Data analytics along the citrus supply chain from farm to consumer to identify the impact of temperature management and other factors on fruit quality

Elin Perler [1*], **Raphael Sacher** [3], **Nikos Prountzos** [3], **Anastasia Biniari** [3], **Bassem Al Sakhawy** [2], **Thijs Defraeye** [2]

[1] *ETH, Department of Health Science and Technology, Institute of Food, Nutrition and Health, Zurich*

[2] *Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*

[3] *ANYFION GREECE S.A., 6th Km Nafplio-Argos, 21100, Nafplio, Greece*

ABSTRACT

To reduce post-harvest losses of fresh fruit and vegetables, they are stored and transported under refrigerated conditions. We currently do not fully know when and where food quality is lost from farm to fork in the fresh produce supply chain. Fruit quality is influenced by a wide range of factors, amongst others temperature management after harvest. We aim to understand the role of temperature management and other factors affecting fruit quality upon arrival at the consumer. This objective was achieved by analyzing data collected along a citrus supply chain from Greece to Central Europe over six seasons from farm to consumer, with a total of 73 refrigerated shipments examined.

We found that there are two groups of seasons with clear differences in their sort-out rate after harvest. Customer complaints do not correlate with the sort-out rate after harvest. This indicates that the sort-out rate is not a meaningful indicator of the quality the consumer receives. For most shipments, the temperature during transport in a refrigerated trailer was close to the optimum range. Customer complaint rates, reflecting fruit end quality, do not directly correlate with transport temperature or shipment duration. Although transport conditions could still affect fruit quality, this is not reflected in the customer complaints. The average temperature in the trailers was significantly influenced by the type of chute used, also known as an air duct. Several trailers had insufficient air distribution or were not cooling to the set temperature and were therefore analyzed in detail to identify potential improvements.

Keywords

Fruit; Temperature; Sensor; Cold chain; Postharvest; Truck; Shipment

1 Introduction

Citrus fruit are a ubiquitous global food with significant economic importance in international trade. In 2016, the estimated total production of citrus fruit exceeded 170 million tons, positioning it as the dominant fruit tree crop on a global scale (Strano et al., 2022; Talon et al., 2020). However, in 2016 over 20 % of harvested fruit and vegetables were lost between post-harvest and distribution (FAO, 2019; Gustavsson et al., 2011a). Such losses have far-reaching consequences and should be minimized. From an environmental perspective, food loss reduces resource efficiency and contributes to greenhouse gas emissions by wasting valuable resources throughout the supply chain, such as land, water, energy, or labor (FAO, 2019). Socially, reducing food loss can also help reduce malnutrition. Yet, it is estimated that one in eleven individuals worldwide is confronted with food insecurity, and the prevalence of micronutrient deficiencies persists across all global regions, despite the ongoing nutrition transition (FAO et al., 2024). Finally, food loss also causes economic losses by wasting resources and reducing productivity, impacting businesses, consumers, and society as a whole (FAO, 2019).

Food loss from farm to fork occurs at various stages of the supply chain, with substantial losses during agricultural production, postharvest handling and storage, processing and packaging, and consumption (Gustavsson et al., 2011b). During postharvest handling and storage, temperature remains the most critical factor influencing the perishability of food products, as it modulates their physiological and biochemical processes (Duan et al., 2020; LeBlanc and Hui, 2005; Mercier et al., 2017). Low-temperature storage has been identified as one of the most effective methods for preserving postharvest quality, as lower temperatures retard the rate of enzymatic and chemical reactions that cause decay (Mercier et al., 2017; Serap and Arin, 2004). For citrus fruit, optimal storage temperatures are typically in the range of 2-7 °C (Gross et al., 2016; Lado et al., 2019; López Camelo, 2004; Talon et al., 2020). Maintaining fruit quality throughout the supply chain depends on effective postharvest handling and storage, with temperature playing a key role.

Fresh fruit and vegetables are primarily transported using refrigerated containers, trailers, or trucks to maintain their quality and minimize metabolic and microbial deterioration (Lu and Wang, 2017). It is critical to control the temperature within the optimal range during transport and storage. Excessively high temperatures accelerate biological reactions, with reaction rates doubling or tripling for every 10 °C increase (Gross et al., 2016). On the other hand, excessively low temperatures can cause chilling injuries, resulting in symptoms such as pitting, discoloration, and off-flavors (Gross et al., 2016; Strano et al., 2022). However, research has shown that the targeted conditions in the cold chain are not always maintained with frequent deviations from the optimal temperature range. These temperature abuses can significantly increase food waste and threaten food safety for some products (Mercier et al., 2017). In addition, humidity and gas composition also affect fruit quality but to a lesser extent (Mercier et al., 2017). To be able to preserve fruit in the best way possible, proper knowledge of temperature management is essential (Duan et al., 2020; Mercier et al., 2017).

Temperature monitoring in refrigerated trailers and containers is common. However, the number of sensors utilized in such transportation is often limited. Typically, in commercial supply chains, a refrigerated container contains one to three temperature sensors, and a refrigerated trailer contains just one. The economic value of a trailer or container filled with fresh products is dependent upon the specific product and can vary considerably. Typically, the value per shipment for fresh fruit and vegetables ranges from $20,000 to $60,000. This indicates the critical importance of effective monitoring and control of the conditions within the container to maintain its quality (Lukasse et al., 2023). Equipping all trailers with sensors and analyzing the resulting large amount of data is, however, too costly and resource-intensive in commercial supply chains (Defraeye et al., 2021). In many cases, even when temperature data is collected with a single sensor per shipment, it is not always analyzed in detail if no quality problems are noticed with the fruit (Shoji et al., 2022). In addition, many other datasets are collected along the entire supply chain but are also not thoroughly analyzed. The reasons are a lack of resources, missing data documentation, or the fact that the data is acquired in different formats and databases, which are not directly interoperable. Collecting data without using it effectively offers little benefit, as the insights that could improve transport and storage conditions remain untapped.

The objective of this study is to identify the impact of temperature management and other factors on fruit quality by analyzing a supply chain from farm to consumer for organic citrus fruit. Based on the findings of this study, recommendations were developed to improve the supply chain and help reduce food quality degradation. The analyzed supply chain focused on citrus fruit cultivated in Greece and transported to Central Europe. Data was collected and analyzed in detail along the entire supply chain, from farm to fork. A central focus of the study was the investigation of temperature behavior during refrigerated transport and its relation to refrigerated trailer design parameters. Additionally, we delved into the sort-out rates after harvest during processing and the customer complaints, which reflect fruit quality at the end of the supply chain.

2 Materials and Methods

2.1 Materials

The supply chain that was analyzed in this study is the one of organic citrus fruit from Greece to Switzerland, Germany, and the Netherlands. Throughout the entire supply chain, data sets of 73 single shipments were collected and analyzed as a whole. The aforementioned supply chain is distinctive in its exclusive emphasis on organic fruit. Organic citrus constitutes a small percentage of the global citrus production, having grown from less than one percent in 2003 to slightly above one percent in 2022 (Liu, 2004; Willer et al., 2024). This modest share can be attributed to the fact that organic citrus is often of inferior quality and has a shorter shelf life compared to conventional citrus fruit (Liu, 2004). The data acquisition was based on the approach outlined in (Defraeye et al., 2025).

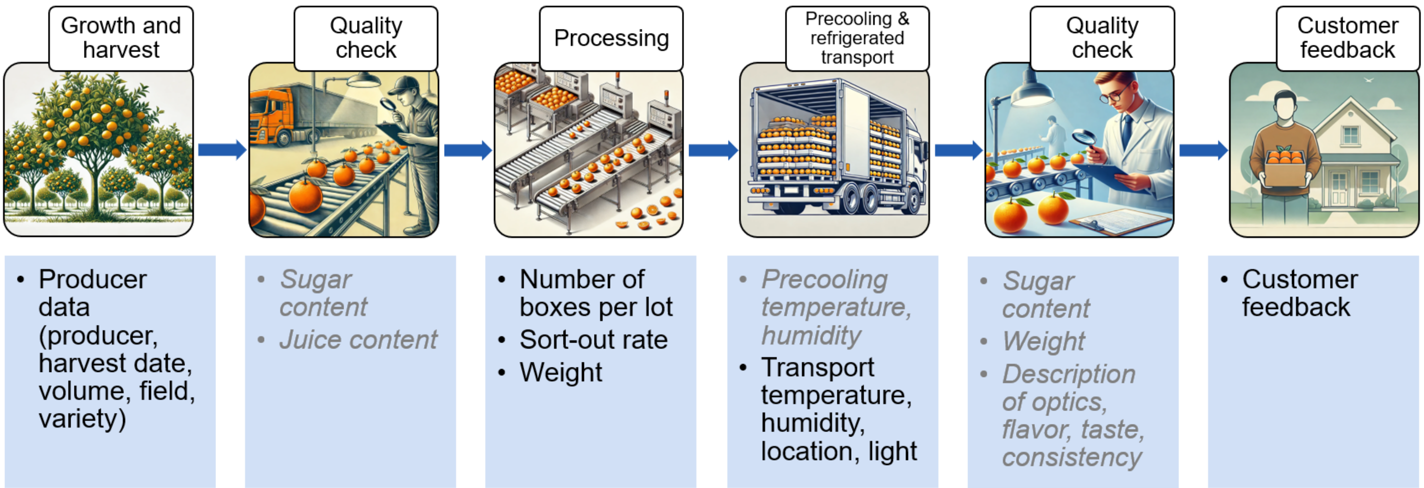


Figure 1: Illustration of the supply chain steps, highlighting the specific datasets collected and analyzed at each step. Datasets in gray italics were collected and analyzed, but these results are not presented in this paper.

2.1.1 Field

The examined supply chain includes a range of different citrus fruit. However, this study focuses on oranges, which account for 80 % of the total volume and thereby representing the predominant category. The first data that was collected was data about the producer over six seasons. The dataset includes information regarding the harvested fruit such as the variety, the quantity of fruit harvested, the date of harvesting, the field of origin, and the producer of each lot. The citrus harvest season runs from late autumn to early summer. The 2023/2024 season was analyzed in more detail than the other seasons and contains 396 lots of oranges. The data was collected manually and provided by the Greek citrus supplier.

2.1.2 Quality Check

After the harvesting, the fruit are transported to the packaging unit. A quality control procedure is conducted, wherein the sugar content, the juice content, and certain visual characteristics are documented. To quantify the sugar content, the PAL-BX|ACID F5 Master Kit from Atago (Tokyo, Japan) is used. The sugar content is expressed as the degree Brix (°Bx, °Brix), where one degree Brix is equal to 1 g of sucrose in 100 g of juice (% w/w) (Ryan, 2014). The degree Brix value is often also referred to as an indicator of total soluble solids (TSS) because it takes into account compounds beyond just sugars. However, sugars are the dominant component, accounting for 90-94 % of the TSS (Considine and Frankish, 2023). The juice content is defined as the percentage of juice relative to the total weight of the fruit. From each lot, five fruit samples are randomly selected and subjected to measurements of degree Brix and juice content. Each orange sample must meet an average minimum sugar content of 10 °Br. For the juice content, Newhall Navel oranges require a minimum juice content of 33 %, while all other orange varieties require a minimum content of 35 %. Again, the data comes from the Greek citrus supplier.

2.1.3 Processing and Packaging Unit

During the processing and packaging stage, fruit not suited for consumption are sorted out according to the EU Regulation No 543/2011. Oranges for consumption are sorted to ensure they are intact, clean, and free from bruises, rot, pests, dehydration, or any damage from frost, with no foreign smell or taste. Furthermore, the diameter of the oranges must be in the range of 62-96 mm (Agricultural Standards Unit and Economic Cooperation and Trade Division, 2023). The oranges that do not match these quality criteria are sorted out and used for juice production. These oranges are not considered in this study. The oranges for consumption are brushed to remove soil, dust, and other impurities. Then they are packed into cardboard boxes with a minimal weight of 13.2 kg each, to ensure that the boxes contain at least 13 kg of fruit at the arrival. The accuracy of the scale is ± 0.001 kg. The total volume of fruit that is packed from each lot, as well as the sort-out volume from each lot, are documented. With this data, the sort-out rate per lot is calculated. This data was again provided by the Greek citrus supplier.

2.1.4 Refrigerated Transport

The packed boxes are palletized and are then put into a cold storage room to precool the fruit before the refrigerated transport. The cold room is set at a temperature of 3-5 °C. Subsequently, the pallets of fruit are transported with a refrigerated trailer from Greece to Switzerland, Germany, or the Netherlands. The transportation takes between one to five days. Refrigerated trailers have a refrigeration unit at the front of the trailer which produces cold air. The cold air is then directed through the trailer via the top, which may be supported by a chute, also called an air duct, guiding the airflow to the back of the trailer. There are several types of chutes used, as shown in Figure 2. In our experiments, two sensors are installed within each trailer, measuring the air temperature and humidity as well as the light levels and the geolocation. The two sensors are positioned on two distinct pallets, as illustrated in Figure 3. One is located at the front of the trailer closest to the driver, and centrally within the trailer. This sensor is called the refrigeration-unit-end sensor, but for simplicity and ease of reading, we will refer to it as the front sensor. The second one is situated at the back of the trailer closest to the door and again centrally within the trailer. The correct name is door-end sensor, however, for the same reason as before it will be referred to as the back sensor. The door-end is the location where in many other supply chains the sensor is placed. It is a convenient place to put the sensor after loading. This location is also often experienced to be the warmest location as it is furthest away from the refrigeration unit. The sensors were TempTale GEO LTE sensors, manufactured by Sensitech Inc. (Beverly, USA). The sensors measure temperatures within the range of -10-55 °C with an accuracy of ± 0.5 °C. The relative humidity ranges from 10-100 % with an accuracy of ± 3.0 % for the range of 10-90 % and ± 4.0 % for the range of 90-100 %. The light intensity measures values in the range of 0-400 lux and was used to detect instances of door openings. The geographic location is determined using cellular connectivity. The sensors were configured to sample at an interval of 15 minutes. The datasets were automatically downloaded from Sensitech's SensiWatch platform with a Python script that was developed for the specific purpose. The 73 monitored shipments in season 2023/2024 were transported with a fleet of 16 different refrigerated trailers. These varied in the model of the refrigeration unit as well as the type of chute. Each trailer has the capacity to accommodate a maximum of 32 Euro-pallets (1.2 m x 0.8 m x 0.144 m). In many instances, a trailer may contain not only oranges, but also other fruits, including lemons, clementines, persimmons, pomegranates, grapefruits, and mandarins. A total of 48 out of 73 monitored shipments in the 2023/2024 season contained mixed fruit. Oranges are packed in open-top cardboard boxes with a volume of at least 13 kg and a size of 0.6 m x 0.4 m x 0.17 m. The other fruits are packed in 8 kg open-top boxes with a dimension of 0.4 m x 0.3 m x 0.19 m. Out of the 73 monitored shipments in season 2023/2024, three shipments were observed to have less than 32 pallets per shipment and were therefore not fully filled, representing less than 5 % of the total shipments.

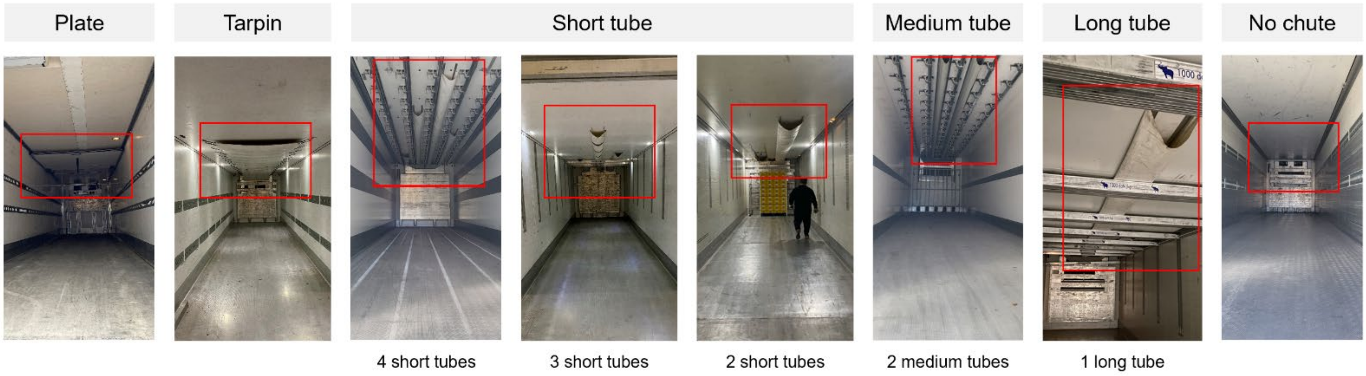


Figure 2: Pictures of the different chute types inside the refrigerated trailers.

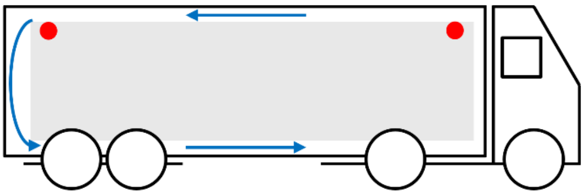


Figure 3: Illustration of a refrigerated trailer, with blue arrows indicating the airflow and red points illustrating the position of the sensors on top of the palettes.

2.1.5 Arrival at the Logistics Center and End Customer

Upon arrival of the shipment at the designated logistics center, situated in Switzerland, Germany, or the Netherlands, a further quality assessment is conducted. In this quality control step, the degree Brix, weight of the box, and descriptive attributes for appearance, flavor, taste, and consistency of the fruit are documented. For the weight measurements, a sample of 1-12 boxes is used. From each of these sample boxes, one fruit is used for the degree Brix measurement. Afterward, the open-top boxes are closed with a cardboard lid and delivered directly to the customers. This is a direct business-to-consumer (B2C) supply chain. The customer can give feedback in the form of a written text or a phone call. The quality and customer feedback data were provided by the Swiss food company specializing in fresh fruit.

2.2 Methods – Data Analysis

The entire data analysis was performed with Python. Different libraries such as Pandas, Numpy, Seaborn, SciPy, Matplotlib, and others were used. First, the raw datasets were preprocessed. This involved handling missing values, detecting outliers, grouping, and sorting the data from different data sources. Then summary statistics and further analyses such as linear regression, one-way ANOVA, or Tukey HSD tests were performed. The data was checked for the assumptions required to perform ANOVA and Tukey HSD tests. The corresponding data can be found in the supplementary material. Finally, the data was visualized.

Customer complaint rates are calculated either per lot or per shipment. A customer complaint is given for an individual box that corresponds to a specific lot and a specific shipment. The calculation of complaints per lot is performed by dividing the number of complaints for a given lot by the total number of boxes in that lot. Similarly, the calculation of customer complaints per shipment is conducted by dividing the number of complaints per shipment by the total number of orange boxes in that specific shipment.

The degree minutes ($Degree\ Minutes$) were used as an indicator for the integrated heat load that the fruit receives during transport. They were calculated for each shipment as the cumulative sum of the products of time intervals (Δt_i) and temperature values (T_i), see equation (1):

$$Degree\ Minutes = \sum_{i=1}^{n} (\Delta t_i \cdot T_i) \tag{1}$$

where Δt_i is the duration of the i-th time interval (always 15 minutes), andT_i is the temperature in degrees Celsius at the i-th interval.

3 Results and Discussion

3.1 How does the sort-out rate of oranges after harvest vary across six different harvest years and throughout the harvest season?

With this analysis, we want to identify if the sort-out rates of the oranges after harvest and prior to shipping in six different harvest seasons have similar patterns over the harvesting period. With the knowledge about the past six seasons, one might be able to make predictions for the coming season, based on the observed trends at the beginning of the season, which would be valuable for order planning.

Figure 4 shows the weekly medians of the sort-out rate of six seasons. We can see two distinct groups, especially in the period from the beginning of the harvesting season until week seven. Seasons 2018/2019 and 2023/2024 have much higher sort-out rates than the other four seasons in this period. After week seven this distinction is not so clear anymore. The total production volume per week is shown as well. From this data, we observe that the highest production happens in the first part of the harvesting season, with two peaks, one in the old year and one in the new year. Around the seventh week of the year, a peak in sort-out rates is observed in all seasons. In certain seasons, additional peaks occur due to specific lots with unusually high sort-out rates, such as in week 22 of the 2022/2023 season. Five different varieties of oranges are harvested at different times during the season, as illustrated in Figure 5. The earliest variety is Newhall Navel, which is harvested from the beginning of November until the beginning of January. In December, Washington Navel oranges take over until the end of February. Washington Navel oranges have higher sort-out rates than Newhall Navel, which results in a general increase in orange sort-out volume in January. Furthermore, the sort-out rate for Washington Navel oranges reaches its peak around week seven and then subsequently declines. In March, Lane Late oranges take over the largest production volume and their sort-out starts at a relatively high level and then decreases until the end of April. This also reinforces the peak around week seven. The sort-out rate of blood oranges is notably high, especially at the beginning of the season. However, their quantity is considerably less than that of the other varieties and has only been present in this supply chain since the season 2022/2023. Therefore, it has a minor impact on the overall sort-out rate of all oranges, as illustrated in Figure 4.

There are two groups of seasons, especially at the beginning. The group with seasons 2018/2019 and 2023/2024 has much higher sort-out rates. In both seasons, this was mainly attributed to the small size of the fruit. The orange trees generally produced smaller fruit that had to be sorted out and used for orange juice. The reason for the smaller fruit was most likely weather-related, as it was a ubiquitous phenomenon throughout the season and the same producers and fields were used as in previous years. However, further analyses are required to confirm that the weather is the most important factor. If we were to find a clear relationship between weather and fruit size, we could use the weather as a predictor to check if the upcoming season might be in one of the two groups. However, already now, knowing about the existence and size of the peak in week seven can help to better organize fruit logistics and orders to avoid a possible delivery bottleneck of oranges.

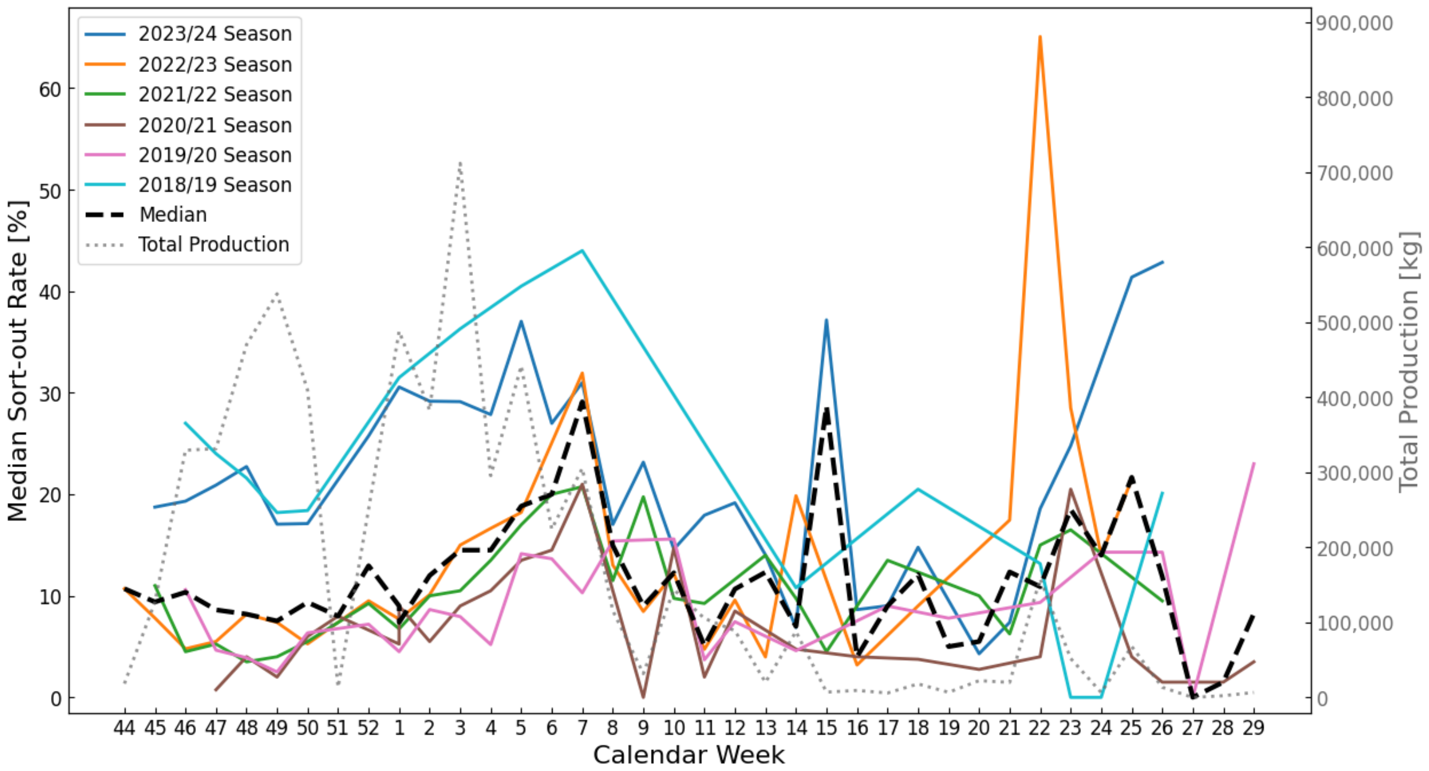


Figure 4: The weekly median sort-out rates of oranges for each season between 2018/2019 and 2023/2024 as a function of the calendar week. The black dashed line shows the median sort-out rate over all seasons. The axis on the right corresponds to the gray dotted line, which represents the total volume of oranges produced per week over all seasons.

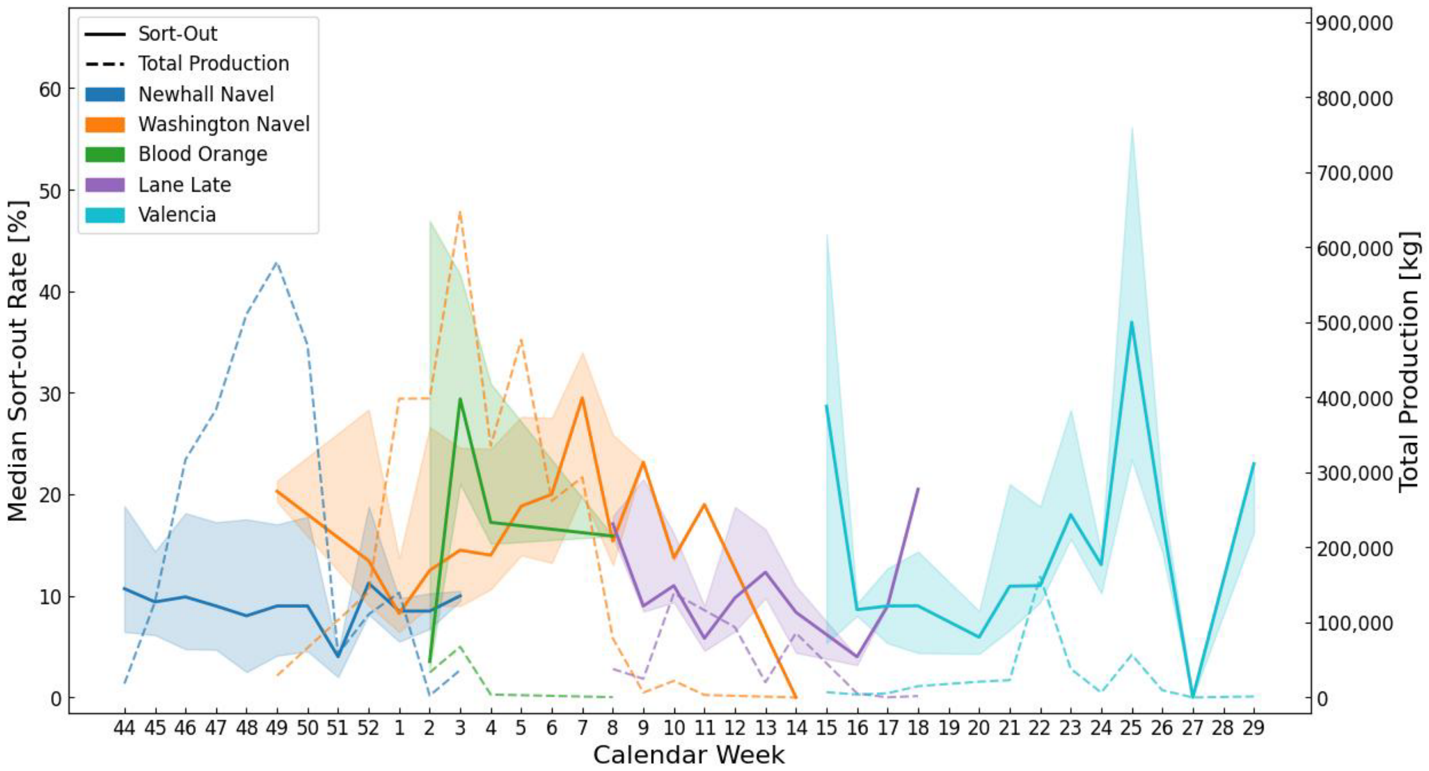


Figure 5: The weekly median sort-out rates of oranges across all seasons between 2018/2019 and 2023/2024 as a function of the calendar week grouped by variety. The colored area around the median represents the weekly

calculated interquartile ranges (IQR). The axis on the right corresponds to the dotted lines, which represent the total volume of oranges produced per week and variety across all seasons.

3.2 Do large sort-out rates imply high customer complaint rates?

We aim to identify if high sort-out rates are a proxy for high customer complaint rates at the end of the supply chain. The customer complaint rate per lot represents the frequency with which specific boxes within a lot received customer complaints. On average a lot consists of 330 boxes weighing 13.2 kg each. However, the size of the lots varies considerably, with a standard deviation of 300 boxes. For each of the lots, the corresponding sort-out rate was calculated. A linear correlation was calculated to assess the potential relationship between the two parameters. The information, if there is a correlation between these two parameters, can give insights on what to improve during the sorting process. In addition, this can identify if and what quality defects develop that cannot be seen during sorting out. If there is a strong correlation, it might be necessary to implement a more rigorous sorting procedure to prevent any adverse impact on the final quality.

In Figure 6 we see the complaint rate as a function of the sort-out rate per lot. The linear regression between the two parameters indicates a slope of -0.02 and an R^2 of 0.03. The slope represents a weak negative linear relationship between the two parameters. The R^2 indicates that only 3 % of the variation in the data can be explained by the linear model, which indicates a very poor fit of the linear model.

With this information, we can conclude that there is no linear correlation between the sort-out rate and the customer complaint rate. Batches with a high sort-out rate do not lead to higher customer complaints. This implies that the sort-out rate is not a good indicator of the customer complaint, which mainly reflects the end quality that the consumer receives. A potential explanation for these findings is that a part of the sorted-out oranges are removed due to their small size rather than inadequate quality. In the season 2023/2024 according to an estimation of the production manager, approximately 10-15 % of the sort-out was size-related. Given that the present analysis is based on a season with an unusually high proportion of small fruit (as discussed in section 3.1), it is not possible to determine whether a correlation between sort-out and customer complaints could be identified in a season where this issue occurred to a lesser extent. The absence of a correlation may also indicate that the sorting process effectively removes a large proportion of fruit of inferior quality and therefore might not be reflected in the customer complaints. Additionally, we could not see any particular nonlinear pattern from the scatter plot between these two parameters.

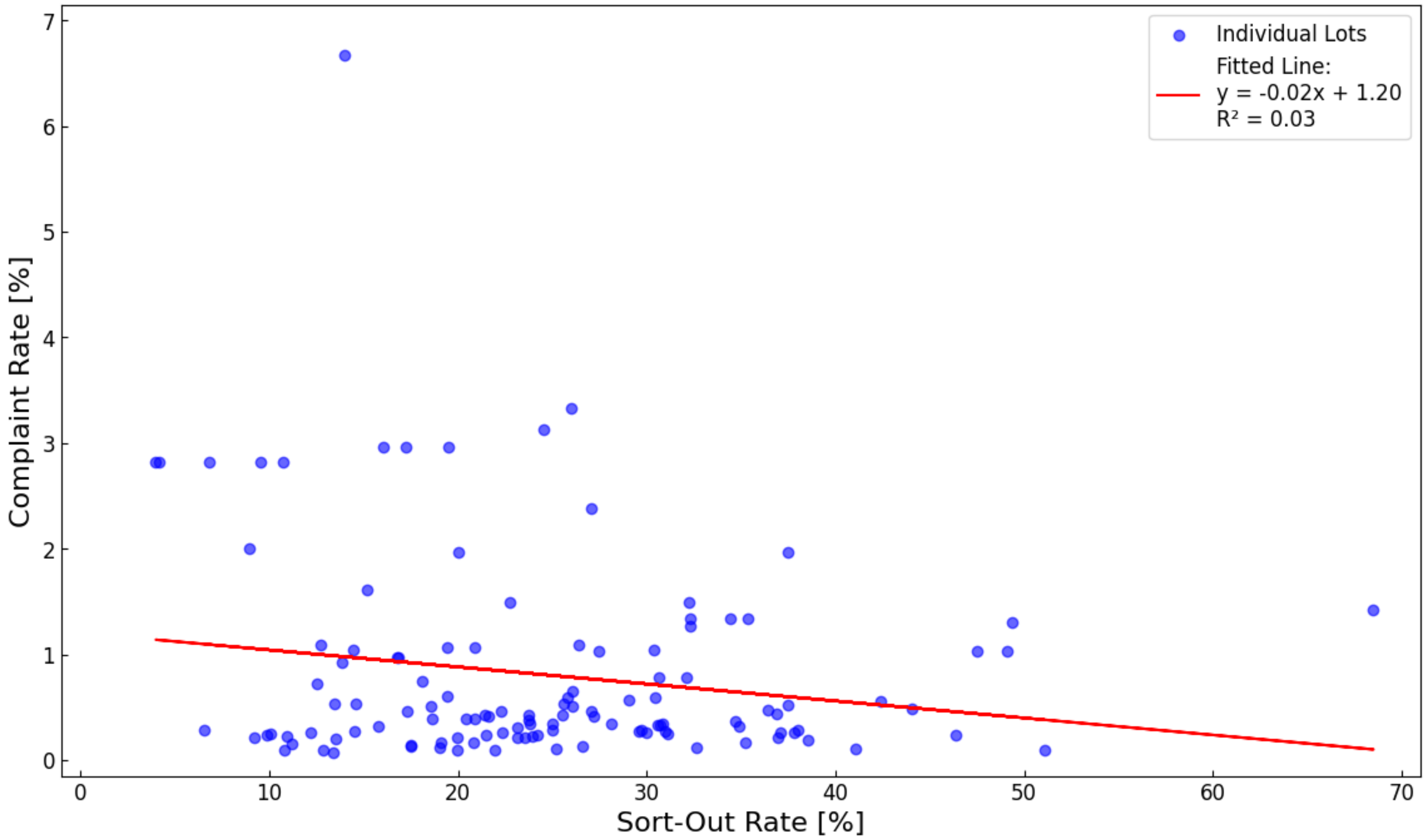


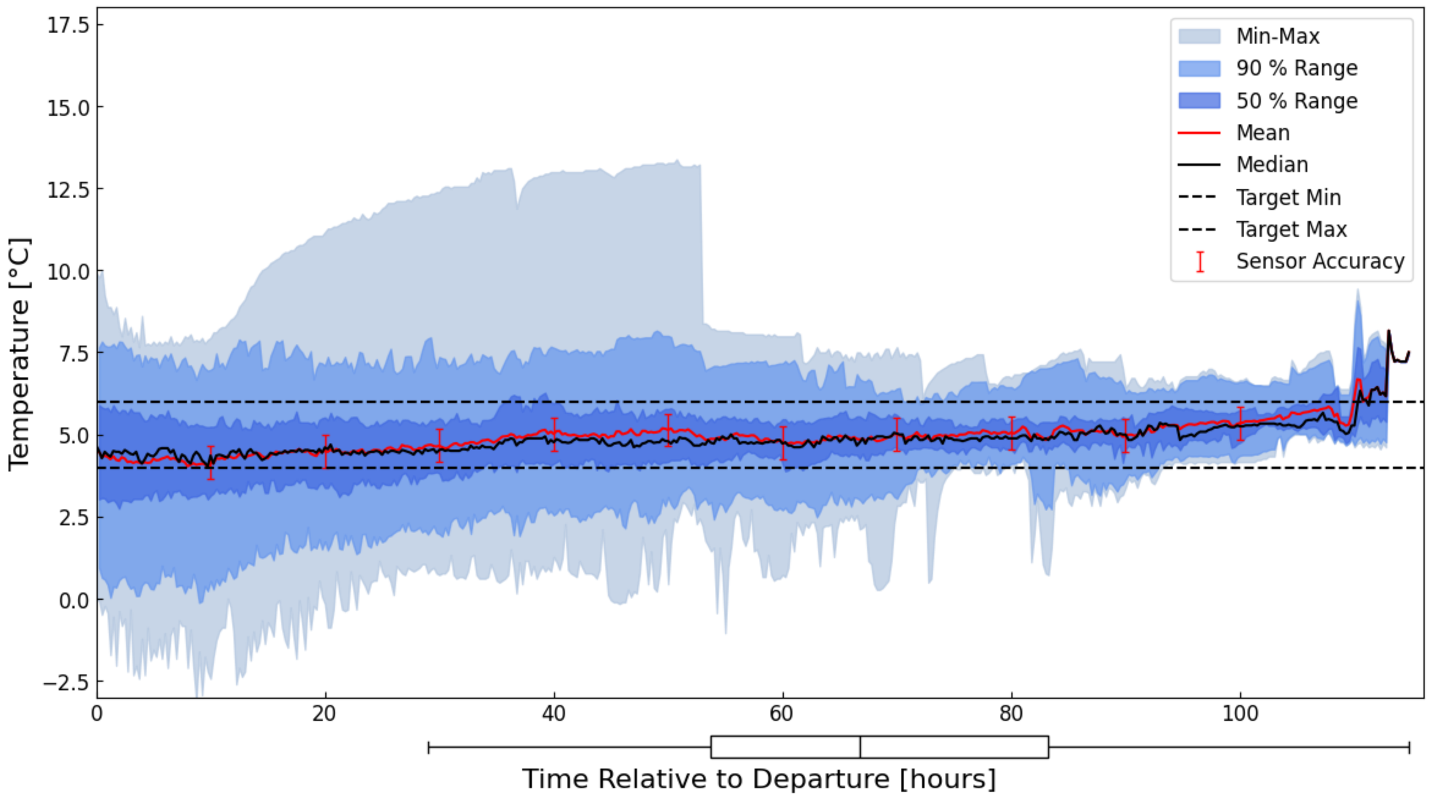
Figure 6: The customer complaint rate per lot of oranges in season 2023/2024 as a function of the sort-out rate. The red line represents the linear regression of the data points. Its corresponding linear equation and R^2 value are provided in the legend.

3.3 What is the typical air temperature management in the refrigerated trailer during transport?

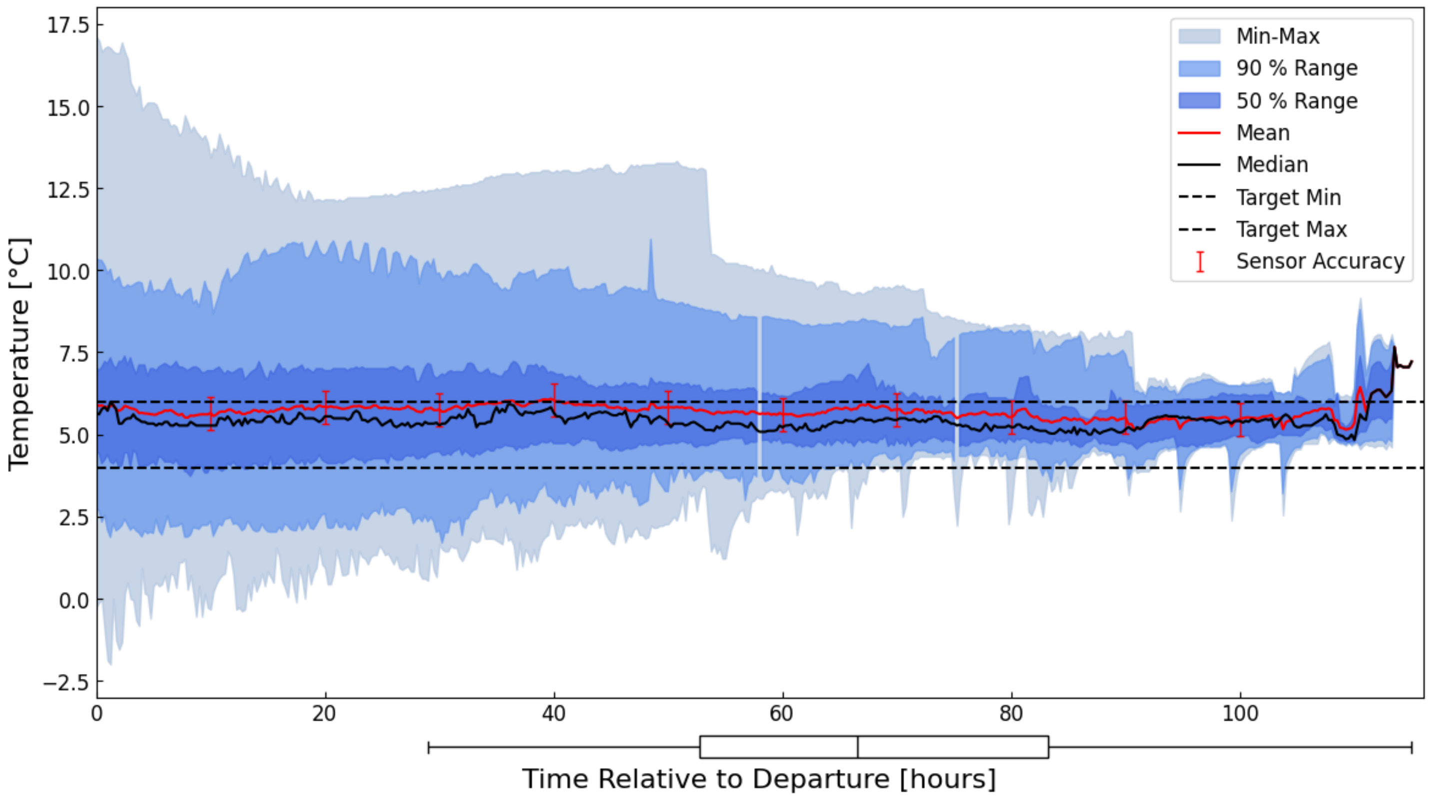
We want to identify the quality of temperature control of the refrigeration units by analyzing temperature records over time during refrigerated transport. Therefore, the temperature time series for each of the 73 shipments were analyzed and summary statistics were presented in two plots, one for the back sensor and one for the front sensor. Note that the back sensor is typically the only one placed in commercial shipments as this location is often deemed the most critical.

The summary metrics illustrated in Figure 7 include the mean, median, and variability (50 %, 90 %, and 100 % ranges) of the temperature relative to the transport duration, once for the front and once for the back sensor. The plots demonstrate the temperature fluctuations during transit, which should ideally be as stable as possible and within the target range. A comparison of both plots reveals potential temperature distribution patterns within the trailer, which is crucial for understanding the refrigeration performance of the trailers. It can be observed that both the mean and the median temperature in both sensors fall within the target range for orange fruit, which is defined as 4-6 °C. Furthermore, the 50 % range is situated within or in close proximity to the target range. At the beginning of the refrigerated transport, the temperature range varies more, particularly for the back sensor, and the cargo seems to not always be completely precooled. As the transit progresses, the temperature approaches the target range. Several shipments exhibit notably low temperatures in both sensors, but particularly the front one, approaching 0 °C. This is reasonable as it is closer to the refrigeration unit and without a chute, for example, the cargo and sensor would be directly exposed to the cold air. This may also give rise to concerns regarding the potential for chilling injuries. The increase in temperature between 15 and 50 hours in the front sensor dataset is attributed to a single shipment that had issues cooling the trailer. The temperature recorded by the front sensor is, on average, lower than that recorded by the back sensor.

In conclusion, it can be stated that the majority of shipments are adequately temperature-controlled and eventually reach the target range after a certain amount of time in transit. The fruit are typically maintained at temperatures within 4-6 °C and are transported for a period of one to five days. It would be optimal if the fruit were fully precooled to the target temperature before the transit, as this would facilitate the maintenance of the target temperature without the need to cool the cargo to the desired temperature. The fact that the front temperature is on average lower than the back temperature implies that the sensor at the back, which is the typical location where air temperature sensors are placed, is the more conservative and critical location to monitor temperature and possible temperature excursions. One potential solution for shipments with temperatures that are too high would be to set the target temperature at a lower level, thereby requiring the trailer to cool the cargo to a greater extent. Nevertheless, given that some shipments have already reached very low temperatures, this approach would not be advisable in general as it could lead to chilling injuries at specific locations. If the option of a lower inlet temperature is deployed, it is advised a chute is used to avoid direct contact of the cold air to the fruit. It would be beneficial to examine the various shipments and ascertain whether there are noticeable differences between those with too low and those with too high temperatures. This could lead to the development of targeted strategies for handling these two groups of shipments.



(a) Figure illustrating the temperature data from the sensor at the front of the trailer.



(b) Figure illustrating the temperature data from the sensor at the back of the trailer.

Figure 7: The temperature during refrigerated transport in season 2023/2024 as a function of transport duration. The temperature was recorded at 15-minute intervals at two locations in the trailer, one positioned at the front and one at the back. The red line represents the mean temperature across all shipments, while the black line illustrates the median. The shaded regions indicate the distribution of the data. The darkest blue area encompasses 50 % of the data, the medium blue extends to 90 %, and the light blue covers the full range of recorded values. A box plot on the x-axis provides additional statistical insights into the duration of the shipments.

3.4 How does the sort-out rate of oranges after harvest vary across six different harvest years and throughout the harvest season?

The aim is to identify differences in the cooling behavior of different trailer types. The temperature data of each shipment was taken and classified according to their trailer. During the 2023/2024 season, 16 distinct trailers were used throughout the season. Paired comparison tests between the back and front temperatures of each trailer were performed. Although the normality assumption for the pairwise comparison test was not fully met, we decided to proceed with these results as discussed in the supplementary material. The remaining assumptions necessary for the execution of the Tukey HSD test were all met.

In Figure 8: The average temperature during transport for all shipments grouped by each trailer used in season 2023/2024. A number of trailers show significant differences between the average front and back temperatures, as indicated by the red asterisks. The corresponding p-values are reported below the asterisks. we can see boxplots of the average transport temperature of each shipment grouped by trailer for the front and back sensors. The pairwise comparison test revealed that out of the 16 trailers, six had significant differences in the average temperature between front and back sensor, indicated by red asterisks in Figure 8. Fife of the six trailers with a significant difference have a significantly lower front temperature. Only one of them has a significantly lower back temperature, marking an exception. For all trailers, the median front temperature is below the upper target temperature of 6 °C. The median back temperatures vary more between the different trailers, and not all of them are below the upper target temperature.

Several trailers were thoroughly analyzed to explore potential reasons for their different performance. This included trailers with significant differences between the front and back temperature readings and those with median average temperatures above the upper temperature limit. The goal of this analysis was to uncover potential underlying factors and provide recommendations for improvement. Trailer number one has a rather low front temperature, indicating that the refrigeration unit is working properly. However, it has a weak distribution of the cold air, which does not reach the back of the trailer. This is probably due to the lack of a chute in this trailer. We would recommend adding some type of chute, preferably a Tarpin chute since it is the best-performing chute type as discussed in section 3.6. Trailer number three has a significantly lower back temperature. However, since both temperatures are within the target temperature range, we would not recommend adjusting this trailer. In trailer number five, both the back and front temperatures are rather high, which suggests that the refrigeration unit of this trailer has a too high set temperature or may not be functioning optimally, leading to insufficient cooling of the cargo. Therefore, we would recommend checking the refrigeration unit on this trailer before changing the chute. Furthermore, the whiskers of this trailer are rather large, indicating a high degree of variability between shipments. Checking the four individual shipments of this trailer provides more detail. It reveals that once the temperature in both sensors reached 12 °C, the temperature was above the target temperature twice, and once fell well below the target temperature (shipments 2, 12, 27, and 57 in Figure 12, Figure 13 and Figure 14). These different performances of the trailer led to the large whisker. Nevertheless, we can still conclude that in most shipments the cooling performance was not good enough and therefore the recommendation to check the refrigeration unit would remain the same. Trailer number six and 13 exhibit the same problem as trailer number one. Given that number six has a plate chute, we would recommend changing the chute type to a Tarpin. Number 13 has no chute, therefore we would add a chute, preferably a Tarpin. Trailer number nine has a significantly lower front temperature, but similar to trailer three both temperatures are within the target temperature range and therefore we would not recommend modifying the design. Finally, trailer number 15 has a front temperature that is within the recommended range, but a back temperature that is too high. Again, we would recommend adding a chute, as this trailer does not currently have one.

The results from Figure 8 demonstrate that not all trailers perform similarly and that some of the trailers have room for improvement. For these trailers, specific recommendations were made. Since the front and back temperatures of some trailers differ significantly, the location of the sensor plays a critical role in how the results are interpreted. It is beneficial to have sensors in both locations because they provide different information and help to evaluate the performance of the specific trailer unit. Nevertheless, if we had to choose only one sensor location, we would choose the back sensor because it seems to be the more critical location in terms of cooling efficiency.

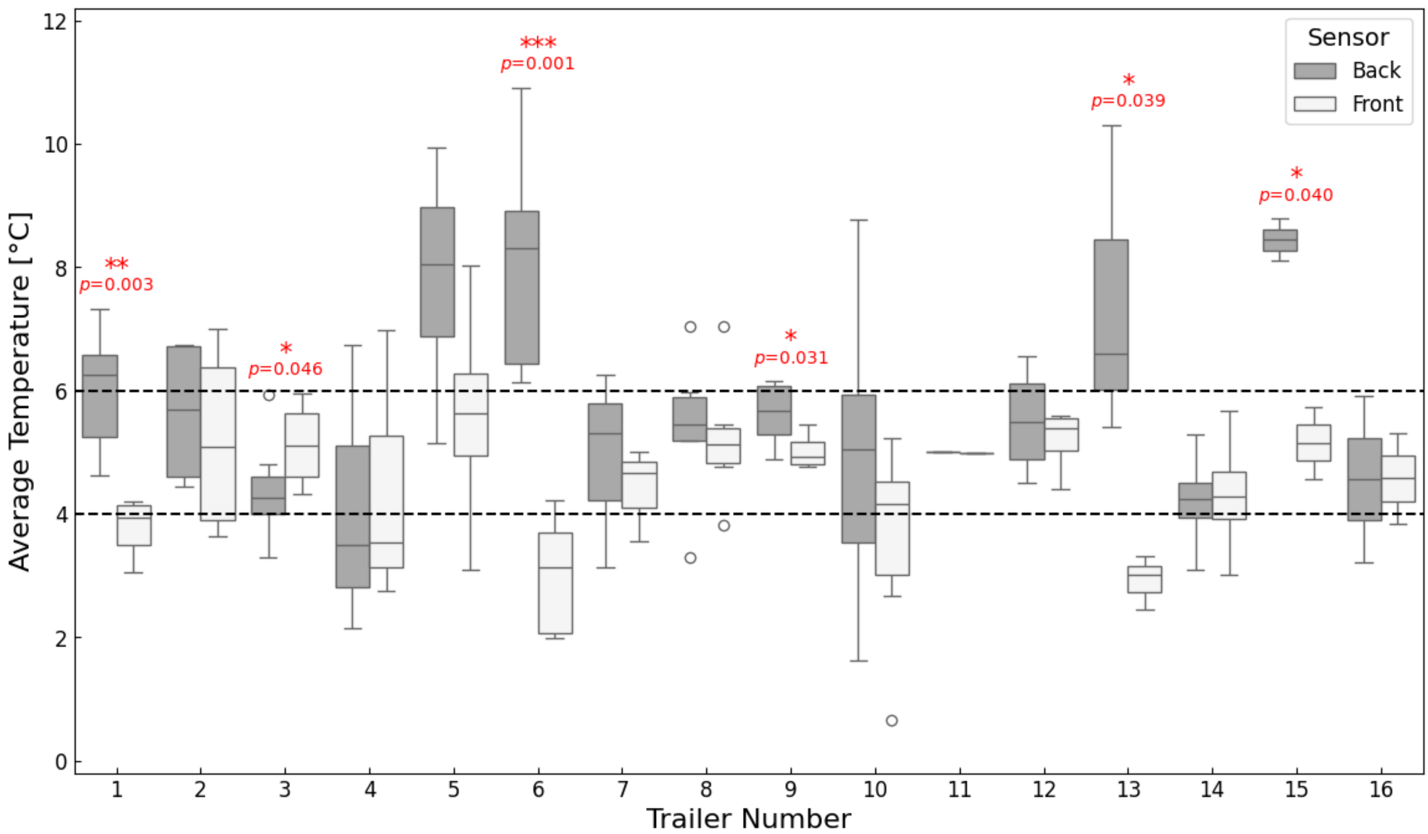


Figure 8: The average temperature during transport for all shipments grouped by each trailer used in season 2023/2024. A number of trailers show significant differences between the average front and back temperatures, as indicated by the red asterisks. The corresponding p-values are reported below the asterisks.

3.5 How does the sort-out rate of oranges after harvest vary across six different harvest years and throughout the harvest season?

We aim to identify if transport conditions contribute to the fruit quality upon arrival at the consumer. Therefore, we examined the relationship between the customer complaint rate per shipment and the degree minutes. The degree minutes per shipment were calculated using the methodology outlined in Equation 1.

In Figure 9 we see the customer complaint rate as a function of the degree minutes per shipment. The linear regression yielded a slope -4.08×10^{-6} %/(min·°C) and an R^2 value of 0.07. The slope indicates a weak negative linear relationship between the two parameters. The R^2 value demonstrates that the linear model does not fit the data points adequately, because only 7 % of the variation in the data can be explained by the linear model.

From this analysis we can conclude that there is no linear correlation between the two parameters. This shows that transport temperature and duration do not have a directly observable effect on the quality perceived by the consumer, as less adequate transport conditions do not lead to more customer complaints, suggesting that other factors may have a more pronounced influence. Furthermore, no discernible non-linear pattern was evident in the scatterplot. Also, customer complaints are a subjective measure of end quality because individuals perceive and define quality issues differently. Some reasons for a customer complaint are inherently not linked to the transport conditions, for example, the occurrence of green fruit color (see category "Appearance" in the supplementary information). Furthermore, many different factors from farm to fork exert an influence on fruit quality. Consequently, it is probable that this relatively brief transportation duration has no directly observable effect on quality.

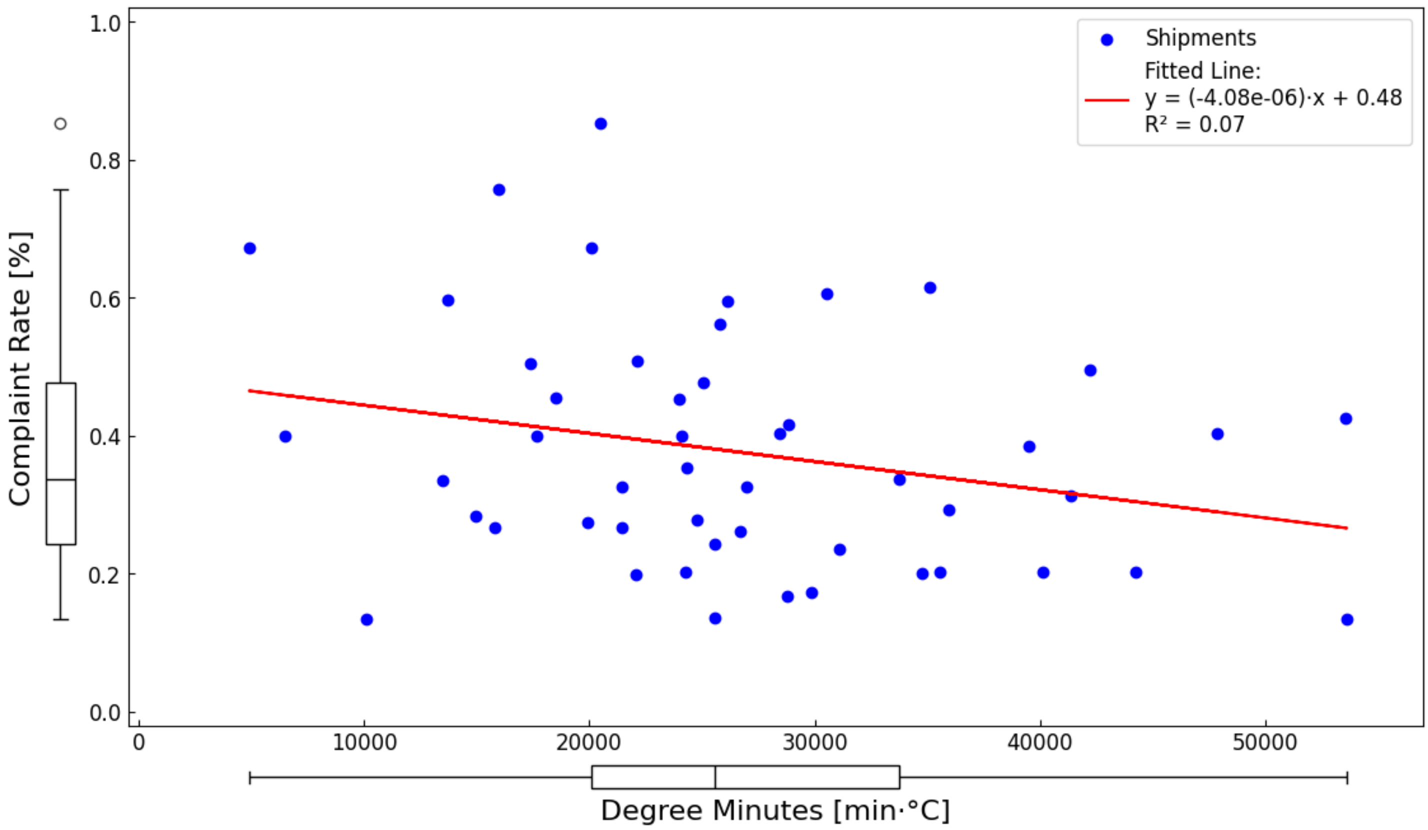


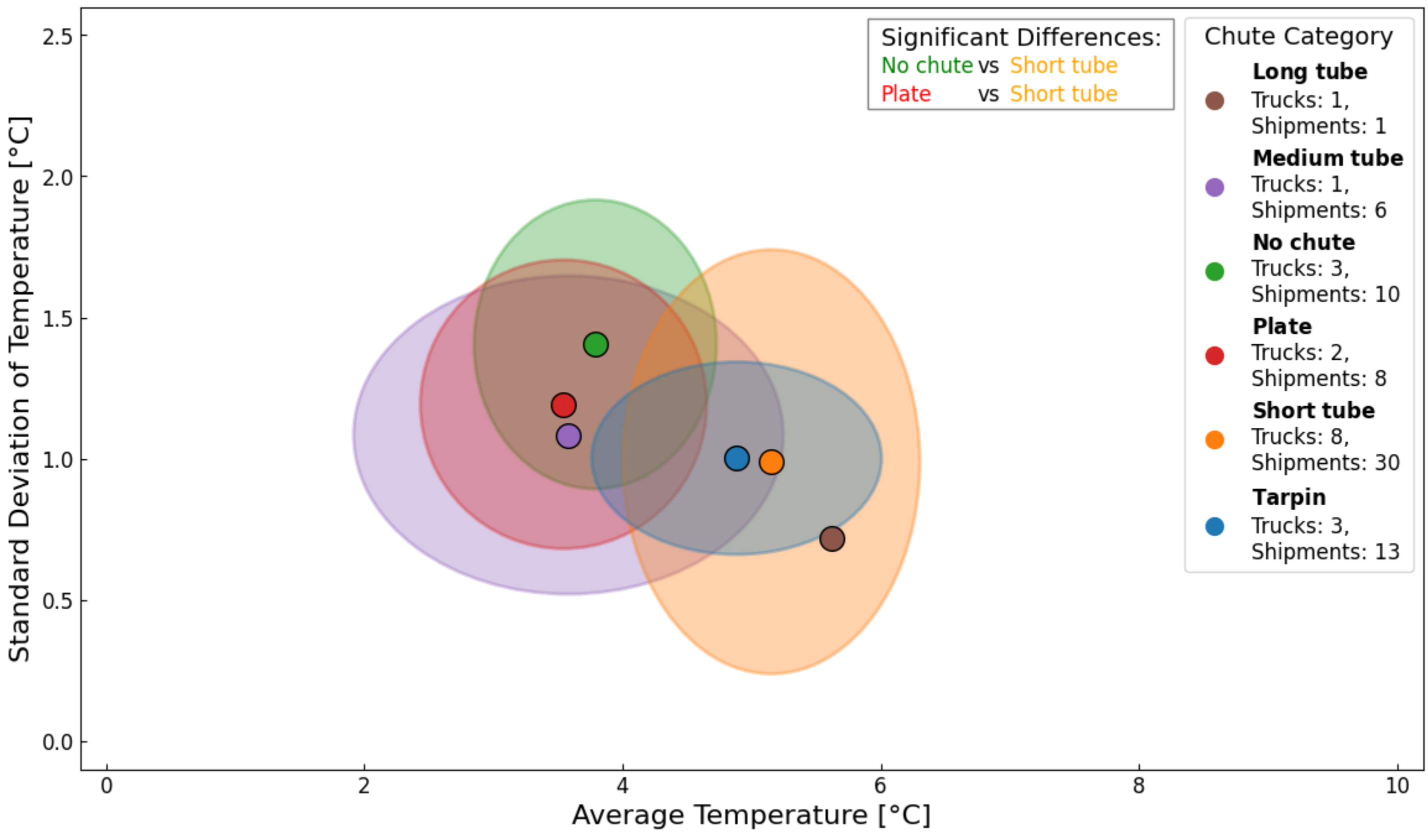
Figure 9: The customer complaint rate per shipment in season 2023/2024 as a function of the degree minutes. The degree minutes are calculated from the temperature time series of the back sensor. A higher value is obtained for longer transport times at higher temperatures. A box plot illustrates the variability and central tendencies in the data on both axes. A linear regression line was fitted to the data, represented by the red line. Its corresponding linear equation and R^2 value are provided in the legend.

3.6 How does the sort-out rate of oranges after harvest vary across six different harvest years and throughout the harvest season?

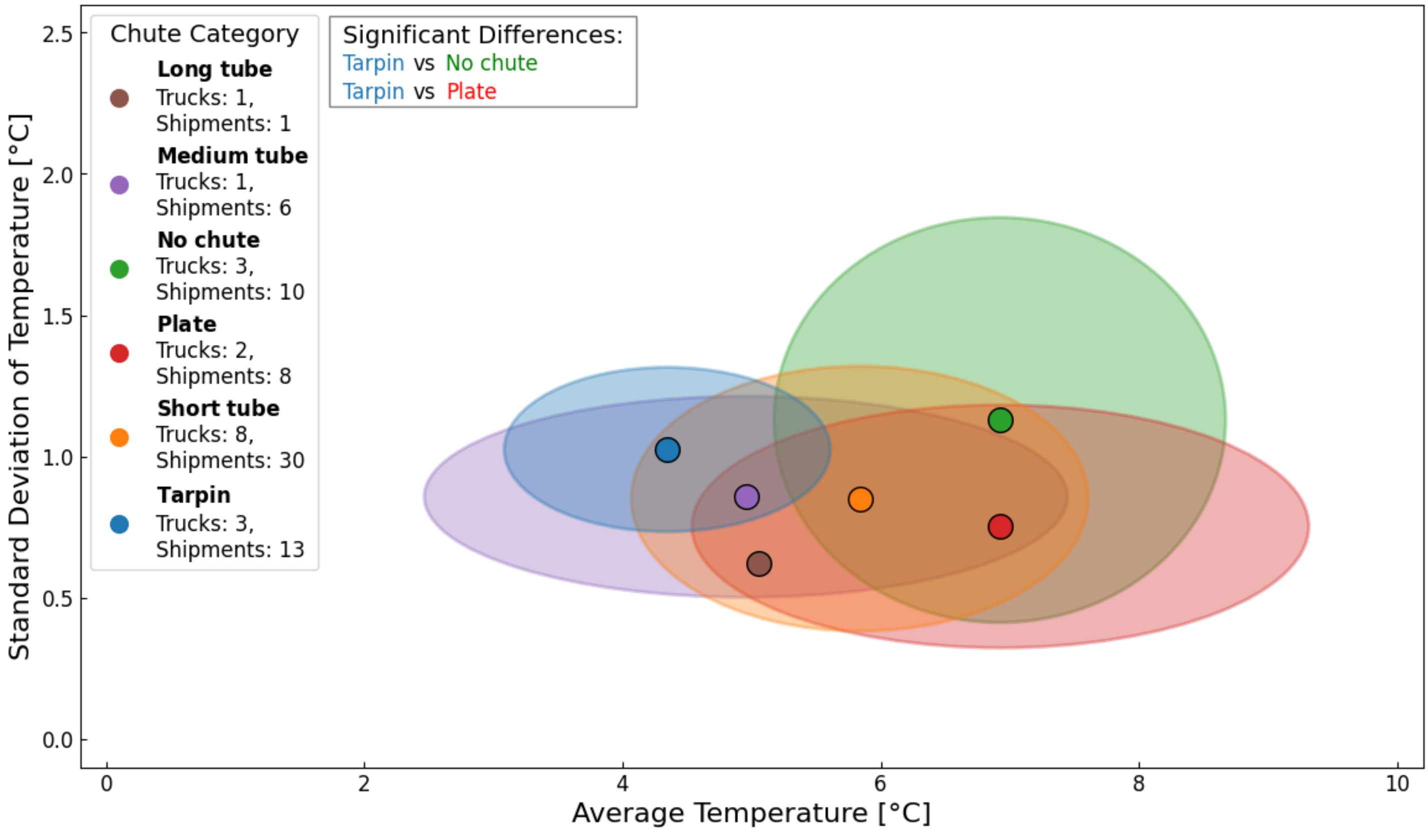
The objective of this analysis is to ascertain whether the trailer refrigeration unit or chute significantly impact the temperature behavior during refrigerated transport and whether we can see this from the measured air temperature. Many factors affect how a trailer cools the fruit, some of which are out of our control, while others can be managed. For example, external factors such as outside temperature (e.g., winter vs. summer) or direct sunlight might affect the inside temperature of the trailer, but we cannot control these conditions. Similarly, while it is difficult to change the design of the installed refrigeration unit itself, we can take steps such as adjusting the chute. By identifying these controllable parameters, we can make targeted adjustments to refrigerated trailers to improve their cooling efficiency. Specifically, we used the concept of chute designs (see Figure 2) to check if this impacts how well the trailer is cooling and how the air distribution works.

Figure 10 depicts the mean and standard deviation of the temperature for each shipment, classified according to the chute type, once for the front and the back sensor data. For each chute category, the mean and standard deviation of the temperature for the corresponding shipments were averaged and are represented by the black-bordered circles. The ellipses represent the variability between shipments within each chute category, showing how the data points are distributed around the average values. It is obtained by centering the ellipse at the mean average temperature and mean standard deviation, with a width and height equal to twice the standard deviations of these values across shipments. A pairwise comparison test (Tukey HSD) was conducted to determine whether significant differences existed. A comparison of the front sensor data revealed a statistically significant lower air temperature for the No chute (P=0.0385) and Plate (P=0.0194) configurations relative to Short tube. In the data obtained from the back sensor, it was determined that the temperature was significantly lower for the Tarpin setup in comparison to both No chute (P=0.0270) and Plate (P=0.0454). No significant differences were identified with regard to the standard deviation of temperature across different chute types. The same analysis was also performed differentiating between refrigeration units instead of chute types, but no significant differences were found. The corresponding results can be found in the supplementary information.

The results demonstrate clear differences in temperature distribution depending on the chute configuration. From Figure 10 it can be concluded that the No chute or Plate configurations behave similarly; they cool very well in the front but not in the back. This suggests the presence of a heterogeneous temperature distribution within the trailer. The present findings are consistent with those of (Moureh and Flick, 2004) who concluded that the utilization of a chute resulted in a more uniform temperature distribution within the trailer when compared with the absence of such a chute. This temperature inhomogeneity presents a challenge for fruit quality, as it introduces differential risks at varying locations. Fruit situated in the front of the trailer may be exposed to cooler temperatures, potentially increasing the risk of chilling injuries or even top freezing. In contrast, fruit located towards the back may not receive sufficient cooling, since the momentum of the airflow is too low to reach the door end, leading to faster respiration and accelerated deterioration. This could result in a reduction of shelf life (Duan et al., 2020; Gross et al., 2016; LeBlanc and Hui, 2005; Mercier et al., 2017). In contrast, the Tarpin configuration demonstrates a uniform temperature distribution, with temperatures at both locations ranging between 4-5 °C, falling within the target range. The Short tube configuration exhibits similar behavior to the Tarpin setup but at a higher temperature level, therefore Tarpin would still be preferred. The Medium tube configuration also demonstrated relatively low temperatures in both sensors. However, the data was collected from only one trailer, and other factors may have contributed to its favorable performance. Consequently, the statistical significance of the Medium tube result is limited. It is therefore recommended that the Tarpin configuration be preferred and that the No chute or Plate configuration be avoided. With our data, we could not find any significant differences in the average temperature nor the standard deviation of the temperature between different refrigeration units. Therefore, we can conclude that in the analyzed supply chain the chute type has a greater influence on how the cargo is cooled compared to the refrigeration unit that is used.



(a) Figure illustrating the data from the sensor at the front of the trailer.



(b) Figure illustrating the data from the sensor at the back of the trailer.

Figure 10: The standard deviation of the average transport temperature as a function of the average temperature during the transport of the 73 monitored shipments in season 2023/2024. Each shipment is classified according to its chute type. The black-bordered circles indicate each chute type's average temperature and standard deviation, while the ellipses illustrate the variability within each group.

4 Conclusions

A comprehensive analysis of the citrus supply chain from farm to fork was conducted to investigate how temperature control and other factors affect fruit quality when it reaches the consumer. We found that there were two distinct groups of seasons with differences in the amount of sort-out rates after harvest. The sort-out rate during processing was not correlated with the customer complaint rate. With regard to refrigerated transport, while the optimal temperature range was maintained for half of the shipments, there is room for improvement in the other half. With effective precooling, the shipment temperatures could likely be further improved, as then any residual field heat does not need to be cooled away during transport. Specifically, seven out of 16 trailer types exhibited suboptimal refrigeration performance, either having a significant temperature difference between the front and back or exceeding the 6 °C temperature limit. We provided customized recommendations to improve the refrigeration for each of these seven trailers based on potential underlying issues. A correlation analysis between degree minutes and complaint rate showed no linear relationship, indicating that transport temperature and duration, measured by degree minutes, may not directly influence customer complaints. Furthermore, a comparison of average transport temperatures between different types of chutes, also referred to as air ducts, revealed discrepancies in their performance. Some chute types led to large differences in temperatures between the door end and refrigeration end locations. The Tarpin configuration yielded the most consistent and cool temperature, while the Plate and No chute configurations resulted in uneven cooling, with elevated temperatures in the back of the trailer.

Several next steps could be pursued: An analysis of the precooling process and conditions would be an interesting addition. Due to the lack of accurate data on precooling, we did not analyze it in this study, but it is essential to remove field heat and bring the fruit to its optimal temperature prior to transport (Duan et al., 2020). This would help to maintain a more consistent and lower temperature during transport, as trailers are designed to maintain the temperature of the fruit rather than cool it down. Also, biological and agricultural factors, including weather conditions throughout the entire growth period and soil characteristics, play a crucial role in determining fruit growth and fruit quality at harvest. By exploring these variables, we could identify which agricultural practices yield superior outcomes, offering valuable guidance to producers in order to improve fruit quality.

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AUTHOR CONTRIBUTIONS

Elin Perler: Writing – original draft, Writing – review & editing, Visualization, Methodology, Investigation, Data curation, Formal analysis.

Thijs Defraeye: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization, Validation, Investigation.

Raphael Sacher: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization, Validation, Investigation.

Bassem Al Sakhawy: Data curation, Methodology, Writing – review & editing.

Nikos Prountzos: Data curation, Methodology, Writing – review & editing.

Anastasia Biniari: Data curation, Methodology, Writing – review & editing.

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

During the preparation of this work, the authors used Grammarly, ChatGPT, and DeepL Write 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. DALL-E (OpenAI) was used to generate selected images.

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5 Supplementary Materials

5.1 Customer complaints

Customer complaints can be categorized into six different groups according to the problems mentioned by customers, namely Overripe, Taste/Quality, Miscellaneous, Packaging, Not ripe enough, and Appearance. The first two categories, shown in blue, are possibly related to post-harvest conditions, the next three groups, shown in green, are diverse issues that are not clearly related to post-harvest conditions, and the sixth category, shown in red, is not related to post-harvest conditions. The two categories of Overripe and Taste/Quality account for more than half of all complaints (55.6 %), suggesting that post-harvest conditions likely play a major role in customer dissatisfaction.

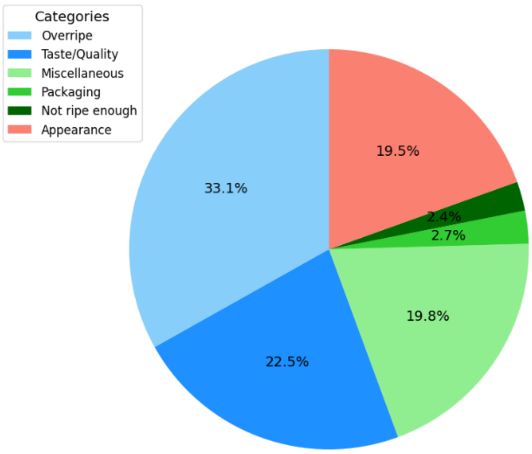


Figure 11: Customer complaints in the 2023/2024 season were grouped into six categories, namely Overripe, Taste/Quality, Miscellaneous, Packaging, Not ripe enough, and Appearance. The Overripe and Taste/Quality problems, shown in blue, may be related to post-harvest conditions. The Miscellaneous, Packaging, and Not ripe enough categories shown in green are not clearly related to post-harvest conditions. The Appearance problems in red are unlikely to be related to postharvest conditions.

5.2 Raw data of shipment temperatures

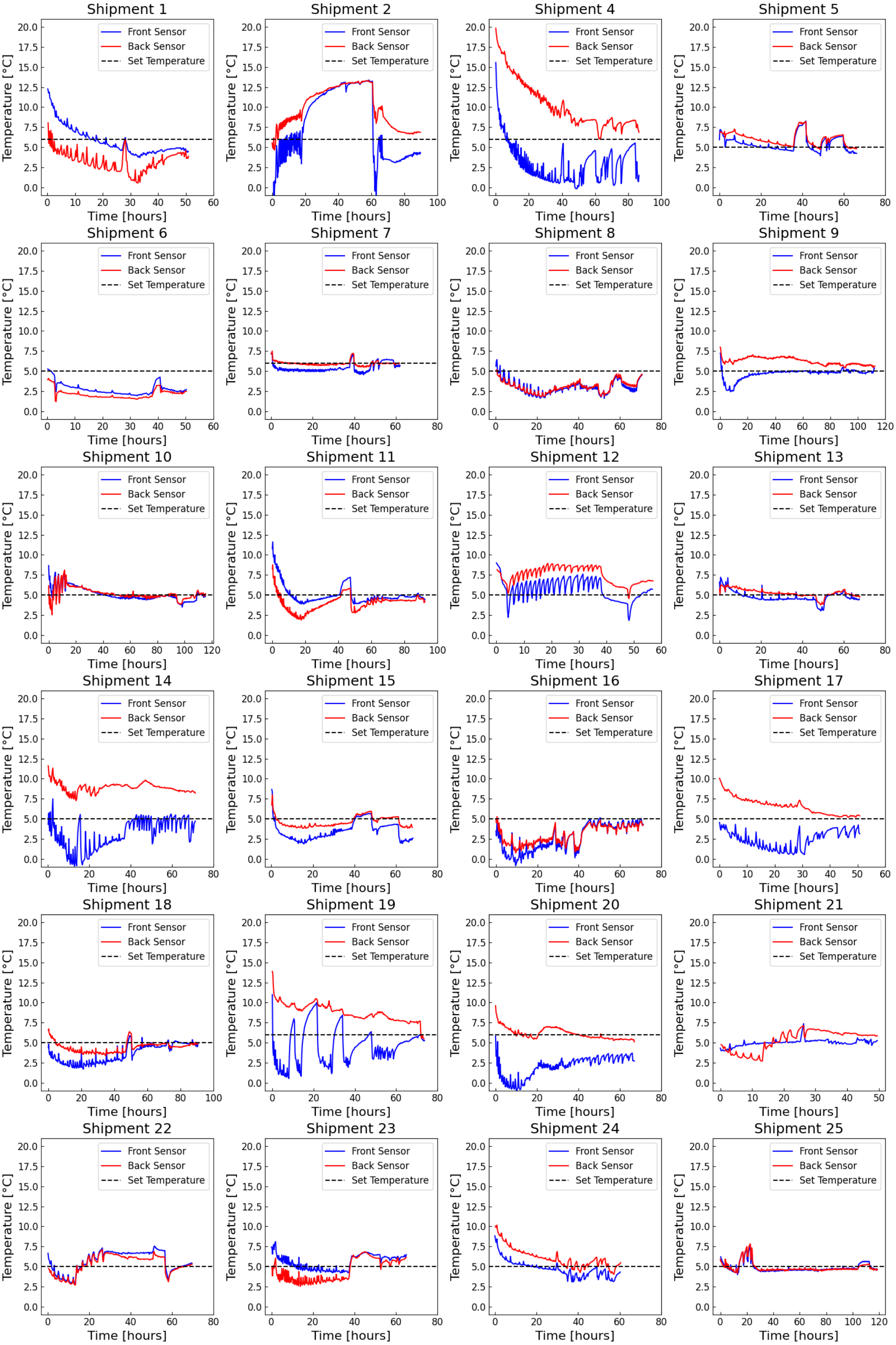


Figure 12: Raw temperature data for individual shipments (Part 1).

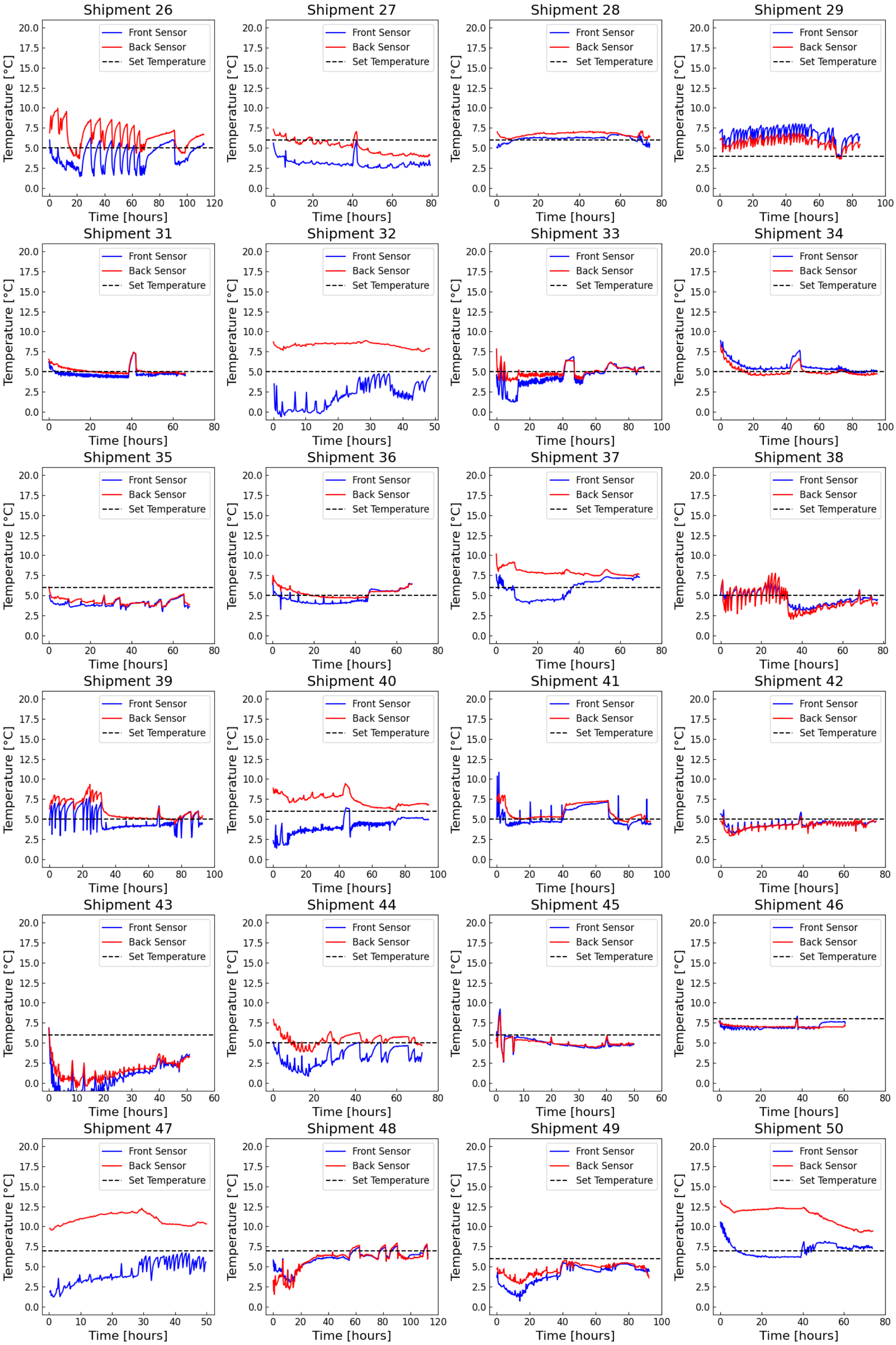


Figure 13: Raw temperature data for individual shipments (Part 2).

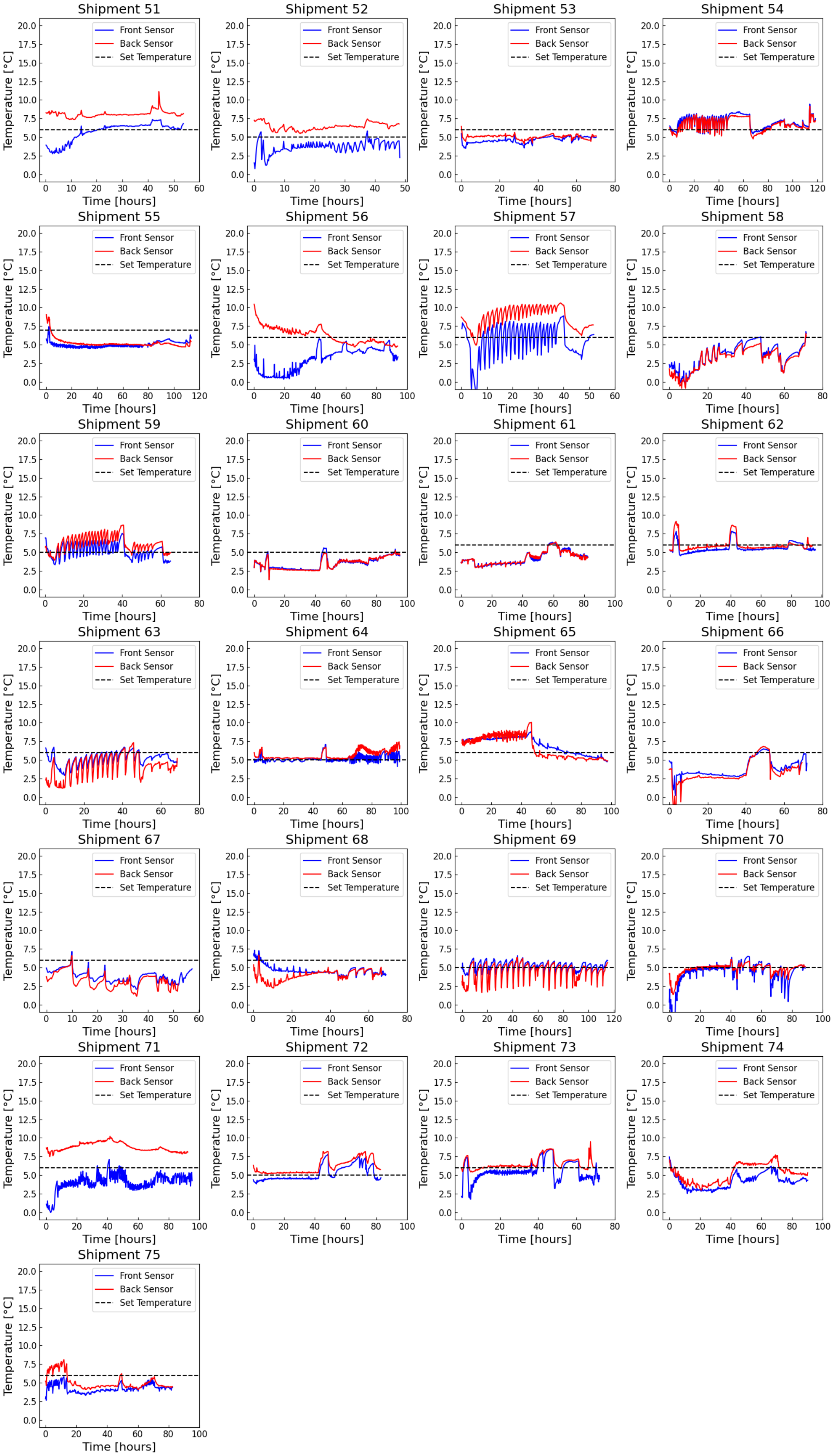


Figure 14: Raw temperature data for individual shipments (Part 3).

5.3 P-values of multiple comparison test in Figure 10

Table 1: Multiple Comparison of Means Front Sensor - Tukey HSD, FWER=0.05

Group 1	Group 2	Mean Diff.	p-adj	Lower	Upper	Reject
Long tube	Medium tube	-2.0381	0.6355	-5.9238	1.8475	False
Long tube	No chute	-1.83	0.7082	-5.603	1.943	False
Long tube	Plate	-2.0756	0.5987	-5.8913	1.74	False
Long tube	Short tube	-0.429	0.9993	-4.1006	3.2426	False
Long tube	Tarpin	-0.7354	0.9919	-4.4686	2.9978	False
Medium tube	No chute	0.2081	0.9994	-1.6496	2.0658	False
Medium tube	Plate	-0.0375	1.0	-1.9803	1.9054	False
Medium tube	Short tube	1.6091	0.0579	-0.0329	3.2511	False
Medium tube	Tarpin	1.3028	0.2704	-0.4728	3.0783	False
No chute	Plate	-0.2456	0.9981	-1.952	1.4608	False
No chute	Short tube	1.401	0.0385	0.0469	2.755	True
No chute	Tarpin	1.0946	0.2851	-0.4185	2.6078	False
Plate	Short tube	1.6466	0.0194	0.1779	3.1152	True
Plate	Tarpin	1.3402	0.1583	-0.2763	2.9568	False
Short tube	Tarpin	-0.3064	0.9774	-1.5452	0.9325	False

Table 2: Multiple Comparison of Means Back Sensor - Tukey HSD, FWER=0.05

Group 1	Group 2	Mean Diff.	p-adj	Lower	Upper	Reject
Long tube	Medium tube	-0.1006	1.0	-6.2214	6.0201	False
Long tube	No chute	1.8661	0.938	-4.0772	7.8094	False
Long tube	Plate	1.8704	0.9402	-4.14	7.8809	False
Long tube	Short tube	0.8351	0.9981	-4.9484	6.6187	False
Long tube	Tarpin	-0.7093	0.9992	-6.5899	5.1714	False
Medium tube	No chute	1.9668	0.3648	-0.9595	4.8931	False
Medium tube	Plate	1.9711	0.4127	-1.0893	5.0315	False
Medium tube	Short tube	0.9358	0.8921	-1.6507	3.5223	False
Medium tube	Tarpin	-0.6086	0.9872	-3.4054	2.1882	False
No chute	Plate	0.0043	1.0	-2.6837	2.6922	False
No chute	Short tube	-1.031	0.7111	-3.1639	1.1019	False
No chute	Tarpin	-2.5754	0.027	-4.959	-0.1919	True
Plate	Short tube	-1.0353	0.7725	-3.3487	1.2781	False
Plate	Tarpin	-2.5797	0.0454	-5.1261	-0.0333	True
Short tube	Tarpin	-1.5444	0.1976	-3.4958	0.407	False

5.4 Assumptions for statistical analysis

All assumptions were met except for the normality assumption for the trailer comparison test in section 3.4, as shown in Figure 19. Although normality was not perfectly met, we chose to proceed with this approach. The potential loss of significance in some cases would not substantially affect our interpretation. The goal of the analysis is not strict statistical significance, but rather to identify those trailers with the most pronounced differences between front and back temperatures for further investigation and optimization. Even if alternative tests yield altered significance levels, the focus would remain on the trailers with the largest temperature discrepancies as the basis for the recommendation. The remaining assumptions necessary for the execution of the Tukey HSD test were all met.

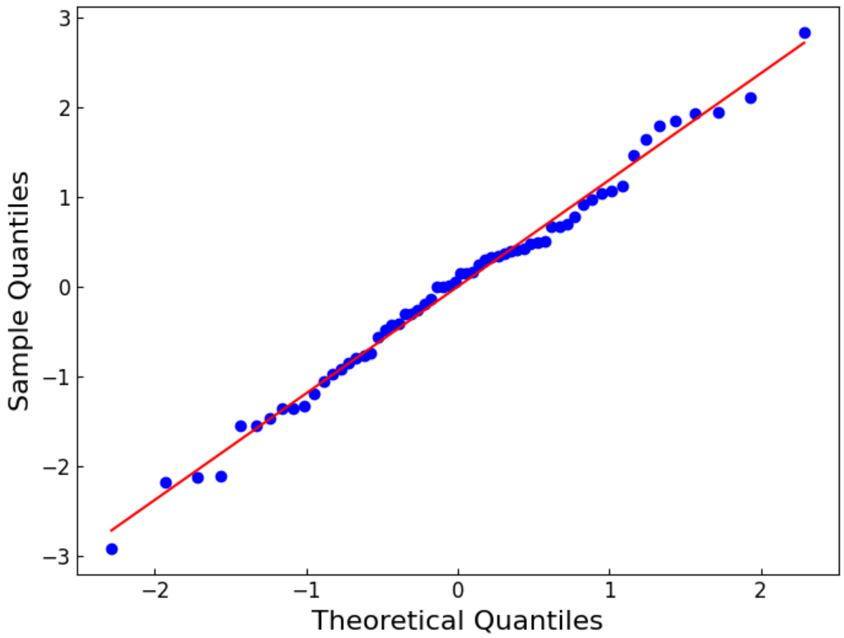


Figure 15: QQ-Plot of the front temperature sensor to differentiate between chute types.

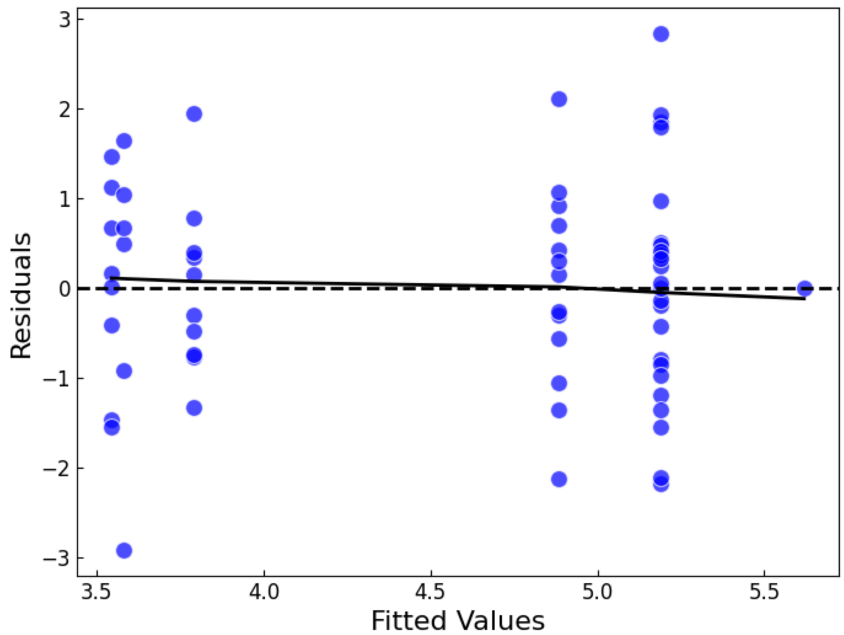


Figure 16: Tukey-Anscombe plot of the front temperature sensor to differentiate between chute types.

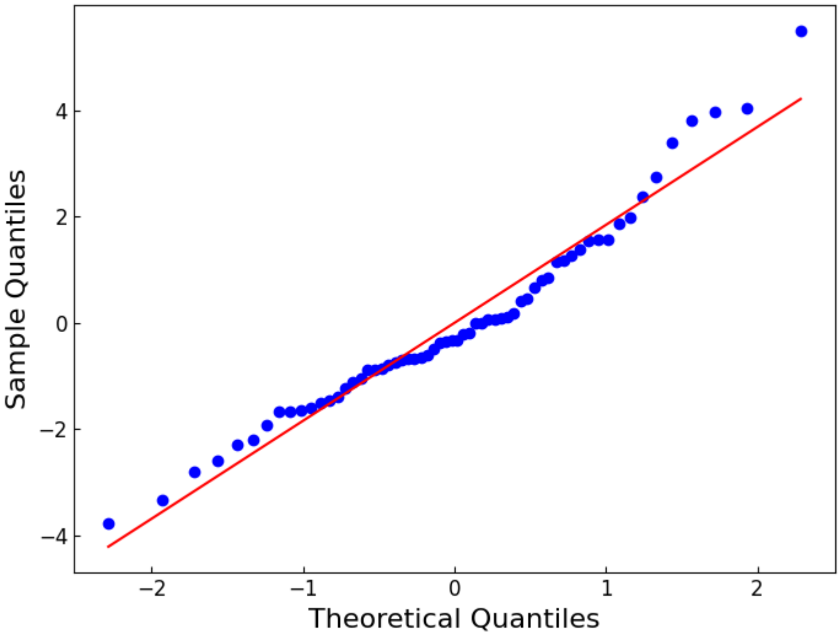


Figure 17: QQ-Plot of the back temperature sensor to differentiate between chute types.

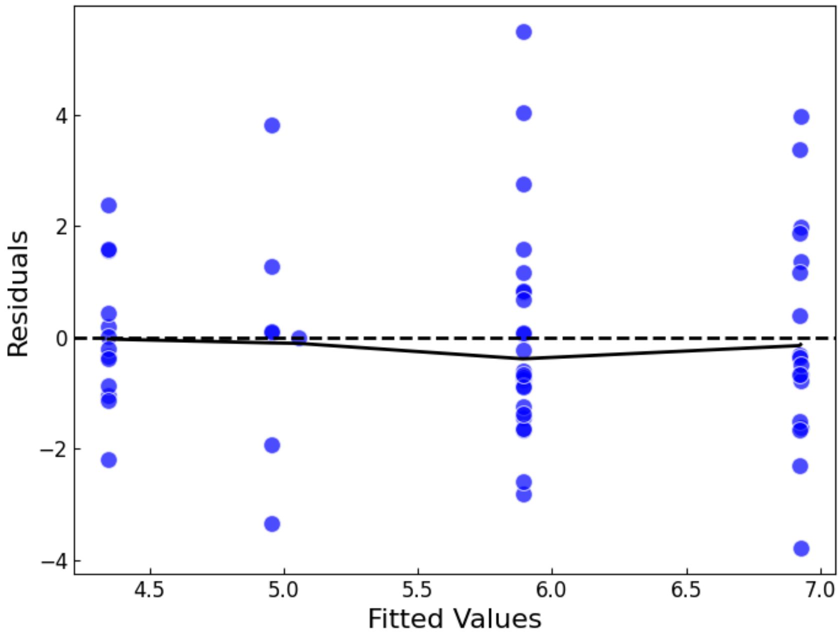


Figure 18: Tukey-Anscombe plot of the back temperature sensor to differentiate between chute types.

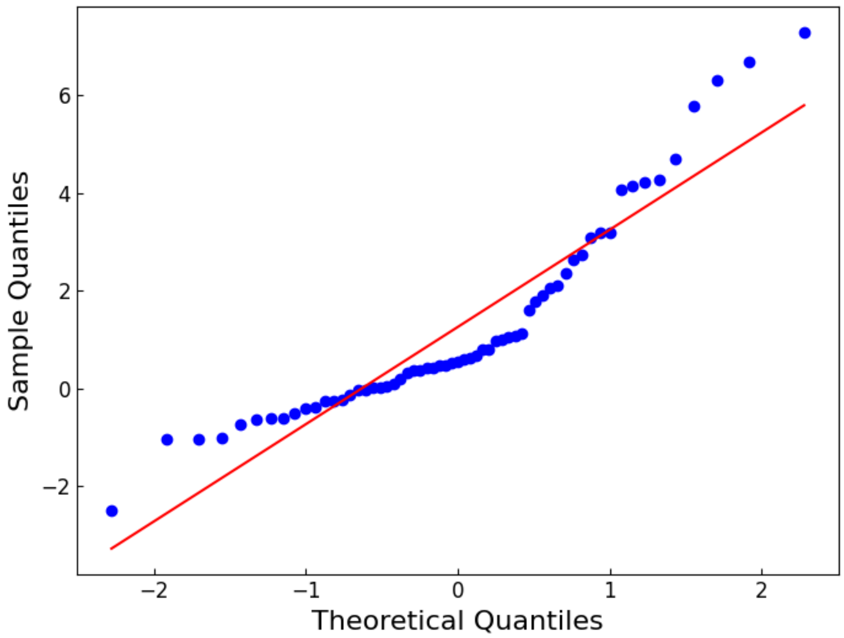


Figure 19: QQ-Plot of the temperature differences to differentiate between trailers.

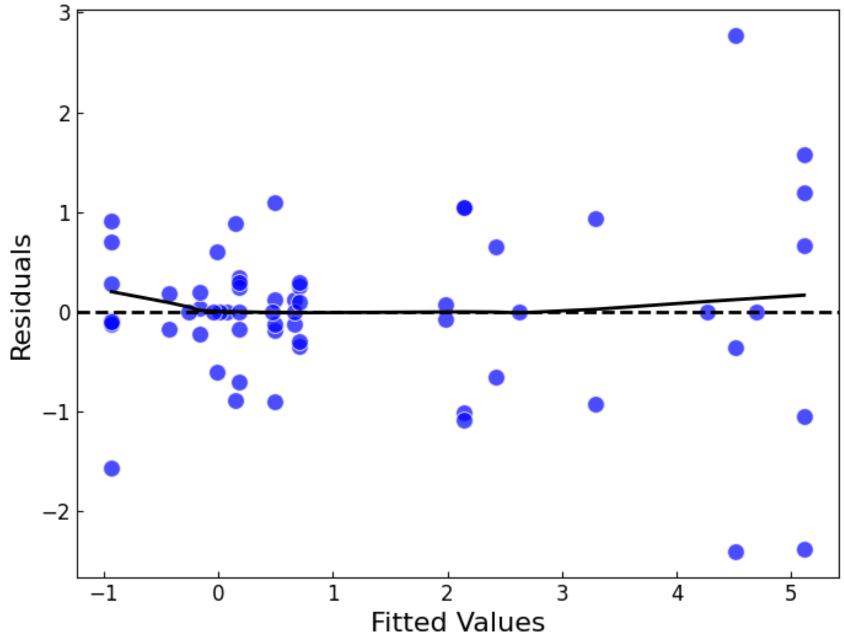
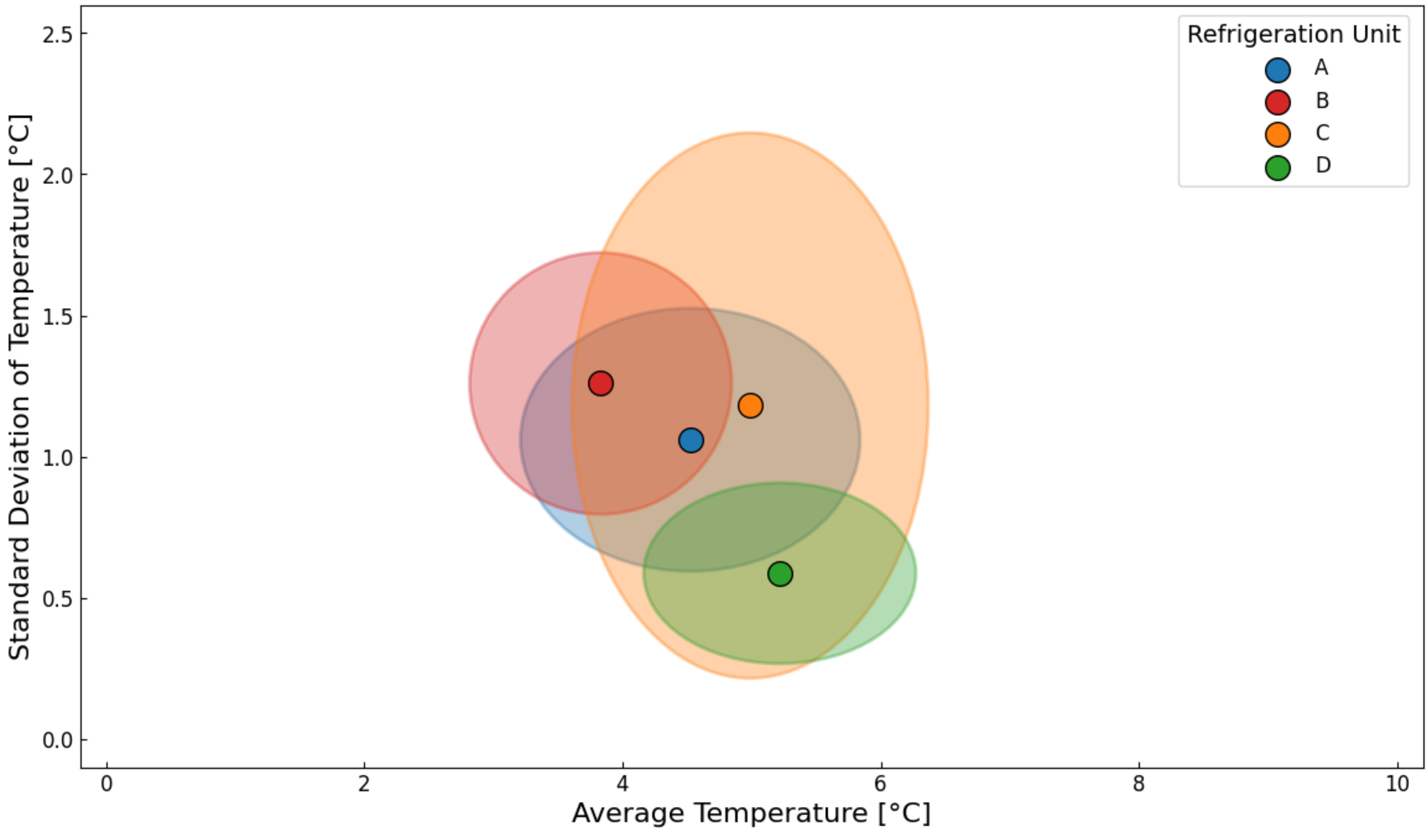
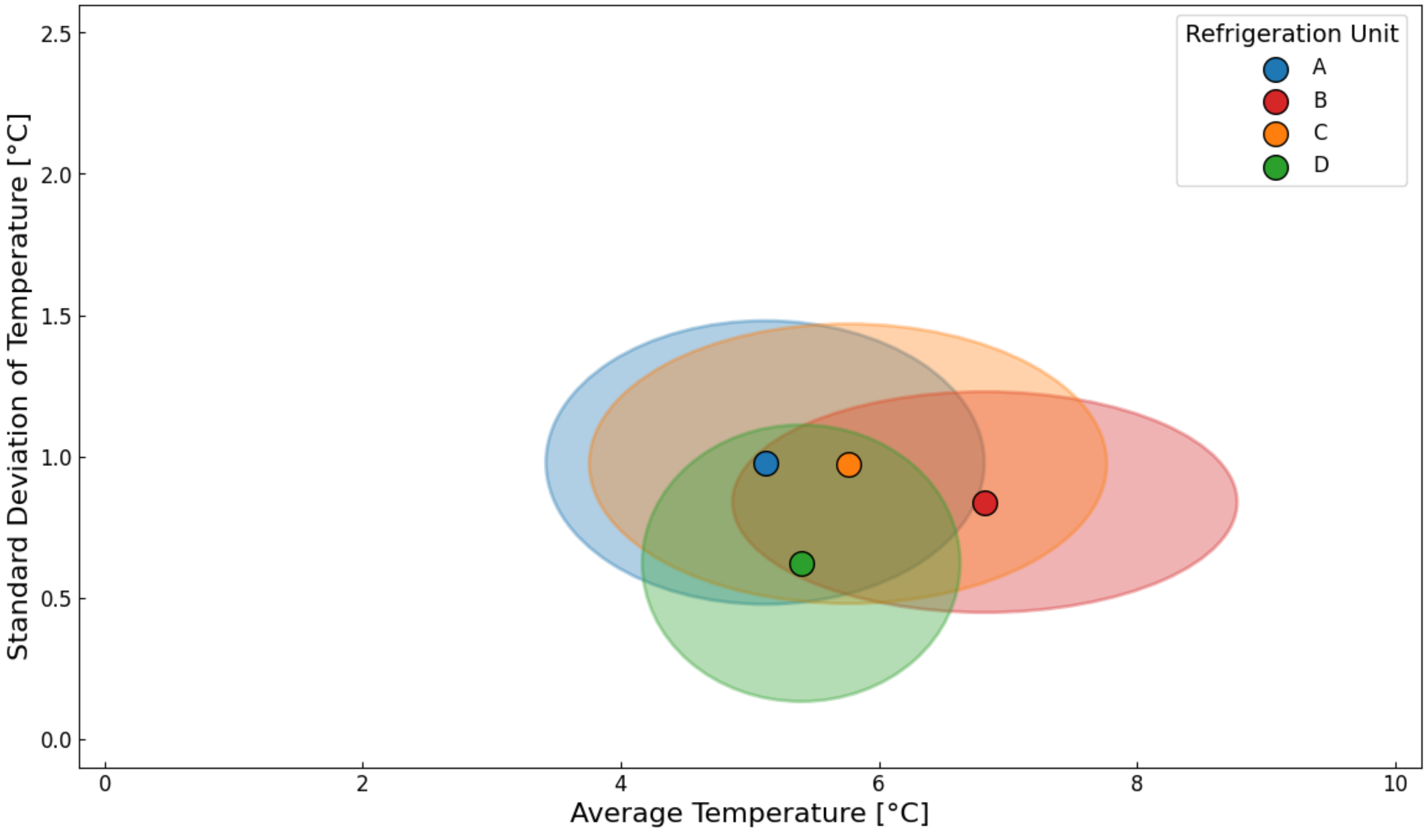


Figure 20: Tukey-Anscombe plot of the temperature differences to differentiate between trailers.

5.5 Additional results of section 3.6



(a) Figure illustrating the data from the sensor at the front of the trailer.



(b) Figure illustrating the data from the sensor at the back of the trailer.

Figure 21: The standard deviation of the average transport temperature as a function of the average temperature during the transport of the 73 monitored shipments in season 2023/2024. Each shipment is classified according to its refrigeration unit type. The black-bordered circles indicate each refrigeration unit type's average temperature and standard deviation, while the ellipses illustrate the variability within each group.