, distributors, and consumers follows a similar trend, primarily because these stakeholders aim to obtain fruit with good quality and marketability attributes. The desirability reaches a maximum for all stakeholders, where after, it constantly reduces. For exporters, retailers, and consumers, the maxima is reached early on in the supply chain. Following this, the desirability declines almost linearly. For regulators, this maximum is reached when the required phytosanitary protocol is fulfilled at the respective air temperature, which is at about 14.5 days at -1.5 °C in the present case. Given that every stakeholder has different targets to achieve, such as saving food, saving energy, or maximizing profits, the discrepancies in stakeholder curves are not surprising. This gives rise to a lack of consensus in decision-making in the citrus cold chain.

3.3. How do we move from where we are now toward an improved situation?

To investigate how we could align the stakeholder curves, we evaluated digital twin variants at different delivery air temperatures for the shipment (-1.5, 0, 1.5, 3, and 4.5 °C). We considered a shipment time of 22 days since it is often difficult to control the shipping duration, as this depends on unpredictable logistical or hydro-meteorological factors. The final metric-wise desirability values for the different metrics at the end of a 22-day shipment are shown in the pie chart in Fig. 4. Note that the risk of condensation is not included here as we considered constant delivery air temperature, whereas condensation primarily arises due to temperature fluctuations.

In Fig. 4, the goal for moving towards an improved situation would be to fill up as much of the pie (blue circle) as possible in the most balanced way so that all the metrics simultaneously reach an adequate desirability value. Note that exceeding the pie (i.e., going beyond the blue circle, which corresponds to $d_i = 1$) does not contribute to an improvement in the situation. We see this in the case of the lethality of the cold treatment against fruit fly larvae, which is greater than the desired treatment efficacy for all temperatures at and below 3 °C. However, the target of Probit 9 mortality of fruit fly is already met when $d_i = 1$. On the other hand, as the fruit is shipped at a higher temperature, the desirability for remaining fruit quality and net mass loss is lowered. Therefore, the respective pie slices diminish with an increase in temperature. However, at higher temperatures, there is less chilling injury, so the desirability towards this metric is the highest at 4.5 °C.

Regarding the environmental impact due to the energy consumed during refrigeration, we do not see a clear change in desirability at different temperatures. This is primarily because, on the one hand, lower energy is consumed for maintaining a lower set air temperature in a container, as the refrigeration unit operates at higher efficiency (GDV, 2022; Jolly et al., 2000). In a contrasting situation, at a lower set air temperature, a larger amount of energy is consumed in the initial

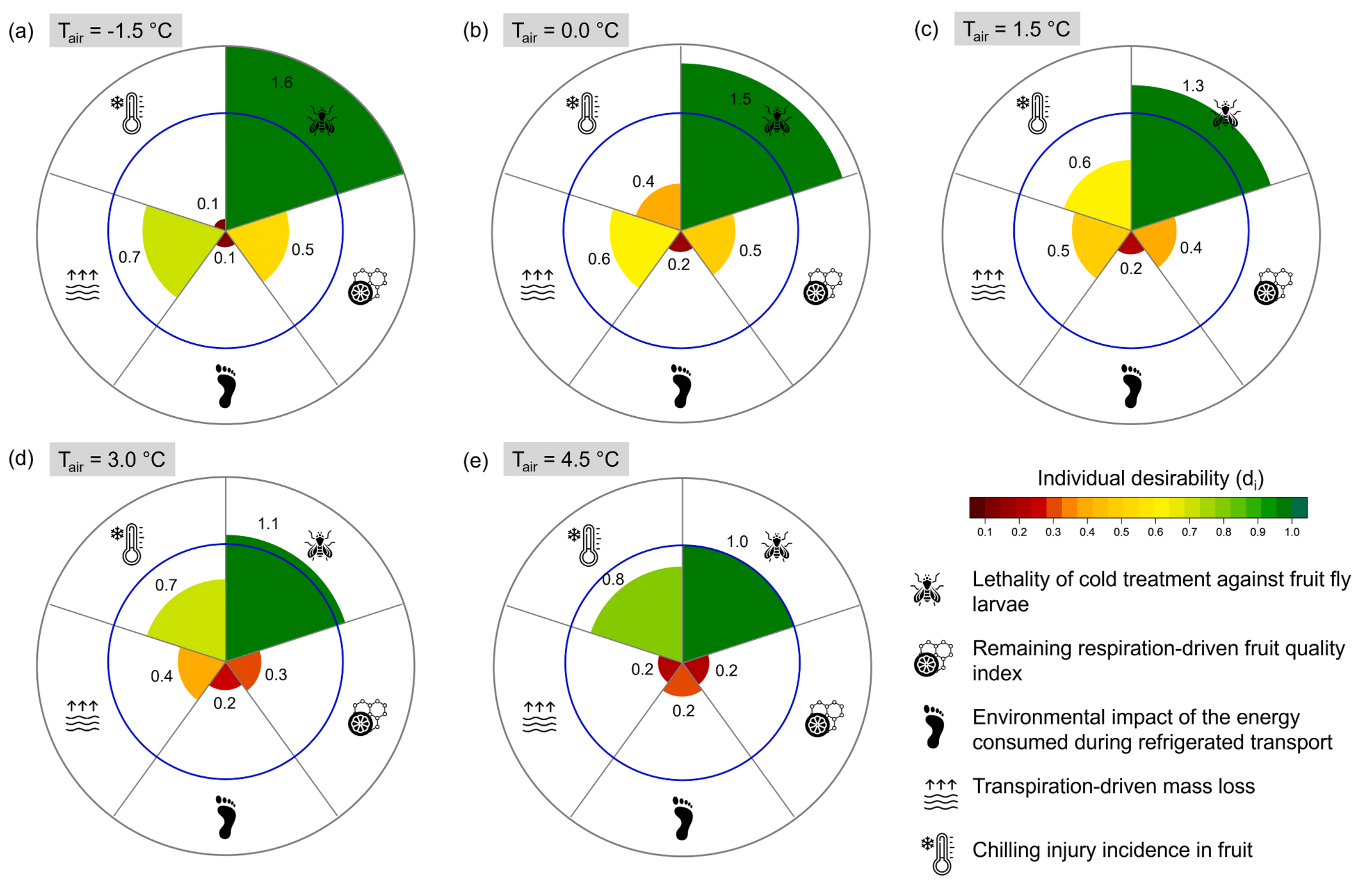

Fig. 4. Pie chart showing the individual desirability for the actionable metrics evaluated in this study at different delivery air temperatures between -1.5 and 4.5 °C. The reported values correspond to the desirability at the end of 22 days. The blue circle indicates a desirability value of 1, implying that the indicated target is achieved. Note that in this figure, the true values of lethality are represented for values greater than 1. However, in the dynamic curves, values higher than 1 are considered equivalent to 1 as the desired target is met.

pre-cooling stage to reduce the temperature of the fresh produce close to the set air temperature. It is noteworthy to mention here that the overall environmental impact of a shipment would be the contribution of the environmental impact of the energy consumed, as well as that of the food lost or wasted.

Altogether, our observations show that these metrics are intricately correlated. Therefore, any improvements in the citrus supply chain require an analysis of the complete picture. Here, a singular focus on optimizing one metric at a time can create a negative impact relating to another metric. This will give rise to a waterbed effect due to problem shifting, such that solving one problem (or pressure on one end of the waterbed) will only cause another problem to appear elsewhere, but the problem still persists in the system. This problem shifting is observed clearly in Fig. 4, in which as the delivery air temperature increases, one slice of the pie increases at the cost of other slices being reduced.

For these different shipping temperature scenarios between −1.5 and 4.5 °C, we also evaluated how the desirability curves evolve with time for various stakeholders (Fig. 5). We observed that at a temperature of 1.5 °C, the desirability curve of all stakeholders (except regulators) almost coincides and is near the limiting value of 0.4 at the end of the shipment. A similar situation is found at delivery air temperatures of 0 and 3 °C. However, at −1.5 °C, the desirability values fall below the threshold of 0.4 about 4 days before the end of the shipment due to the increased risk of chilling injury. On the other hand, even temperatures higher than optimal (such as 4.5 °C) are not favorable for longer shipping times, as the rate of respiration- and transpiration-driven quality loss is higher. Therefore, temperatures lower or higher than optimal can be detrimental to the fruit and not in the interest of the stakeholders.

We also observed that as the shipping temperature increases, the maxima for the regulators shift to the right on the time axis. However, the maxima still occur before the end of 22 days. This is primarily because different time-temperature combinations exist to obtain the same lethality against fruit pests. Phytosanitary markets represent a select component of exports from South Africa, as the majority of fruit can not withstand low-temperature shipments. Sensitive markets can have vastly differing requirements, depending on what scientific literature is available to the respective regulator. For instance, South African protocols targeting the same past (e.g., Mediterranean fruit fly) range from 2 °C for 16.7 days to −0.6 °C at 22 days (Perishable Products Exports Control Board PPECB, 2019; USDA-APHIS, 2016). However, operating shipments at higher temperatures (such as 1.5 °C or 3 °C) seems to be sufficient to maintain the same required treatment efficacy (Probit 9), particularly when in cases where shipping times are longer.

Nevertheless, currently, the importing country's phytosanitary protocol governs the shipment's operating conditions. As a result, only the desirability curve of the regulator remains above the set threshold of 0.4 at the end of the shipment. This is often to the detriment of the other stakeholders, as key concerns relating to quality, cost, and environmental considerations are largely ignored. It is noteworthy to mention here that given the challenging nature of assessing pest mortality on large-scale shipments, such protocols are often overstated and are based on studies conducted decades ago (Myburgh, 1965). Moreover, the time length of the shipment must also be considered when prescribing equivalent time-temperature treatment combinations. At present, this is not the case, as longer shipments (>20 days) must also be shipped at sub-zero temperatures rather, although exporters prefer shipping fruit at temperatures > 2 – 3 °C. As a result, at least 3 – 5 % of fruit could be lost due to chilling injury (Zacarias et al., 2020).

In an ideal case, phytosanitary protocols should also consider that an acceptable desirability value is obtained at the end of the shipment for all the stakeholders, which is not the case at sub-zero temperatures. Models such as the lethality model detailed in this study and in (Shrivastava et al., 2022) can help determine these time-temperature treatment combinations based on the death kinetics of fruit fly larvae at different temperatures. Revisiting existing protocols based on more recent studies, as well as in light of the trade-offs in the supply chain, can help reduce food loss, primarily due to chilling injury, without compromising on the lethality of the disinfestation treatment. Additionally, linking real-time shipment data with such models through the digital twin technology can provide case-by-case analysis for every shipment and prescribe the course of action as constrained optimization.

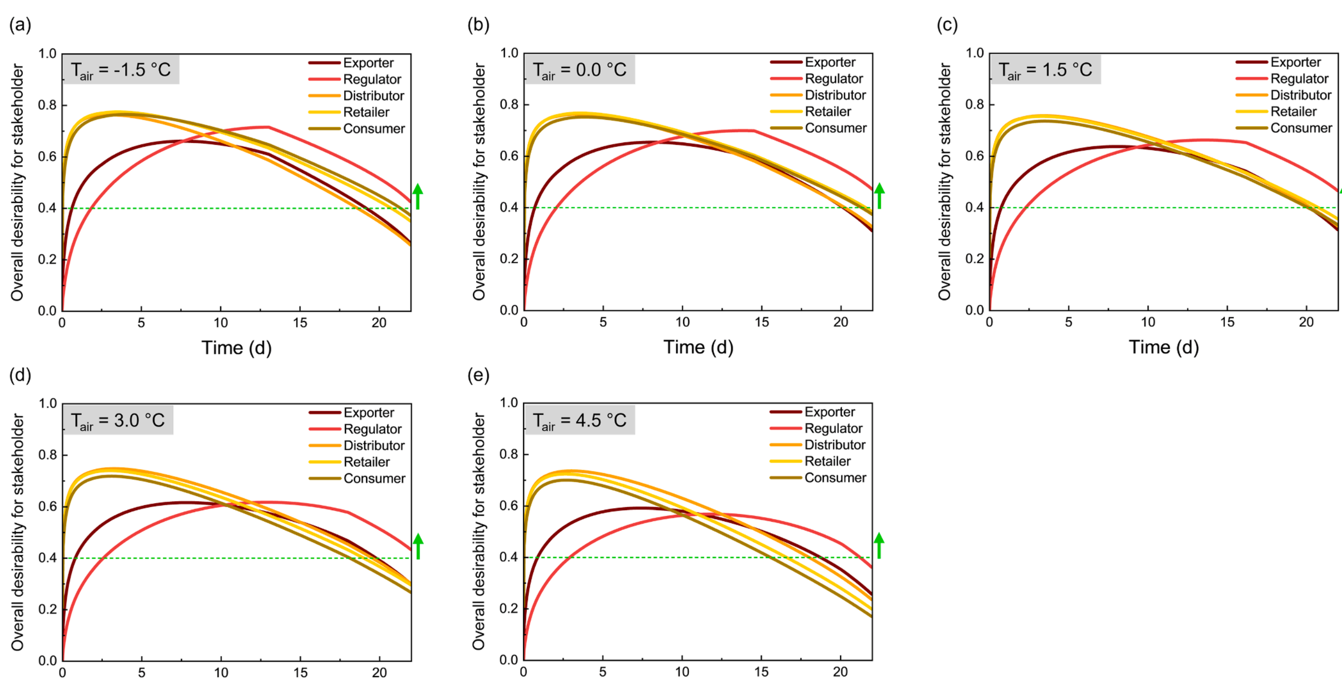

Fig. 5. Dynamic profiles of how the overall desirability curves evolve for different stakeholders for citrus fruit shipped at different delivery air temperatures between −1.5 and 4.5 °C. The dotted green line corresponds to an overall desirability value of 0.4. Below this value, the solution is deemed undesirable (Marinković, 2021).

4. Discussion

Given the increasing interest of researchers in the last decade in reducing food loss and optimizing the supply chain, incorporating stakeholder incentives with scientific technologies and solutions is the next logical step. This has been reflected in recent years in several fields with the rise in participatory research in agri-food supply chains (Jacobi et al., 2019; Schot, 2010). One of the main hurdles in including stakeholder incentives in research is the subjective nature of stakeholder perspectives, more so because concepts such as 'desirability' are not tangible. Our study can be improved if the weightings assigned to the actionable metrics by every stakeholder are based on stakeholder elicitation. This could be in the form of iterative participatory workshops, expert interviews, and surveys (Hicks et al., 2013). Future studies could build on this approach by adopting more sophisticated desirability functions, such as adjustments to the shape factor of the functions (Costa et al., 2011).

Nonetheless, this study bridges a large gap in the quantitative estimation of stakeholder perspectives. Digital twins play a key role in bridging this gap, providing actionable metrics on the shipped fruit and how its quality and marketability attributes evolve. These metrics are not always measured along the entire supply chain as they are time- and resource-intensive. Also, quality losses are sometimes invisible early on in the supply chain and only manifest at the later stages, such as retail or consumption. The use of digital twins can capture these invisible losses and provide complementary information for every shipment, thus bringing these important trade-offs into light. The added insights offered by digital twins also provide a playground to test different scenarios, thus facilitating the establishment of stakeholder consensus on the conflicting requirements in the supply chain.

However, several questions remain to be answered to allow for a more reliable analysis combining digital twins with stakeholder perspectives. One very relevant question is - are all stakeholders equally important? Several studies have attempted to answer this question through power-interest matrices to categorize stakeholders based on their power and interest in the supply chain (Jacobi et al., 2019). The economic aspect was also not considered in this study, for instance, concerning the equitable distribution of profits amongst all supply chain stakeholders or the true cost of losses. Including the economic dimension would enhance this analysis by explaining how the economic value pie is distributed across stakeholders and how these six critical success factors weigh in a cost-benefit analysis for every stakeholder.

5. Conclusion

In conclusion, supply chains do not operate in a vacuum, requiring that several conflicting shipment metrics and stakeholder perspectives be considered from a holistic perspective. In this study, we presented a multi-actor, multi-criteria analysis using physics-based digital twins and desirability functions to quantify the key trade-offs and the associated conflicting interests of stakeholders in the transcontinental citrus supply chain. Each stakeholder had a distinct desirability curve throughout the cold chain. We evaluated different shipping temperature scenarios to propose interventions to improve the supply chain of exported citrus fruit. Our findings showed that amongst all stakeholders, only the desirability curve of the regulator remains at a satisfactory level at the end of the supply chain. For all other stakeholders (exporters, distributors, retailers, and consumers), the desirability curve shows a large dependence on the temperature at which the fruit is shipped. We also observed that temperature trade-offs inevitably exist, and in order to navigate through them, all metrics must be analyzed simultaneously to prevent problem-shifting. Phytosanitary protocols against the target fruit pest must be defined for different time-temperature combinations so as to not serve as a bottleneck in this supply chain. Additionally, the potential of digital twins can be exploited to design phytosanitary protocols for different time-temperature combinations, as well as to check for their compliance. With this approach, we take a step closer to involving all relevant stakeholders to identify the best practices and policies influencing the citrus supply chains. Only in this way can we better understand and optimize the supply chain from the perspectives of food quality, safety, and environmental sustainability.

CRediT authorship contribution statement

Defraeye Thijs: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Shrivastava Chandrima:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Cronje Paul:** Methodology, Supervision, Writing – review & editing. **Berry Tarl:** Methodology, Supervision, Writing – review & editing. **Koenderink Nicole:** Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

There is no conflict of interest to report

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fbp.2025.02.003.

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