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Review

Interactions between Package Design, Airflow, Heat and Mass Transfer, and Logistics in Cold Chain Facilities for Horticultural Products

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Abstract: Homogeneity and temperature levels within a refrigerated facility are vital in preserving the quality of horticultural products throughout the cold chain to the consumer. These temperatures are affected by different factors at different scales, including the shape and thermal properties of the horticultural products, package design, pallet arrangement, or characteristics of the cold chain unit of operation. Therefore, airflow and heat transfer studies are valuable in evaluating these factors to optimize the cold chain and achieve and maintain an optimal product temperature. This paper provides an overview of the different scales of the numerical model and experimental setup used to assess the influence of the different factors on the cooling performance, as well as any challenges and limitations of each scale. The importance of considering other aspects in the cold chain studies, such as product quality, energy consumption, and package mechanical strength, will be discussed through an integrative approach. Finally, we propose new perspectives on how multi-scale modelling approaches can be helpful in tackling different challenges and how to investigate the effects of different factors on the cooling efficiency.

Keywords: cold chain; fruit quality; model scale; computational fluid dynamics; experiment; package; performance indicators; multi-layer of package; multi-scale modeling approach; integrated approach

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1. Introduction

Fresh fruits and vegetables are very beneficial for human health; the World Health Organization (WHO) recommends consuming more than 400 g per day per person [1]. Therefore, post-harvest preservation by cooling the product to its optimal temperature is critical to providing consumers with high-quality horticultural produce [2]. Maintaining products at a low temperature reduces the rate at which changes in perishable foods occur, such as the growth of microorganisms (e.g., pathogens and spoilage flora), ripening rates, browning reactions, or water loss [3,4]. It is estimated that 46% of food products require refrigeration [5]. All of the logistical operations between upstream producers and final consumers (pre-cooling, refrigerated transport, cold storage, display cabinets, and domestic refrigerators) that aim to maintain the products at a low temperature and adequate relative humidity to ensure their quality are termed the "cold chain".

Any failure in ensuring an optimal and uniform temperature at any point along the cold chain can lead to a reduction in product quality [6]. Temperature abuse during any cold chain, which can lead to excessive quality loss, can result from temperatures that are either too high or too low. For example, high temperatures cause fruits to increase respiration and transpiration, which leads to greater loss of moisture and freshness [7]. Wu, et al. [8] reported that a temperature increase of 10 °C above the optimal reduces the shelf life of citrus fruits by half. It is important to point out that different causes can be responsible for these losses and waste, like biological, microbiological, chemical, mechanical, physical, and physiological [9]. Losses and waste in the fruit and vegetable supply chain after harvesting may occur in any link of the cold chain and can be as high as 13–38%, even before they reach the consumer [10]. In France, strawberries' cumulative losses and waste during the supply chain (production, transformation, distribution, and consumption) are 25% [11]. Food waste is also a source of significant environmental impact since the balance of this waste must also integrate all the resources used and lost throughout the supply chain, including water, energy, and the resulting polluting emissions, with the final production of greenhouse gases and other environmental impacts [11]. Food waste represents approximately 38% of all energy consumed in the food industry [10,12]. Losses and waste continue to increase due to various reasons: the high demand for fresh horticultural products, globalization, and the emergence of new food consumption markets for fresh produce that are increasingly distant from the point of production, which poses many technological challenges.

The non-optimal temperatures that lead to losses are driven by different factors, such as refrigeration system outages, incorrect temperature settings in refrigeration systems, airflow heterogeneity within the stack, very irregular temperature distributions due to heterogeneity of air, exposure to ambient air during delivery loading and unloading, and the presence of local heat sources in trucks or warehouses [6,13].

Investigations have been conducted to study the airflow and heat transfer characteristics between and inside pallets for different cold chain units of operation, including precooling, cold storage, and transport. These analyses have helped researchers, firstly, to better understand the diverse phenomena within a refrigerated unit in different operating units of the cold chain and, secondly, to evaluate the cooling rate and uniformity inside a cooling room and then to assess the effect of the different factors on the cooling and, thus, the quality of products. Extensive studies have focused on different factors, such as package design (vent area, shape, number, position, etc.), fruit stacking pattern in the package, and package stacking pattern on the pallet. As packages perform functions of containment, protection, preservation, storage, and distribution of food [14], this subject has attracted much attention in the last decade. These experimental and numerical studies were performed on different scales, such as a whole cooling facility, one pallet, or even the scale of a corrugated tray. The main focus of most studies was analyzing the characteristics of the airflow and the cooling and storage performance. Recent studies that analyze the effect of a new package alternative, cold chain scenarios, or cooling conditions started focusing on other aspects such the product quality, energy consumption, and packaging mechanical strength.

Existing reviews synthesize studies on different aspects, such as mathematical models for analyzing airflow, heat, and mass transfer during forced convection cooling (a porous medium approach and direct meshing of each product) [15]. Pathare, et al. [16] targeted studies investigating the effect of varying package vent designs on the homogeneity of the cooling process. Defraeye, et al. [17] reviewed the relevant packaging functionalities used to evaluate the performance of a package design. Mukama, et al. [14] presented research studies on package functionalities in terms of cooling rate, box ventilation, product quality, mechanical strength, energy consumption, computational fluid dynamics (CFD) and computational structural dynamics (CSD) used to analyze airflow, heat transfer performances, and compression strength in vented carton design. Ambaw, et al. [18] summarized recent numerical studies, especially CFD and CSD, used by researchers to perform abstract conceptual designs and analyzed alternatives.

This review intends to present the different scales of numerical models and experimental setups used to investigate the effect of packaging and cold chain conditions on the cooling rate, cooling uniformity and airflow behavior in different cold chain links, and discuss the limitations of each scale. Section 2 explores numerical and experimental approaches used to study airflow and heat transfer. The types of turbulence models are applied, and methods for validating the predicted values by the numerical approach are also presented. A review of the different scales found in the literature is performed in Section 3, including the most recent discoveries and main considerations, the overall airflow and heat transfer within the refrigerated chamber, and inside the packages. Section 4 highlights the effect of a new cold chain scenario or alternative packaging solution on aspects other than the cooling rate and ventilation heterogeneity. Finally, the review discusses how a multi-scale modeling approach can be implemented to provide a solution to evaluate different packaging levels and the influence of several factors concurrently on cooling performance and thus product quality.

2. Numerical, Experimental, or Both Methods for the Analysis of the Cold Chain

Field studies are essential to track the time-temperature evolution along the cold chain. These measurements map the temperature inside the pallets and thus reveal unacceptable deviations from the optimal temperature [19–21]. Despite the measurements in actual industrial conditions, which are essential, real-time monitoring of product temperature at each cold link is a difficult task given the practical limitations of instrumenting each box in a product pallet [22]. Airflow and heat transfer studies, both numerical and experimental, aim to better understand and interpret the airflow behavior inside and around the packages and its influence on the temperature distribution. Further, these studies aim to understand how these physical phenomena affect product quality to prevent post-harvest losses effectively. These investigations cover different cold chain units and deal with several features, including products, packaging types, dimensions, stack loading, and packaging stacking arrangement.

The main difficulties encountered by researchers during their investigations are related, but not limited to: (1) high compactness of packages and of the refrigerated facility (e.g., transport vehicles), which makes it tedious to access and place the sensors in field studies; (2) the opacity of products and packages that restrict the use of laser devices for accurate velocity measurements; (3) numerical limitations when working on a large scale such as an industrial room; (4) difficulties in repeating experiments due to cost and biological variations and the challenge of reproducing the same experimental device.

2.1. Experimental Approach

Despite the extent of numerical methods, the experimental study remains required. It better represents reality without the simplified assumptions generally used in numerical models. Moreover, the experimental process is crucial for validating the numerical model. Real-time temperature, pressure drop, and velocity measurements are conducted using experimental setups at different scales depending on the study's purposes. These scales include field tests, full-scale laboratory experiments, a single pallet, or one level of a pallet (Figure 1a–d [23–26]).

There are various methods to measure the airflow rate, which include a pitot-tube device connected to pressure transmitters [27], hot wire anemometry [13,28], hot film omnidirectional air velocity transducer: TSI 8475, TSI Incorporated, Shoreview, MN, USA [29], or an air velocity meter: TSI AVM410, TSI Incorporated, MN, USA [30].

To characterize the airflow, particularly for the validation of CFD models, in some cases, the flow field measurement is required for an inner view of the local airflow. The two most common methods are Laser-Doppler Velocitymeter (LDV) [31–33] and Particle Image Velocimetry (PIV) [34–37]. Both of these techniques use non-invasive quantitative methods. Moureh et al. [28] used indirect velocity measurement techniques by placing heated spheres inside the stack; these spheres calculated the convective heat transfer coefficient, which is related to the velocity through a Nu vs. Re correlation. Praeger, et al. [38] used two types of sensors to characterize the airflow in the bins and the gaps between bin stacks: an air speed logger-ASL for lower speed air between fruits in the bin and newly developed wireless anemometers-WAWs for airflow measurements in the gaps.

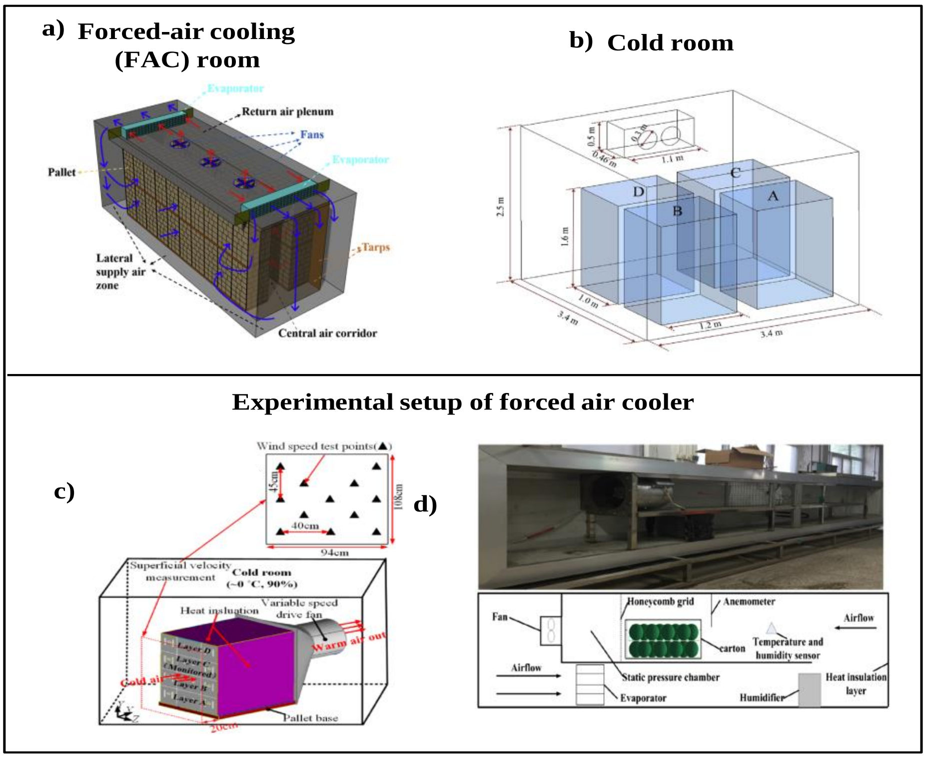


Figure 1. Different experimental setups built at different scales: (**a**) [23] and (**b**) [24] scale of a refrigerated facility, (**c**) [25] scale of a pallet, (**d**) [26] scale of one box.

For temperature measurements, different types of sensors have been found in the literature: type T thermocouples [28,30,39,40] usually with an accuracy after calibration of ±0.3 °C, i-buttons with an accuracy ±1 °C (disk-shaped sensors with a diameter = 16.3 mm and a height = 5.9 mm) [41], sphere-shaped thermal probes equipped with electrical resistance [28], thermometer TESTO (resolution + 0.1 °C, accuracy + 0.5 °C) and wireless sensor SPY (resolution + 0.5 °C, accuracy + 1.0 °C) [42].

The pressure drop can be measured using a tilted-tube pressure gauge (micromanometer, ±0.5 Pa) [28], pressure transducer device [43], or a differential pressure transmitter (measuring range of 0–5000 Pa) [30].

Experimental studies are challenging to conduct. They are usually expensive and time-consuming [44]. In addition, they are restricted due to complications caused by handling biological materials and fluctuations in the physical properties of agricultural products [30].

2.2. Numerical Approach

Numerical methods are considered one of the most potent alternatives to expensive and tedious experiments. This approach allows the evaluation of the influence of different systems and operating conditions on the airflow and temperature patterns in the fruit stack as well as providing details on the process mechanisms and performance [14].

One of the tools that has become widely used in various fields is CFD. CFD is based on the fundamental governing equations of fluid dynamics and predicts fluid flow, heat and mass transfer, and other phenomena [45]. CFD solves equations for the conservation of mass, momentum, energy, etc. It provides details on the spatiotemporal airflow and temperature distribution. Two methods exist for modeling the cooling of fresh produce: the porous medium method and direct CFD simulation. In direct CFD simulations, a model based on the explicit geometry of produce stacked in boxes is developed and used to study the local airflow and heat transfer through stacks of horticultural products. Each product item is meshed in detail. This method solves the Navier-Stokes (NS) equations numerically for laminar flow or the Reynolds Averaged Navier-Stokes (RANS) equations for turbulent flow. The whole domain (air and solid products) is meshed into elementary volumes. All equations are solved in each elementary volume until the desired convergence criterion is reached. Direct CFD simulations lead to a more "fundamental" understanding of the local behavior of the fluid flow and heat transfer in the pallets.

RANS-conservation of mass:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

RANS-conservation of momentum:

$$\rho_f \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\right] - \rho_f \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \tag{2}$$

RANS-conservation of energy:

$$\frac{\partial \overline{T_f}}{\partial t} + \overline{u}_i\left(\frac{\partial \overline{T_f}}{\partial x_i} + \frac{1}{\rho_f C p_f}\frac{\partial \overline{p}}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left(\frac{\lambda_{eff}}{\rho_f C p_f}\frac{\partial \overline{T_f}}{\partial x_i}\right) \tag{3}$$

The Reynolds stresses in Equation (2) can be expressed according to the Boussinesq hypothesis:

$$-\rho_f \overline{u_i' u_j'} = \mu_t\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\rho_f k \delta_{ij} \tag{4}$$

$$k = \frac{1}{2}\overline{u_i' u_j'} \tag{5}$$

The effective thermal conductivity λ_{eff} in Equation (3) is given by:

$$\lambda_{eff} = \lambda_f + \frac{C p_f \mu_t}{Pr_t} \tag{6}$$

Other terms can be added to these equations to represent the natural convection or for example $S_{PM,i}$ which is a momentum source term used only in porous medium.

However, incorporating detailed geometries in the model of a fully-loaded cold storage room or a reefer container is still impractical because of limitations in computational resources. As an alternative, a porous media approach could be used, but the geometric complexity of multi-layer packaging cannot be described properly for large systems. The porous medium approach simplifies the mathematical model, and reduces computing time and simulation costs [45]. In the porous medium model, an elementary volume contains a relatively large number of product items (Figure 2 [46]). The fluid's flow is characterized by Darcy's velocity, which corresponds to the space average of the fluid velocity over a representative elementary volume. A source term is added to the momentum equation, representing the flow resistance as given in the Darcy-Forchheimer equation:

$$S_{PM,i} = -\frac{\mu_f}{K} u_i - \rho_f \frac{F}{\sqrt{K}} |u| u_i \tag{7}$$

K and F depend on the stacked product diameter, porosity, stacking pattern, fluid property, product shape, roughness, confinement ratio $(\frac{D_h}{d_p})$, and box vent hole ratio (A_{hole}/A_{box}) [29].

Researchers used different methods to determine K and F. Zou, et al. [44] applied the Ergun [47] correlation, but the latter does not consider the effect of the confining and vented box walls [24,29]. Ambaw, et al. [48], Delele, et al. [49], and Sajadiye, et al. [50] applied a numerical approach by using a combination of discrete element and CFD modeling in which the explicit geometry of stacked products in boxes is considered.

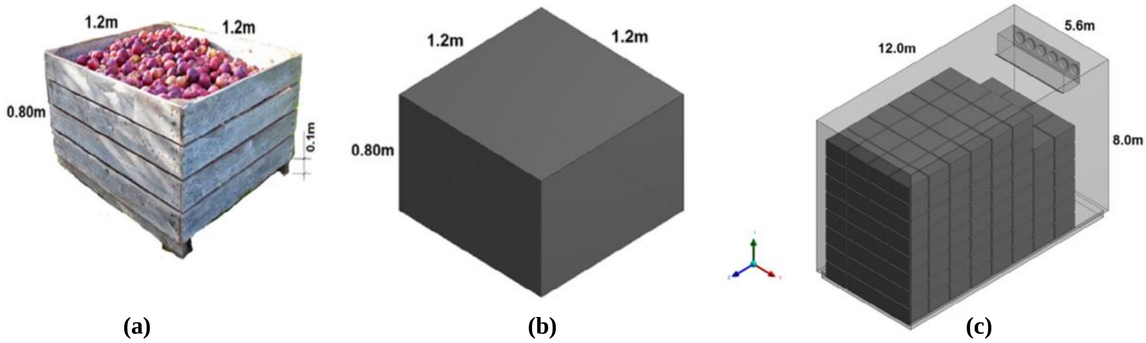


Figure 2. (**a**) Wooden bin loaded with randomly packed fruit (**b**) porous medium model of a bin (**c**) porous replica of bins placed in a cold room [46].

Getahun, et al. [51] and Delele, et al. [52] applied an experimental approach where they measured the pressure drop as a function of air velocity and fitted it to the Darcy–Forchheimer equation. From the fitted equations, the values of K and F were determined.

The flow resistance can be determined using the power law relationship of the Ramsin equation [53].

Hoang, et al. [24] tested two CFD approaches to predict the airflow and heat flow inside a cold room filled with apple bins: apple pallets are considered (1) as a porous medium or (2) as eight solid blocks (products were simulated as a uniform block). Both approaches were capable of predicting the airflow pattern, but the simulated velocities were too far from the measured ones due to the poor accuracy of the velocity measurements. The solid block approach gave better results for cooling rates with the smallest error between the experimental and numerical data. The authors stated that the porous medium approach gives better results in terms of the temperature trend if a fine mesh grid is used.

An issue encountered by researchers is when modeling the interface between the porous medium and the external airflow, mainly when the porous medium is located inside slotted boxes. It is very challenging to mesh each hole of the slotted walls in detail. Usually, researchers model the interface as a porous medium with a simplified hypothesis based on pressure losses related to the normal flow through the plate [54], but significant differences between numerical and experimental results can be found. To overcome this difficulty, Diop, et al. [54] proposed a numerical interface law to simulate the effect of a perforated plate on the flow. To achieve this objective, the perforated plate was modeled as a fictitious thin porous zone into which appropriate source terms were implemented, taking into account the aerodynamic effects of the perforated plate on the flow related to the pressure drop, the drag, the turbulence damping, and the momentum transfer.

Numerical resources can also be significantly reduced using a simplified model. Applying this numerical method, Hoang, et al. [42] drastically reduced the computational time from 60 h (CFD approach) to 1 min. To characterize the heat transfer inside a refrigerated vehicle and a cold room, Hoang, et al. [42] and Laguerre, et al. [55] used a simplified model based on the concept of zones or compartments for which average bulk air and load temperatures are considered. Energy and mass balances are then calculated for each zone, while experimental data are used to define airflows. The model includes parameters that can impact the load temperatures, such as outdoor air temperature, wall insulation, thermostat setting, and product breathing heat. Different parameters, such as infiltration caused by the open door, heat flux through insulated walls, the heat of respiration, and air recirculation and bypass, were included in this model [42]. This method also requires the development of appropriate interface models between zones [56]. The predicted results were in good agreement with the experimental results. Hoang, et al. [42] reported a maximum difference of 1 °C between experimental and simulated average load temperatures for the transport of oranges and 0.7 °C for frozen food transport. Laguerre, et al. [55] found that the half-cooling time (HCT) and the half-warming time are higher in the front pallet than in the rear one, which agrees with the experimental results. The maximum difference in product average temperature between the measured and calculated values was 2 °C. A major limitation of this approach is the necessity of knowledge of the airflow rates in the different zones, which are generally estimated via experimental measurements [4]. Moureh, et al. [57] developed a simplified zonal model of airflow and heat transfer in a pallet of food-generating heat. Based on a hydraulic network analogy and pressure drops through vent holes and air gaps, it predicts the global airflow through the box faces and the product temperature. The average difference between the experimental and calculated temperatures is 0.8 °C.

The motivation for this development is modeling the cold chain from production to consumption, allowing the prediction of the time-temperature history of the product as a function of packaging and operating conditions [4,57].

Overall, this type of simplified model is limited to specific packaging and palletizing configurations. Therefore, it is not appropriate to use this method to compare the effects of different packaging, which directly influences the airflow pattern between zones, if there is no associated experimental data [56]. The application of this method to the different phases of the cold chain and the links between them, and coupled with the quality and microbiological evolution model, can then be used as a risk assessment tool to help operators manage the supply chain to ensure food quality and safety [58,59].

2.3. Turbulence Models

The RANS equations must be completed by a turbulence model, which provides a computational procedure to close a system of mean flow equations [60] by adding additional transport equations to solve the variables like Reynolds stresses, turbulence kinetic energy, and a specific dissipation rate.

The accuracy of the CFD simulations depends on the turbulence model applied to capture the eddy velocity fluctuations and the boundary-layer approach, and their validation is required [61]. The selection of a turbulence model depends on the grid resolution, computational cost, and accuracy of the solution required. For most problems, different RANS-based turbulence models were applied: RSM [62], k-ε [40], and SST k-ω [30,41,63,64]. The features of the numerical simulation for some selected studies are presented in Table 1.

Numerous studies use the previously described standard k-ε model [65] or its derivatives to predict airflow patterns in enclosures since it is easy to program and has broad applicability. However, according to the complexity of internal flows underlined above, some fundamental studies [66–69] agree on the inadequacy of the k-ε model to predict airflow patterns and underline its limitations by comparison with experimental data.

Moureh and Flick [70] and Moureh, et al. [71] tested and compared various turbulence closure models, including the standard and low Reynolds number forms of the two-equation k-ε model and the more advanced RSM. The author concluded that only RSM was able to accurately predict the separation of the jet from the ceiling and the general behavior of airflow patterns related to primary and secondary recirculation in loaded and unloaded enclosures. In a loaded enclosure, Tapsoba, et al. [72] compared experimental measurements of velocities with predictions given by two turbulence models: RSM and k-ε. The authors found that RSM gave better predictions about jet penetration, jet deflection, and its attachment by the Coanda effect on the top of the pallets. Predicted velocity profiles obtained with the RSM were generally within an error range of 3 to 30% of the measured velocities. Hoang, et al. [73] conclude that enhanced turbulence models such as Reynold stress models (RSM) could contribute to improving the numerical predictions obtained in a cold store.

Several authors have validated the SST k-ω model for ventilated packaging design [30,41]. For the spherical product, better accuracy and solution convergence were observed for the SST k-ω turbulence model than for the other two-equation turbulence models (standard k-ε, RNG k-, and standard k-ω) that were tested by Delele, et al. [30]. However, using the SST k-ω model appropriately necessitates very fine mesh near wall boundaries with respect to y+ = 1. Therefore, the computation time and memory requirements are significantly higher than when using high Reynolds number models associated with wall functions. These aspects constitute the principal limitation for the SST k-ω model, especially within the large loaded cold store.

Table 1. Studies applying different numerical approaches and turbulence models.

Reference	Software	Turbulence Model	Mesh Type and Size	Numerical Approach
[74]	ANSYS Fluent 13	SST k-ω	Hybrid grids (hexahedral and tetrahedral cells) base model: 4.1×10^6 cells model 2: 4.9×10^6 model 3: 5.9×10^6 model 4: 7.2×10^6 cells	Direct CFD simulation
[52]	ANSYS Fluent	SST k-ω	Tetrahedral hybrid mesh 4.62×10^6 cells	Porous medium
[40]	ANSYS	K-ε	Tetraedrique 7.4×10^6 cells	Direct CFD simulation
[75]	Fluent v.6.1.18	RNG K-ε	A non-uniform quadrilateral mesh 74,430 cells	Porous
[29]	Fluent 6.3.26	SST k-ω	Tetrahedral hybrid mesh	Direct CFD simulation
[32]	Fluent	RSM	624,000 cells for the empty configuration 419,000 cells for the loaded configuration as the load is not part of the modeled domain	Direct CFD simulation

2.4. Validation of the Predicted Values

The numerical model is verified by comparing experimental measures such as temperature, pressure drop, and air velocity to the predicted values. The main method used in cold chain studies for validation is the comparison of cooling profiles between numerical and experimental results and the calculation of the standard deviation between the results.

O'Sullivan, et al. [40] used the HCT or seven-eighths cooling time (SECT), which is defined as the period required to cool the product to one-half or seven-eighths of the temperature difference between the product and its surroundings (cooling medium) [76]. The SECT is more representative of actual cooling because it is more practically applicable in cooling facility operations. When this temperature is reached, the products can be moved to the storage room or transport vehicle, where the remaining heat is removed [64].

Numerous factors can be responsible for the discrepancy between experimental and numerical values: Imperfect stacking during experiments that could increase airflow through the vents (e.g., in experiments, gaps between boxes) or the vents are blocked by fruit or another package [30,63]; experimental instruments like thermocouples can block vents and affect the airflow inside the package, significantly impacting the incoming refrigerated airflow [40]; poor calibration of thermocouples [46]; In the numerical model, constant values of the inlet velocity and temperature are imposed, but in reality, there are fluctuations [63,77]; near the inlet region where there is high turbulence, prediction of the velocity is difficult [24]; The simplified shape of the product taken into account in the model is also undertain [40,77]; uncertainties in material properties, for example, estimation errors of the actual thermal mass of the stack [40,46]; and finally, numerical oscillation [77].

3. Facility Conditions, Logistic Aspects, Pallets, and Package Impacts

Researchers have built experimental setups and developed numerical models to study the different factors that affect the cooling performance of horticultural products. The scale depends on the parameters that should be studied, for example, package designs, pallet patterns or gaps between pallets, the resources available, and the required accuracy. In this section, the different scales used by researchers to study the airflow characteristics and evaluate the influence of different factors on the temperature heterogeneity of horticultural products are described. First, the airflow characteristics and air temperature heterogeneity studies around pallets at the scale of a refrigerated or cooling facility are identified for the three main cold chain units of operation. Next, the section will look into the studies that investigate the airflow behavior and cooling performance inside the package; for this purpose, these investigations are divided into three scales: refrigerated room, pallet scale, and box scale. Figure 3 summarizes the different scales of experimental setups or models used in most studies. This figure provides an overview of the various factors assessed and the performance indicators used for the evaluation.

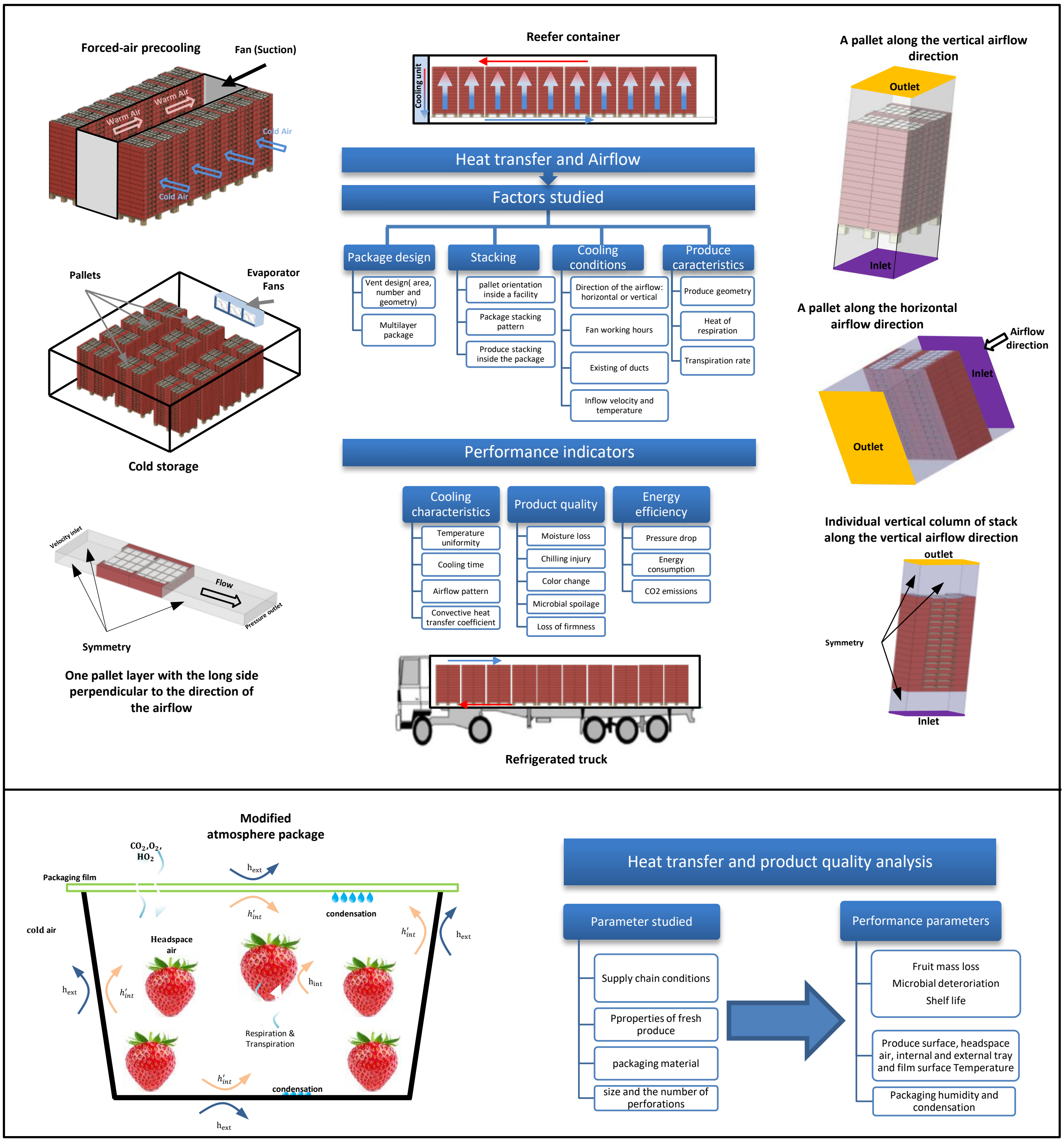


Figure 3. Different scales of model used in heat transfer and airflow studies.

3.1. Global Airflow Characteristics within Refrigerating Facilities

The refrigerated equipment installed inside a cooling facility plays a crucial role in the ventilation mode. Several factors controlled by this equipment, such as the airflow velocity and cooling working hours, affect mainly the airflow distribution around the pallets, which directly impacts the airflow inside the package and thus the temperature homogeneity as well as the product quality.

Failure to manage the phenomena taking place in the unit results in excessive weight loss or deterioration in product quality. Because of these numerous and interconnected factors, understanding the airflow and heat transfer within a refrigerated unit is very challenging. At such a large scale, CFD models are required for an accurate description of the airflow patterns and temperature heterogeneity [13]. To avoid an expensive discretization domain, these CFD models use a porous medium of simplified geometry to model the fruit-loaded bins. Figure 4a–f [28,33,50,51,63,78], shows the behavior of airflow inside a refrigerated facility for different unit operations of the cold chain.

Table 2 summarizes airflow and temperature distribution studies around pallets placed inside a transport truck, reefer, cold room, or pre-cooling facility.

Table 2. Studies investigating the airflow pattern and temperature distribution around pallets inside a cooling facility.

Reference	Method	Produce Type	Unit of Operation	Produce Phenomena	Type of Study	Performance Indicators
[71]	Exp & Num	Spheres	Transport	-	Thermal Aerodynamic	Airflow rate Velocity magnitude Nusselt number Air and core product temperature
[79]	Exp	Apples	Storage	Moisture	Thermal, Aerodynamic, Product quality	Air velocity Convective heat transfer coefficient (CHTC) HCT Temperature field in the cold room Weight loss
[46]	Exp & Num	Apples	Storage	Respiration	Thermal Aerodynamic	Airflow Temperature Natural convection Refrigeration load
[51]	Exp & Num	Apples	Transport	Respiration	Thermal Aerodynamic	Pallet pressure drop Airflow pattern Air velocity SECT HCT
[13]	Exp	Strawberries	Pre-cooling	-	Thermal	HCT Air and Produce temperature
[38]	Exp	Apples	Storage	-	Aerodynamic	Air speed Air velocity
[7]	Num	Oranges	Storage	Respiration, Transpiration	Thermal Aerodynamic	Air velocity Product temperature Surface heat transfer coefficient Absolute deviations of mean product temperature
[80]	Exp	Apples	Storage	-	Aerodynamic	Air velocity Air speed Air volume rate
[81]	Exp	Citrus	Transport		Thermal product quality energy consumption	Air temperature SECT Mass loss Chilling injury Decay incidence Energy consumption Power use of refrigeration unit

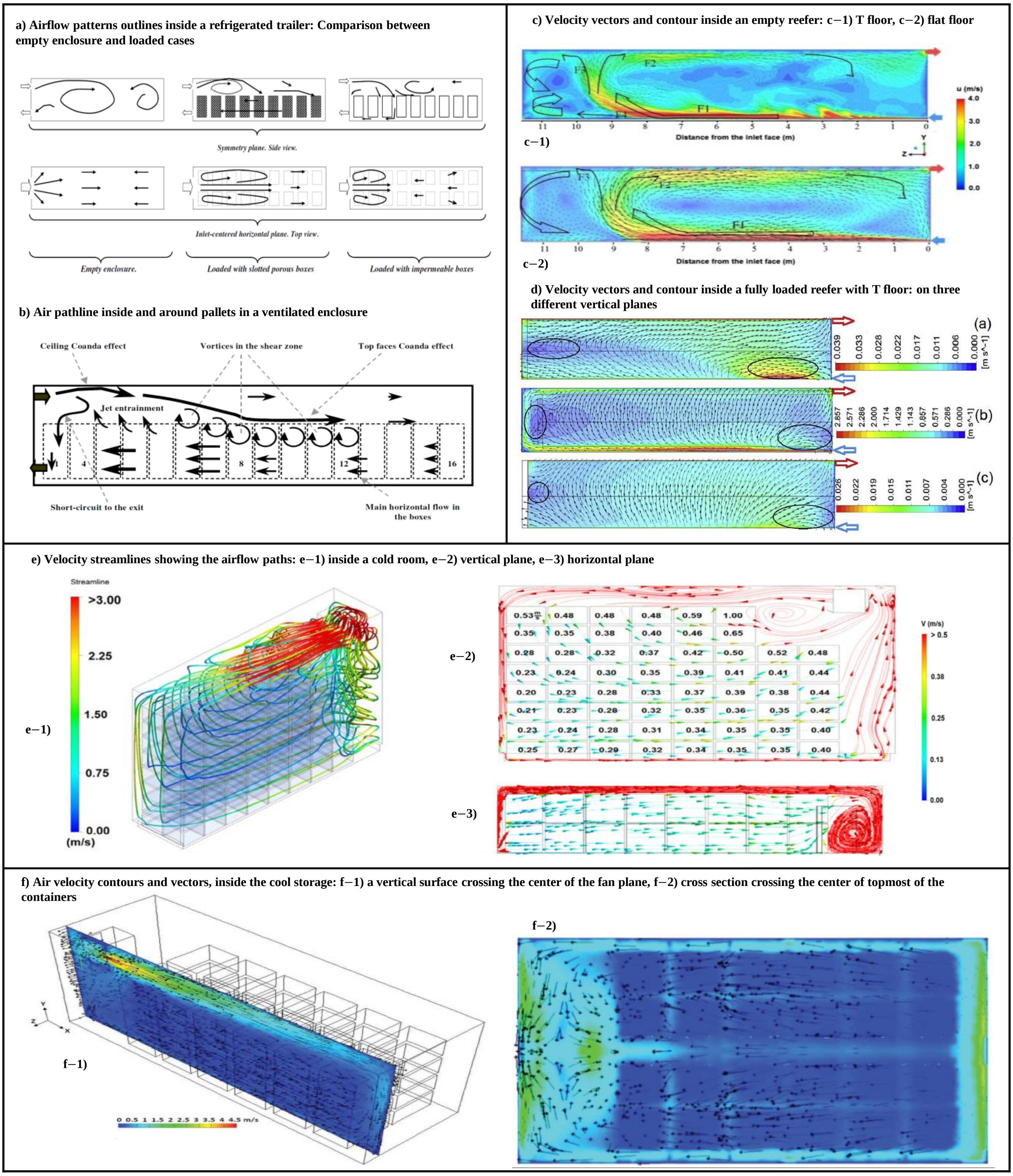


Figure 4. Airflow patterns inside a cooling unit for different cold chain links found in the literature (**a**) [33], (**b**) [28], (**c**) [51], (**d**) [78], (**e**) [63], and (**f**) [50].

3.1.1. Pre-Cooling Facility

The first unit operation after harvesting is pre-cooling, which cools down the horticultural products to the recommended temperature by removing the field heat. The most common type of pre-cooling is forced air, where the refrigerated air is drawn in through the stacked and packed fruit using exhaust fans that produce a pressure difference across the stack of pallets [64]. The velocity is relatively high to remove heat quickly and can be approximately 5–10 times faster than during the storage phase [13]. The produce is cooled by forced convective heat transfer. Mercier, et al. [13] performed a field study to monitor the real-time temperature of strawberries inside a commercial pre-cooling facility. They found that the heterogeneity in initial product temperature (a difference of 8 °C between strawberries was observed), due to differences in harvest and transport conditions, has an impact on cooling. An additional factor that may decrease the uniformity of product temperature after pre-cooling is the commercial pressure to limit pre-cooling durations, which can be especially significant at the peak of the harvest season, to ensure that all pallets are at least partially precooled on the day of harvest.

Mainly, in the pre-cooling process, factors like package design, the stacking pattern of boxes on the pallet, the compactness of the fruits, and their positions inside the packages affect the efficiency of the pre-cooling process. Usually, researchers work at the pallet or box scale to study these factors because of the symmetry of airflow and the temperature between pallets. For this reason, there are few studies dealing with the pre-cooling step at this scale.

3.1.2. Transport Vehicles

The aim of this unit of operation, also for the cold storage facility, is to maintain the horticultural products at the recommended temperature by removing the respiration heat generated by all fresh fruits and vegetables, residual heat from the air inside the refrigerated container, heat transmitted through the walls of refrigerated facilities by conduction, convection, solar radiation, and infiltrating heat through openings or doors.

For inland and marine transports, the air inlet and outlet are located on the same side of the refrigerated enclosure. The direction of the flow can be vertical or horizontal.

In inland transport, the evaporator blows cold, high-velocity air along with the ceiling from the front to the back of the vehicle. Some of the air flows downward, while some travels to the end of the vehicle. When the air reaches the vehicle's rear, it flows along with the rear door, under the load, along the floor, and back to the front. It then flows to the evaporator, which provides cooling [82].

Moureh and Flick [70] studied the wall-jet characteristics and the airflow patterns within an isothermal slot-ventilated enclosure representing a typical refrigerated truck. According to experimental data obtained on a reduced scale model with respect to the Reynolds number of an empty configuration, the adverse pressure gradient generated by the confinement effect strongly affected the stability of the wall-jet and caused its separation from the ceiling, implying the creation of two contra-rotative recirculations. The primary recirculation, located in the front part of the enclosure, delimits the primary jet's reach and action. The recirculation located in the rear part is poorly supplied by the primary jet (Figure 4a). This phenomenon occurs when we have a long enclosure. Moureh, et al. [33] compared the airflow between an empty and a loaded enclosure, and they discovered that the presence of pallets increases the confinement effect and the jet decay more rapidly in a loaded enclosure, and the impermeability of the load (impermeable boxes in the case) tends to limit the wall jet development. The detachment of external flow from the ceiling and its attachment at the top of the load greatly influence the flow's behavior inside the boxes [28]; this interaction will be detailed in Section 3.2.1. As a result of the confinement effect, Moureh, et al. [71] observed a significant difference in air velocity and the heat transfer coefficient measured with heated spheres between the front and the rear part of the truck. Due to the high heat transfer coefficients in the front, products located near the air outlet could suffer from over-chilling, while the last pallets at the rear could be subjected to overheating. Moureh and Flick [32] found that using air duct systems improve the overall homogeneity of ventilation in the truck. These devices removed areas of stagnant air in the rear part of the load while reducing air movement at the front.

In marine transport, a bottom distribution system is generally used. The air is blown along the floor rather than along the ceiling. Getahun, et al. [78] studied the effect of reefer geometry on the external airflow, where they compared two types of floors (flat and T-bar type). Similar results to previous reports [32,62,70] were obtained, where they observed a jet separation from the floor and the formation of two recirculation zones (Figure 4c). They reported that, in comparison with a flat floor, using a T-bar floor increases the proportion of vertical airflow and reduces the dead zone in the rear part. Figure 4d shows the simulated local airflow direction (vector) inside a fully loaded reefer. As the air flows from the front to the back, it is "pushed" up through the cargo. When the air reaches the rear of the container, it rises between the cargo and the rear doors to the ceiling and then returns to the chiller at the front of the container [82].

Since the airflow is mainly vertical in reefers, it is recommended that the boxes have ventilation holes on the bottom and topsides. In their airflow and temperature distribution study, Getahun, et al. [51] reported high airflow resistance in the vertical direction in a reefer because of the absence of a vent hole on the bottom face of the packaging box, which caused non-uniform airflow and highly heterogeneous cooling. They also confirmed that the pallets' orientation inside a reefer affects the cooling rate.

3.1.3. Cold Storage Facility

In a cold room, which is used for storing food at low temperatures, the refrigerated air constantly circulates at a low velocity (0.1 $m \cdot s^{-1}$) [75,83]. Figure 4e,f show the airflow pattern inside a cold room. The air exits the cooling unit and flows over the pallets directly to the opposite corner. The air speed decelerates before reaching the opposite wall due to an adverse pressure effect. It then passes through the bins back to the cooling unit, taking on the residual heat of the product. Maintaining a homogeneous temperature, controlled by a uniform airflow distribution inside the cold room, is essential to avoid quality degradation and, consequently, losses [46,50,79].

Hoang, et al. [73] studied a cold room in which air was blown by two clockwise rotating fans. They found out that symmetry could not be assumed because of the swirling effects of the fans, which greatly impacted the overall airflow. In addition to the geometry of the cold room and the evaporator characteristics, the global airflow pattern is also greatly influenced by the pallet positions, like the gap sizes between stacks [38] or pallet arrangement (in-line, staggered) [7]. For example, results of the study conducted by Sajadiye and Zolfaghari [7] showed that the air velocities within the pallets are 40% lower in the case of a staggered arrangement than in the case of an in-line arrangement for air spaces between 0.1 and 0.25 m but remain similar for 0.5 m. This phenomenon is explained by the fact that the in-line arrangement leads to a pressure deficit between the pallets and, thus, forced air circulation within the pallets. However, despite the lower air velocities, the staggered arrangement reduces the SECT by 38% compared to the in-line arrangement. This is due to the increase in turbulence caused by the staggered arrangement, which leads to an increase in the heat transfer coefficients on the perforated surfaces of the pallets. Praeger, et al. [80] studied how the dimensions of vertical gaps (gaps between pallets and between pallets and the walls) affect the ventilation uniformity. They recommended positioning the fans above the spaces between the bins, having a vertical space every other row, and leaving a significant distance between the bin and the wall opposite the fans, which provides an advantage to ventilation uniformity.

3.2. Produce Packaging Design: The Impact on Produce Cooling

The description of airflow and temperature around the pallets is insufficient to evaluate some factors that lead to temperature abuse. To better understand the role of these factors, such as packaging, the airflow and heat transfer inside the packaging must be analyzed.

Packaging considerably affects pre-cooling, cold storage, cold transportation processes, and the ultimate fruit quality.

The design and complexity of the packaging depend on the characteristics of the product (e.g., shape, heat of respiration, and physical surface of the product), the cold chain unit of operation, and phytosanitary requirements to maintain product quality. There is a different layer of packaging. Some products are placed right into cartons [23,30,64]; then these boxes are placed on pallets and are ready for post-harvest cooling. Products like strawberries, kiwifruits, or table grapes are wrapped in multi-layer packaging. Before being placed in boxes, the products are packed in plastic clamshells or carry bags, providing additional protection to maintain quality. This additional layer can be modified atmosphere packaging (MAP) which is a technique that combines the benefits of cold storage (low temperature and high relative humidity) for horticultural crops. Air composition inside the MAP is altered (lower O_2 and higher CO_2 levels) to extend the shelf life of fresh horticultural products by slowing their respiration rate and the development of microorganisms [84]. However, MAPs are by definition close and limit great heat exchange with the surrounding air. The more layers that are added to the package, the more complicated the study of airflow, heat, and mass transfer becomes.

Ventilated packages (cartons, bins, corrugated trays, and plastic clamshells) should be designed to ensure uniform airflow distribution and produce uniform cooling. Several studies on packaging designs were conducted to understand the mechanisms by which different factors affect the rate and homogeneity of the ventilation and cooling processes [16,41,85–88]. Focus areas were, amongst others, the number, shape, or position of vent holes, the total open area of the packaging, the impact of internal packaging (plastic liners, trays), and the occurrence of airflow bypass [17]. The performance of the existing packaging design and its alternatives is evaluated and compared using quantitative variables for some functionalities, such as product cooling time, rate, or product quality, etc. [17]. In the literature, different variables known as performance parameters have been used, including SECT, HCT, cooling heterogeneity, fruit temperature, air temperature, transpiration coefficient, chilling injury, mass loss kinetic rate-law quality model, and others.

In the following paragraphs, we will review studies that analyze the effect of package design on airflow patterns and product cooling, ranging from works that use a full-scale model to those utilizing a model suited to the scale of a packaging box.

3.2.1. Cooling Facility Scale

Despite the importance of a large-scale airflow and heat transfer study to investigate the uniformity of product cooling, there are few studies at the scale of a commercial cooling facility [23]. Several reasons justify the fact that full-scale experiments with FAC facilities or transport refrigerators are rarely reported in the literature. The main reason being that large quantities of fruit are required to fill commercial facilities, and if the cooling process does not proceed as quickly as expected, there can be a significant loss of product quality. Furthermore, when conducting experiments in a commercial facility, the sensor placement and retrieval process must be done quickly to not disrupt the commercial cold chain.

A full-scale model of a cooling room loaded with pallets allows to explore and assess the influence of different factors on the airflow distribution, the heterogeneity of product cooling, and thus the quality of products within each pallet along the cooling unit's length and width. Table 3 presents some studies on airflow and temperature distribution inside the fruit package conducted inside a pre-cooling facility and transport container.

Table 3. Studies focusing on the cooling inside a pallet at the refrigerating facility scale.

Reference	Method	Produce Type	Unit of Operation	Produce Phenomena	Type of Study	Performance Indicators
[89]	Exp	Strawberries	Pre-cooling	-	Thermal	SECT Produce temperature
[90]	Exp & Num	Apples	Transport	Respiration	Thermal, Aerodynamic	Pressure drop Vertical air velocity Produce temperature HCT SECT
[23]	Exp	Citrus	Pre-cooling	-	Thermal	HCT
[91]	Exp & Num	Oranges	Transport		Thermal Aerodynamic Product quality	Product temperature Cooling time Quality parameter

At this scale, the interaction between the flow inside boxes and the main flow around the boxes can be identified [72]. Tapsoba, et al. [72] concluded in their study inside a trailer that the presence of vortices on the top of the downstream boxes is caused by the strong interaction with the main flow developed above the pallets. They demonstrated that the flow in the load is horizontal, passing from the rear to the front exit (Figure 4b). The results showed a high heterogeneity of velocity levels between the boxes placed in the rear and the boxes in the front. Derens-Bertheau, et al. [92] reported that the external ventilation around the pallets plays a determining role, both on the level of temperatures and their homogeneity inside the packages.

Another significant factor that can be tested at this scale is the palletization patterns [92]. Comparing the maximum temperature found in different forms of palletization, Derens-Bertheau, et al. [92] observed a difference of 1.7 °C when pallets are well ventilated.

Some researchers have studied the performance of different packaging designs at this scale, which is a more realistic evaluation than other scales regarding ventilation conditions around the pallets, thus allowing the new packaging alternative to be assessed at different pallet positions within the facility. Wu, et al. [23] concluded in their full-scale experiments that the cooling heterogeneity mainly occurred along the flow direction through the pallet and that despite the different designs of the packaging box, the slowest cooling rate and highest cooling heterogeneity occurred in the cartons at the outflow side. Anderson, et al. [89] discovered that the vent design of plastic clamshells and corrugated trays plays a significant role on the cooling rate and the homogeneity of the forced air cooling. They showed that the highest percentage of vents on the corrugated trays did not necessarily correspond with the fastest cooling package. Wu, et al. [23] reported that adding paper wrapping increases the airflow resistance, which affects the cooling rate; on the outflow side, the fully wrapped fruit cooled 3.9 h slower than the non-wrapped fruit, and cooling heterogeneity in the pallets. Within reefers, where vertical cooling is predominant, the product package must have bottom vents. Getahun, et al. [90] found that for the vertical cooling process in reefers, by adding vent holes at the bottom of the packages, vertical airflow resistance can be reduced by 75% compared to the base model, which resulted in up to a 62% increase in the specific flow rate of the cooling air and a 37% reduction in the average cooling time of fruits.

One of the advantages of large-scale commercial experiments is that, for example, in pre-cooling tunnels, different packaging designs can be tested at the same time, such as Anderson, et al. [89] who tested different designs of plastic clamshells and corrugated trays, and Wu, et al. [23] who compared the impact of two types of cartons filled with citrus products.

3.2.2. Pallet Scale

The pallet-scale model or experimental setup can be a single level or a full pallet (multiple levels). Each level is formed from four, five, or six boxes arranged in a pattern (depending on the size of the pallet base and the box) and placed on the pallet base. Several researchers used this scale to study the effect of different factors on the uniformity of cooling, mainly the impact of packaging design, vent hole design, packaging pattern, and multi-layer packaging. Most recent studies assessing the influence of package design on cooling performance at the pallet scale are summarized in Table 4. Most studies at this scale deal only with the pre-cooling step. The computational time and resource are much less than those of a full-scale model. It should be pointed out that at this level of study, different types of packages have been examined: bins [93,94], telescopic CFCs [41,95], corrugated packaging boxes [63], strawberry plastic clamshells [85], grape bunch carry basg [43,96], and polyliner bags [40,97].

Table 4. Studies conducted to evaluate the effect of the package design on products cooling at the scale of a pallet.

Reference	Method	Produce Type	Unit of Operation	Produce Phenomena	Type of Study	Performance Indicators
[93]	Exp	PVC spheres	Pre-cooling	-	Aerodynamic	Air velocity Turbulence intensity
[94]	Exp	PVC spheres	Pre-cooling	-	Thermal	CHTC
[85]	Num	Strawberries	Pre-cooling	Moisture	Thermal Aerodynamic	Air velocity Fruit temperature
[39]	Exp	Strawberries	Pre-cooling	Moisture	Thermal	Fruit temperature Air temperature Moisture loss SECT
[98]	Num	Strawberries	Pre-cooling	Moisture	Thermal Aerodynamic	Airflow rate Fruit temperature Air temperature Cooling time Moisture loss
[37]	Num & Exp	Strawberries	Pre-cooling	Moisture	Thermal Aerodynamic	Fruit temperature SECT Energy consumed Airflow rate
[30]	Num & Exp	Oranges	Pre-cooling	Heat of Respiration	Thermal Aerodynamic	Airflow velocity Pressure drop Turbulence Produce temperature
[41]	Num & Exp	Oranges	Pre-cooling	-	Thermal	SECT CHTC
[95]	Num & Exp	Oranges	Pre-cooling	-	Thermal	SECT CHTC
[40]	Num & Exp	Kiwifruit	Pre-cooling	-	Thermal Aerodynamic	Air velocity Flowrate % HCT Air temperature Produce temperature SECT
[99]	Num & Exp	Strawberries	Pre-cooling	-	Thermal Aerodynamic	Air velocity Airflow HCT air temperature Produce temperature

Table 4. *Cont.*

Reference	Method	Produce Type	Unit of Operation	Produce Phenomena	Type of Study	Performance Indicators
[63]	Num & Exp	Pomegranates	Pre-cooling	-	Thermal Aerodynamic	Pressure drop SECT Produce temperature Air velocity Heat transfer coefficient
[97]	Num & Exp	Kiwifruit	Pre-cooling	-	Thermal Aerodynamic	HCT Air velocity Fruit temperature net energy requirement
[100]	Num	Citrus	Pre-cooling, Storage, Transport	-	Thermal Aerodynamic Product quality	Air velocity SECT Fruit temperature Overall fruit quality
[25]	Num & Exp	Apples	Pre-cooling	Transpiration	Thermal Aerodynamic Product quality	SECT Airflow rate Fruit temperature Energy consumption Fan power Transpiration coefficient Chilling injury Mass loss
[8]	Num	Orange	Pre-cooling, Storage, Transport	-	Thermal Aerodynamic Product quality	Kinetic rate-law quality model SECT Air velocity Fruit temperature
[101]	Num & Exp	Strawberries	Pre-cooling	Moisture	Thermal Aerodynamic	Fruit temperature Air temperature Air velocity Airflow % SECT

The main disadvantage of studies at this scale is that it is impossible to evaluate the produce's cooling rate for different pallet positions, especially for the transport step and the cold room, where there are no symmetries between pallets like in the FAC facility. On the other hand, the studies at this scale do not consider factors like logistics or the effect of a new package design on the loading configuration. Any modifications in logistics, such as a new package design, different stacking patterns, or refrigerated conditions attributed to the alternative package, can be costly. The applicability of alternative designs in an actual situation remains questionable.

Figure 5a–d [97,100,102,103] shows the behavior of airflow inside the package for different designs.

Cooling Heterogeneity

The package design was the main cause of the heterogeneity of cooling [85]. Ferrua and Singh [85] found about a 6 °C difference in average fruit temperatures between the packages after 1 h of cooling. O'Sullivan, et al. [40] showed that the HCTs of the slowest cooling package, located at the back of the pallet layer, depended on the rise in air temperature as it was pulled through the pallet layer rather than increases in airflow rate. Delele, et al. [30] observed that the regions near the package vents showed relatively higher cooling air velocity and turbulence intensity, and that there is a decay in air velocity and an increase in produce temperature as the cooling air moves from entrance to exit areas of the box. However, as the air progressed from the entrance to the exit vents, there was an increase in the uniformity of airflow and produce temperature.

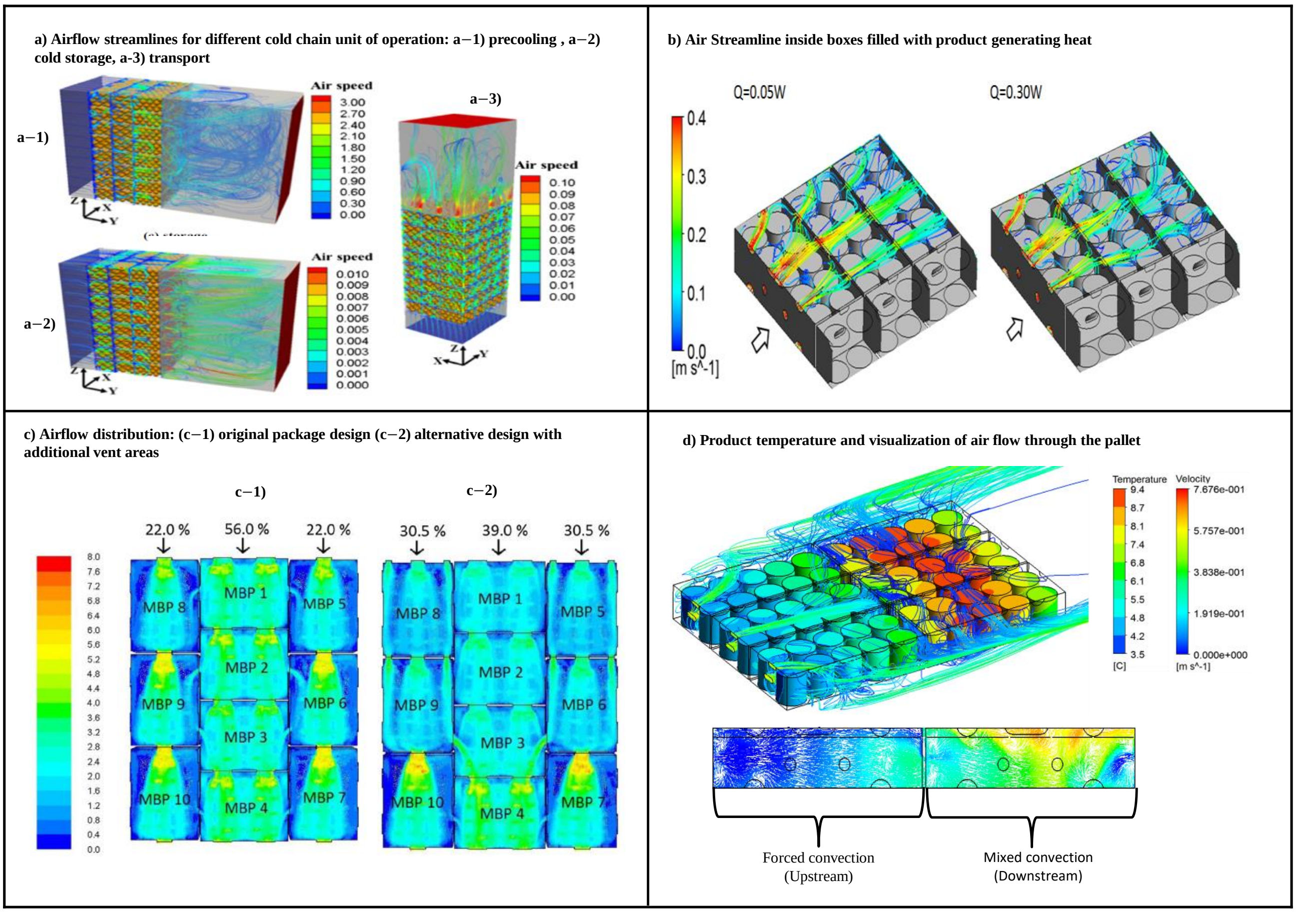


Figure 5. Airflow profiles inside different packaging designs: (**a**) [100], (**b**) [102], (**c**) [97], and (**d**) [103].

Cooling heterogeneity can be evaluated by local parameters like air velocity, product temperature, and CHTC. The latter parameter depends on air velocity, produce geometry, product orientation, packaging design, and other factors.

Kumar, et al. [104] found that the CHTC for oranges was 30% higher than that of tomatoes for an air velocity of 1.2 $m{\cdot}s^{-1}$, but only 9% higher for an air velocity of 4.4 $m{\cdot}s^{-1}$. It is common to report the dependence of experimentally determined CHTC in terms of correlations between the Nusselt, Reynolds, and Prandtl numbers [104]. Alvarez and Flick [93,94] reported high heterogeneity inside bins filled with spherical products. They observed a 40% decrease of the CHTC between the first and fourth rows of spheres, which then remained constant from the fourth row onwards. The authors explained the changes in the air temperature and the CHTC by the aerodynamic behavior inside the bin. A correlation between the local CHTC and airflow parameters was developed (Table 5).

Table 5. Nu-Re correlations found in the literature. Data extracted from [102].

Reference	Product	Correlation	Range of Value
[104]	Orange Tomato	$Nu = 0.58Re^{0.48}$ $Nu = 0.07Re^{0.59}$	$25{,}000 < Re < 95{,}000$
[94]	Sphere in a stack	$Nu = 2 + 3.78Re^{0.44}Tu^{0.33}Pr^{0.33}$	$4000 < Re_t < 15{,}000$ $0.2 < Tu < 0.49$, $Re_t = ReTu$
[105]	Spherical product Cylindrical product	$Nu = 1.56Re^{0.426}Pr^{-1/3}$ $Nu = 0.29Re^{0.529}Pr^{-1/3}$	-

$Re = \frac{\rho v d}{\mu}$, d: is the diameter of products (spherical or cylindrical).

Heat release caused by respiration is an important phenomenon to consider in this type of analysis, especially for long pre-cooling processes [106] and during the product storage phase, where the forced convection airflow becomes weak compared to the natural convection. This heat is a function of temperature and varies from one product to another as shown in Table 6. This heat may affect the airflow behavior and, thus, the cooling heterogeneity. The assumption that the heat of respiration is a negligible factor is common [41,107]. At low air velocities (i.e., below 0.1 m·s^{-1}), natural convection can become prevalent, and as a result, heat transfer is no longer solely dominated by forced convection [108], so buoyancy forces can be of the same order of magnitude as inertial forces. The flow structure is modified by buoyancy forces [109], which can enhance or diminish heat transfer. Therefore, in this type of situation, it is necessary to thoroughly study the interaction between forced and natural convection.

Table 6. Correlations for the heat of respiration as a function of temperature. Data extracted from [102].

Reference	Product	Heat of Respiration (W·Kg^{-1})
[77]	Apple	$q = 1.7 \times 10^{-6}(1.8T + 32)^{2.5977}$
[110]	Potato	$q = \rho_b \frac{0.8039(T-273)+14.303}{1000}$ $T > 276.13$ K, $\rho_b = 660$ kg·m^{-3} $q = \rho_b \frac{-0.8039(T-273)+20}{1000}$ $273.13 \leq T \leq 276.13$ K, $\rho_b = 660$ kg·m^{-3}
[111]	-	$q = a(T - 255.35)^b$ a et b depend on fruit type

Pham, et al. [112,113] carried out an experiment on a pallet filled with heat-generating products. Their study aimed to understand the dynamic interactions between forced convection and natural convection and the effect of that on cooling heterogeneity. These interactions depend on the products' heat fluxes and the packaging's opening (shape and distribution of the openings). Pham, et al. [112] demonstrated that when high heat is generated by the cheese product, the natural convection generated in the stagnant areas or where the velocity is low (in the downstream part of the pallet) can affect the airflow by the formation of a reverse flow with respect to the main airflow direction. Figure 5d shows that this second flow can let in cold air from the holes downstream, causing displacement of the hot spot from the last row downstream.

Multi-Layer Packaging

The packaging usually causes aerodynamic resistance, but this depends on how many layers it is composed of. Multi-layer packaging is when the fruit is wrapped in more than one material to pack it for the market. Trays, plastic bags, liners, and plastic clamshells are frequently used internally for positioning fruits in place and for moisture control to minimize fruit decay. A multi-layer influences the resistance to airflow, the airflow pattern package, and thus the cooling rate of fruit. Therefore, it is essential to evaluate the effect of each layer of the packaging and the different materials (bags, clamshells) on the behavior of the airflow and, thus, on the performance of product cooling.

As an example, table grapes is characterized by multi-layer package combinations. The package primarily contains liner film, moisture absorption sheets, and SO_2 pads. What can be different is the package that will carry the fruits like bunch carry-bags, plastic clamshell punnets, or open-top punnets (Figure 6, [96]). Ngcobo, et al. [43] studied the airflow resistance and cooling rate through multiscale packaging (several types of liner films, carry bags, and containers (carton)) during table grapes cooling. The results showed that liner films contributed more than 50 percent of the total pressure drop compared to the other package components of the grape's multi-packaging. Although the perforated liner films contributed less to the airflow resistance than the non-perforated liner films.

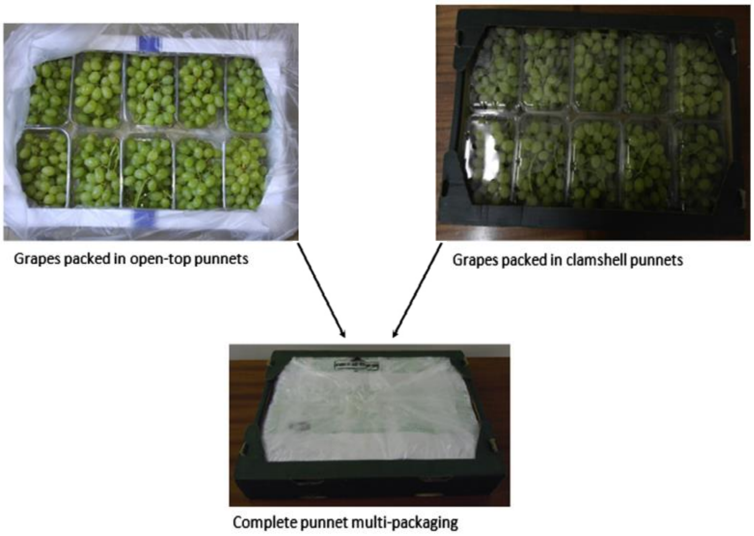


Figure 6. Multilayer of packaging for table grapes [96].

Despite the importance of liners, which reduce weight loss from the fruit by acting as a barrier to moisture transport from fruit to bulk air, Ambaw, et al. [63] found that adding a plastic liner to a pomegranate package increased the airflow resistance and reduced CHTC from produce, leading to an increase in the cooling time and the energy use. The average SECT was increased from 4.0 h and 2.5 h to 9.5 h and 8.0 h, respectively, for the two different box designs evaluated.

Alternative Designs

To improve the homogeneity and the rate of cooling, the package design should be optimized to improve the uniformity of the ventilation and cooling (Figure 7, [90]). Ngcobo, et al. [96] compared the performance of three different grape packaging systems based on airflow, cooling, and quality characteristics. They found that some systems (grapes in a carry bag) cool slower than others (grapes in a punnet), but have better quality in terms of moisture loss and bunch stem dehydration rates.

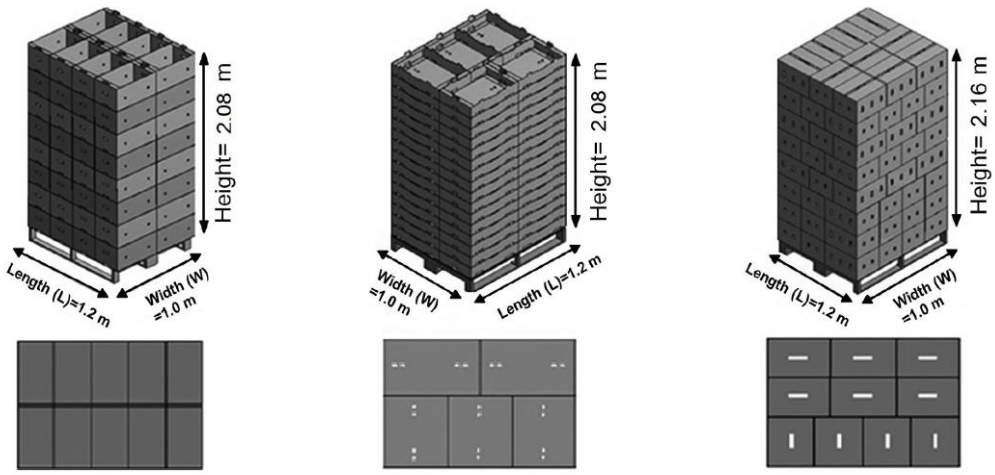


Figure 7. Different packaging box designs and different stacking patterns [90].

The following are some examples of studies that have proposed new packaging solutions and compared their performance with existing designs:

Ferrua and Singh [37] proposed a new bypass system for packaging strawberries. This new solution, instead of forcing air through two corrugated trays, equally splits the main flow into two parallel streams and increases the vent area on the side and inlet walls of the corrugated trays and plastic clamshell. The new system provided a relatively improved uniformity of cooling of products between the two corrugated trays, and reduced the total cooling time (by 6%), pressure drop, and energy consumption of the process.

O'Sullivan, et al. [97] proposed an alternative cardboard box design for handling kiwifruits. This new solution has additional side vents, allowing airflow channels to be created along the pallet's side, directing it towards the slowest cooling packages located at the back of the pallet (Figure 5c). The authors remarked that at constant flow rates the new design: (1) reduced the pressure drop and thus the energy requirement by 24% compared to the current design and (2) improved the cooling uniformity by 19%.

Defraeye, et al. [41] investigated the cooling performance of an existing package (corrugated fiberboard container) and two new ones (Supervent and Ecopack). The authors showed that a preferential pathway is created by the new design, Eco, where air can easily bypass the fruit and, in turn, reduce the airflow rate through the fruit. As a result, a lower convective heat transfer rate can be found in this design compared to the two others. Thus, Ecopack cooled the oranges in the most uniform way, which is beneficial for product quality.

It is crucial to evaluate the performance of a new package design throughout the different unit operations of the cold chain, not just the pre-cooling step, despite its importance. Wu, et al. [8] conducted a study investigating the temperature levels and heterogeneities of an entire pallet through three different stages in a virtual cold chain (VCC): pre-cooling, transport, and cold storage. The objective was to compare the performance of three carton designs—Standard, Supervent, and Opentop (Figure 8, [8]), used to transport oranges. The results lead to the following remarks:

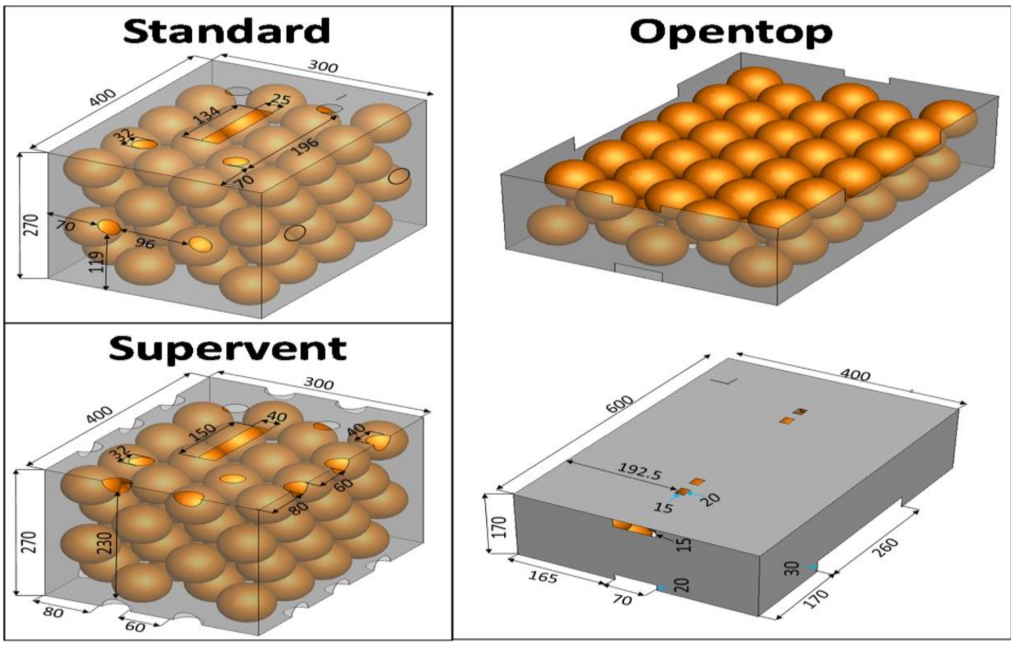


Figure 8. Packaging designs studied by [8].

- Faster cooling and better thermal homogeneity for the Supervent package. This is due to the alignment of the side holes, which improves the distribution of the flow in the boxes. For the transport link (vertical flow), the superiority of the Supervent is explained by the presence of a large central orifice associated with orifices close to the side walls, which together promote the emergence of a uniform flow within the box and greatly reduces the thermal heterogeneities of the products.
- The poor thermal performance of the Opentop package, which is open on its upper part and whose configuration is close to that of cheese packages, can be explained in particular by:

- The big difference in the opening between the two faces of the cardboard favors the establishment of a short circuit and, thus a transfer of the flow towards the cartons having the big opening surface compared with the cartons of the weak opening section. This is because on the same level of the pallet, we find boxes with a small and a large perforated section facing the flow.
- The strong disproportionality between the relatively large openings in the upper part of the package above the products and those in the lower part facing the products. This configuration strongly reduces the accessibility of the cold caused by the flow from the top openings to the products located in the lower part of the box. This results in an increase in temperature heterogeneities and an increase in the cooling time of the products.

- The palletization mode (regular or irregular) considerably affects the cooling time and the temperature heterogeneities. This phenomenon concerns, in particular, the downstream cartons whose openings do not communicate with the upstream cartons.

3.2.3. Box Scale

At this scale, one single package (box or corrugated tray) filled with products is modeled. Researchers are restricted to looking at the effects of different package designs on airflow distribution and heat transfer within the package, mainly during the pre-cooling process (Table 7). These studies do not explore the cooling rates of different boxes on a pallet. The influence of airflow distribution outside the package on the cooling rate, the stacking of boxes on a pallet, and the orientation of the package could not be considered.

Table 7. Studies conducted to evaluate the effect of the package design on product cooling at the scale of a box.

Reference	Method	Produce Type	Unit of Operation	Produce Phenomena	Type of Study	Performance Indicators
[88]	Num	2 D circles	Pre-cooling	-	Thermal	Heterogeneity index Produce surface temperature
[114]	Exp & Num	Oranges	Pre-cooling	-	Thermal Aerodynamic	Airflow velocity Pressure drop Produce temperature HCT SECT
[77]	Exp & Num	Apples	Pre-cooling	Respiration, transpiration & moisture	Thermal Aerodynamic	Airflow velocity Turbulent kinetic energy Produce temperature HCT
[64]	Num	Apples	Pre-cooling	-	Thermal Aerodynamic	SECT CHTC Pressure drop Pressure loss coefficient Ventilation power usage
[26]	Exp & Num	Apples	Pre-cooling	-	Thermal Aerodynamic Product quality	Airflow velocity Produce temperature HCT SECT Fan energy consumption Chilling injury Mass loss
[86]	Num, Exp	Apples	Pre-cooling	-	Thermal Aerodynamic mechanical resistance	SECT CHTC Total fan energy consumption

Table 7. *Cont.*

Reference	Method	Produce Type	Unit of Operation	Produce Phenomena	Type of Study	Performance Indicators
[115]	Num	Citrus	Pre-cooling, storage & transport	-	Thermal Aerodynamic Product quality	Air velocity SECT CHTC Fruit temperature Overall fruit quality
[87]	Exp & Num	Strawberries	Pre-cooling	-	Thermal	Produce quality Airflow velocity SECT

One of the critical parameters that can be studied at this scale is the air-inflow velocity. Han, et al. [26] demonstrated that an optimal inlet velocity must be provided to ensure a high and efficient cooling rate and optimal energy consumption. However, any further increase in the airflow rate wastes energy as it leads to a relatively small increase in cooling rate and uniformity.

Most studies at this scale assess the impact of vent hole design on the cooling of produce (Figure 9, [86]). The uniformity of products cooling within a box increases with the number of vents added [88]. But on the other hand, the number, area, and shape of the vent hole should not be blindly increased [87] as it negatively affects the mechanical strength.

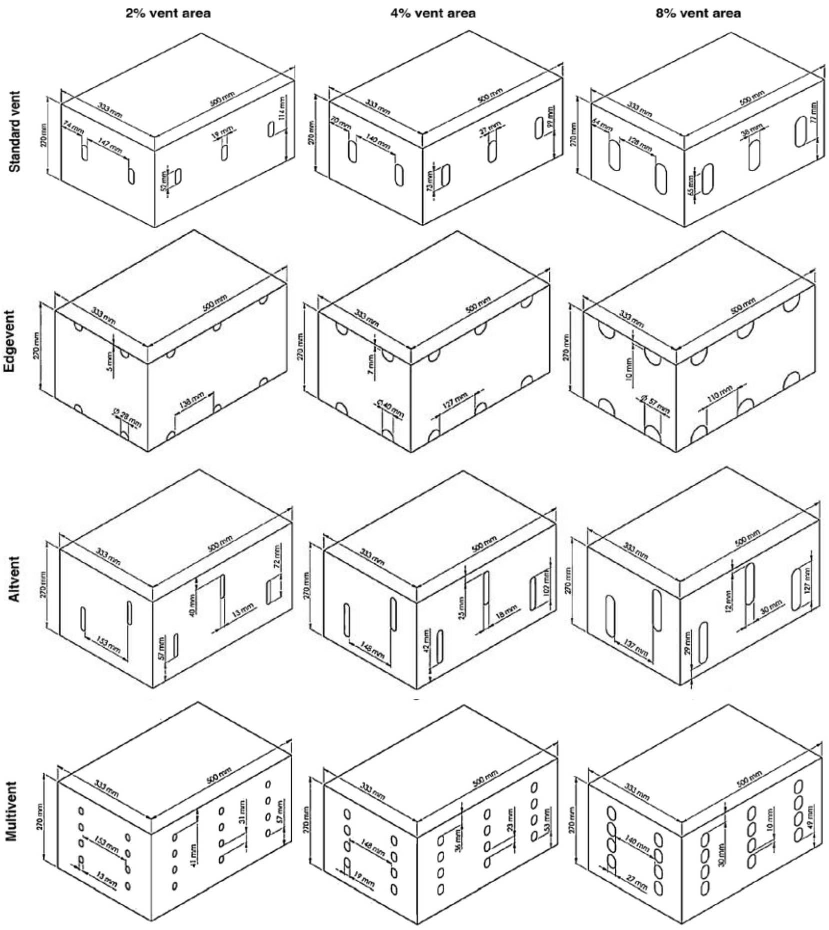


Figure 9. Different designs of vent holes [86].

Han, et al. [77] developed a CFD model to study the cooling performance of two apple box designs (containing two layers of apples), an existing container, and a proposed box with a greater number of vent holes. It was concluded that the uneven airflow distribution between the 2 layers inside the existing design caused a maximum temperature difference of 8 °C between the two layers. In contrast, the new solution distributed the airflow more uniformly between the two layers, reducing the maximum temperature difference to 2.5 °C, and halving the cooling time. Delele, et al. [114] reported that the vent position mainly affects the products' temperature distribution and that the vent area is the most critical design parameter that affects the airflow and produce cooling characteristics. They found that an increase in the vent area from 1% to 7% improved the cooling rate by 183.85%, compared to only 62.04% when increasing the vent area from 7% to 100%.

Another consideration when adding ventholes to a package is to respect the symmetry of the packaging ventholes, as it has a significant impact on the produce cooling rate and cooling uniformity [26]. In addition to that, ventholes should be designed with respect to their connectivity between two successive packages in order to promote the internal air circulation within the pallet. Also, the position of the vent hole should not interfere with the tray or be blocked by the produce [26]. In the case where there is a multi-layer package, such as a corrugated tray filled with clamshells, the two layers should be designed together to find the optimal combination of vent hole area in order to maximize air-to-product contact during cooling [87,89].

4. Other Aspects of Evaluation

While numerous studies focus on products' temperature heterogeneity and the characteristics of airflow between and inside the packages, they do not provide the operator with quantitative information on: 1—how this heterogeneity can affect the deterioration of fruits and vegetables; 2—how a new package design or new cooling conditions can affect the total energy consumption of a refrigerated facility; and 3- whether this new package alternative can handle and protect the fresh products.

This requires researchers to focus on aspects other than ventilation and cooling performance. Defraeye, et al. [17] and Berry, et al. [116] cited the most important functionalities that should be considered when designing a new package, these include cooling performance, ventilation, product quality, mechanical performance, its evolution by the effect of humidity and vibration, cost, logistical factors, and environmental impact. Most of these functionalities, apart from mechanical performance, can be taken into account when assessing a new solution to preserve the quality of horticultural products and ensure efficient cooling.

Product quality is a relevant functionality to follow its evolution during the post-harvest cold chain to examine the influence of the airflow distribution and, thus, the cooling rate and uniformity on the quality. Additional insight can be gained by quantifying each fruit's percentage quality loss per unit operation in different cold chain scenarios. The quality of a product can be represented by factors such as taste, firmness, color, flavor, moisture loss, and chilling injury.

However, there is a lack of in-depth studies that analyze the local evolution of product temperature within the stack to assess its impact on fruit quality throughout the supply chain. The measured or predicted temperature does not directly address its effect on the remaining shelf life of the products. Thus, for this data to be used to its full potential for decision-making, it must be translated into actionable metrics, such as remaining shelf life [117]. Few published studies incorporate produce quality into their airflow and heat transfer investigations, and most are experimental works. Han, et al. [26] evaluated the influence of increasing air-inflow velocity on the mass loss of all fruit in a single box and the incidence of chilling injury experimentally. Duret, et al. [79] performed experimental measurements of apple weight loss to compare the apple weight loss at different positions in the cold room to validate a simple model of quality evolution. The calculated and measured weight losses of the apples were in good agreement. Ngcobo, et al. [96] evaluated the performance of different table grape package systems based on airflow, cooling, and quality characteristics such as bunch weight loss, stem drying, browning, SO_2 injury, and decay incidence. The quality assessment was carried out experimentally.

Jalali, et al. [118] developed a simplified mathematical model to evaluate the quality of strawberries inside a MAP throughout the cold chain. The method used simulates the interaction between respiration and transpiration of produce, the behavior of packaging material such as permeability to gases and water vapor as well as moisture absorption, and the ambient conditions such as temperature, relative humidity (RH), and gas composition. This method aims to predict in package conditions such as gas concentration, humidity, condensation, fruit mass loss, microbial deterioration, shelf life, temperature changes on produce surface, headspace air, internal and external tray, and MAP film according to changes in ambient temperature.

Integrating fruit quality models in the CFD simulations is interesting because such a model can be used for a virtual investigation of the effect of different cooling conditions on the quality of the produce. This will further make it possible to identify critical operational requirements during postharvest storage and improve decision-making in cold chain logistic management and inventory control. Wu, et al. [115] coupled the CFD with a generic quality model. This method is called VCC and is used to track the temperature history of packaged fresh fruit and the quality evolution, down to each individual fruit, throughout the three unit operations. Wu, et al. [8,100] used the VCC method to assess the influence of different package designs and cold chain scenarios on the products' cooling and their quality evolution.

Another relevant functionality is energy consumption. The energy consumption of a new solution must be calculated and compared to the existing one so that its environmental impact can be assessed.

The energy consumption in a cooling facility is composed of two parts:

The heat extracted by the refrigeration unit: the heat of the produce, heat generated by running fans, heat gained from the outside environment, and heat from other miscellaneous sources [95,119].

Package design affects airflow resistance, thus affecting fan power. Many researchers have worked on this factor by calculating the total energy consumption of the fan as a function of airflow, resistance (pressure drop across the package), and the operating time required to reach the desired temperature [25,26,86,95,97].

O'Sullivan, et al. [97] used the HCT of the slowest product to calculate the net energy requirement. It was demonstrated that the new package design with more opening areas leads to 24% energy savings in comparison with the current design for the kiwi package. Mukama, et al. [119] estimated the energy consumption of a FAC process based on the power used for the driving fan and refrigeration unit. In addition, the authors calculated the heat load extracted by the refrigeration load, which is formed by: field heat from the produce, heat generation from the fan motors (evaporator fan and FAC fan), and the rate of heat conduction from the outside environment. Defraeye, et al. [95] found that the new alternative designs seem a cost-effective way of improving forced-convective pre-cooling of orange fruit, concerning the operational cost of the system. Han, et al. [25] proposed an integrated modeling approach with a CFD model to evaluate the efficiency of forced convection cooling on apple pallets. The model predicts cooling kinetics, temperature uniformity, energy consumed, and apple quality evolution. The experimental device is realized in an air stream on a pallet filmed laterally at the top and bottom. This avoids heat transfer between neighboring pallets and between the cold room and the products located at the top and bottom of the pallet. The study is based on a heterogeneous palletization layout. It shows that it is important to maintain not only a longitudinal but also a transversal alignment of the openings. The comparisons between the simulations carried out with and without lateral openings showed that the presence of lateral openings between cartons on the internal faces makes it possible to reduce the cooling time by approximately 14.5% for the cartons located downstream of the pallet. These side holes also reduce thermal heterogeneity by about 10%. The results show an exponential increase in the energy consumed as a function of the airflow rate. However, beyond 600 Pa or 0.83 m/s (surface velocity), the effect on the cooling time is no longer significant, although it induces high energy consumption.

Packaging also serves as a protective layer against product damage. Adding more vents to a carton can improve the cooling uniformity but, conversely, will affect the package's mechanical strength. Therefore, when testing or designing a new packaging design, it is vital to verify the mechanical integrity throughout the supply chain [120]. Numerically, computational structural dynamics (CSD) is used to simulate the package compression strength. Stability, compression strength, shock resilience, and vibration resilience are three performance indicators that should be observed for different package designs [17]. Many other factors that can affect the mechanical performance of packages should be considered in this type of evaluation, including box dimensions, stacking configuration, transportation, and handling conditions, weight of products, temperature and humidity fluctuations, and vibrations [46]. As for vibrations, their effects are not only limited to the packaging but can reach beyond and cause mechanical damage to the products inside, resulting in losses [121]. The susceptibility of packed horticultural products inside the packages to vibration damage should be included in the study.

Product packaging designs or cold chain strategies must be carefully selected and optimized to meet different objectives: maintaining product quality, extending its shelf life, reducing food losses, reducing energy consumption and thus environmental impact, optimizing the logistics, and finally, cost efficiency. To achieve these goals, different performance parameters that represent the various functionalities need to be included in the investigation by applying a multi-parametric approach. Few studies applied an integrated approach and mainly evaluated the effects of different packaging designs. Berry, et al. [86] compared the performance of different vent hole designs using a multi-parametric approach by assessing airflow resistance, cooling rate, uniformity, package-related energy consumption, and box compression strength. The produce quality parameter was not included in this investigation. They noticed that the configuration of the vent holes and the total vent area (TVA) had a considerable influence on the energy consumption and the homogeneity of the cooling. Vent hole configuration, total vent area, and corrugated fiberboard grade significantly affected the carton's mechanical strength. Ambaw, et al. [120] applied a multi-parametric approach called virtual prototype and aimed to reduce the cost of physical prototyping by numerically testing different package designs. The strategy is based solely on a numerical concept employing CSD to test the compression strength of the package, CFD, and CHT (computational heat transfer) to examine cooling uniformity, energy consumption, and product quality. Wu, et al. [122] took their investigation a step further by coupling the VCC model to a life cycle assessment model to evaluate the influence of different box designs and cold chain strategies on cooling rate, uniformity, produce quality, and the environment.

5. Discussion

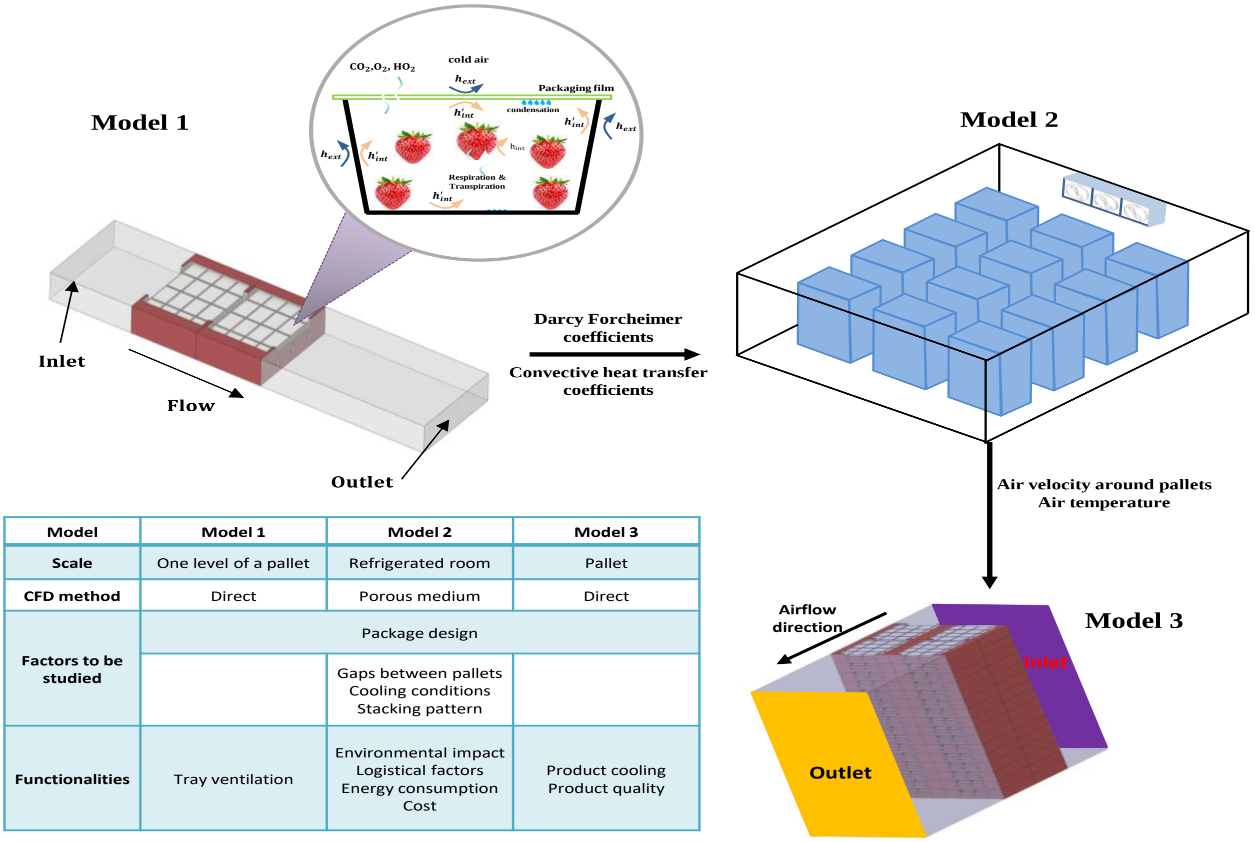
The different scales presented have their specifications and constraints. Each of these scales can be identified by the factors that can be manipulated to evaluate cooling performance. These factors include vertical/longitudinal gaps between pallets, fans' position and number, package design, product shape, size, position, package stacking patterns, multiscale packages, different cold chain conditions, and cold chain strategies. The scale of a refrigerated container filled with pallets can be considered an appropriate scale to study the effect of several factors mentioned above on the cooling performance. But many constraints make modeling at this scale challenging, such as the numerical limitations and experimental difficulties cited in previous paragraphs.

Most studies focus on airflow and temperature distribution, as temperature is the main parameter influencing food products. In contrast, few studies focused on the relative humidity (RH) distribution in the equipment [75,79]. The study of the RH is important as it drives mass losses due to water evaporation, especially for the products located near the outlet of the equipment where the air is usually the driest in the equipment. Products in this zone may be subjected to both chilling injuries and excessive mass losses. Moreover, because of the high RH in the refrigerated equipment and temperature fluctuations, condensation may occur on the product surface. On the one hand, the presence of condensation is generally not suitable as it promotes microbial growth and may cause product waste and losses due to spoilage. On the other hand, the presence of water at the product surface limits the mass loss of the product. More detailed studies integrating air temperature, humidity, condensation, evaporation, and their links with food quality should also be studied to optimize cold chain performances.

Another important issue, neglected in most investigations, is the local airflow features related to the aerodynamic interactions between the jets issuing from vent holes and the stacked products. These aspects are of primary importance but are still difficult to analyze due to the three-dimensionality of the airflow development within the stack with respect to the product arrangement. The CFD-direct approach can help to gain more insight into the development of the internal jets issuing the vent holes within the closed space of the packages and their interaction with products. The internal airflow analysis helps to improve the package design process by revealing the internal jet trajectory and their diffusion within the air headspace and between products, and therefore areas of relatively low air velocity, which negatively impact product temperature uniformity. Also, it is challenging to develop a direct CFD model at the scale of a cooling room to investigate this behavior; the scale of one carton or one level of a pallet is more suitable and requires less computing power and resources to perform experiments. However, in this case, many factors cannot be evaluated.

Moreover, it is essential to highlight that, to the author's knowledge, no study has examined the airflow behavior inside a tray filled with MAP and the effect of local velocities on the heat transfer process between the air outside the MAP and fruits inside it. In addition, no comparison was made in terms of heat transfer and airflow between standard multilayer packages (plastic clamshells) and MAPs. As the use of MAP is expanding due to its advantage in extending produce shelf life, such as strawberries. It is essential to evaluate the effect of the MAP stacking patterns and different corrugated tray designs (vent hole design) on the mechanism inside the MAP. Most literature studies evaluate cooling conditions based on one MAP, neglecting other factors [118,123]. One of the challenges to this type of investigation is the difficulty of measuring temperature profiles and velocity inside the MAP, which will prevent a good experimental characterization of the process [37,39]. Another experimental limitation is the difficulty of modeling all the phenomena occurring inside the MAP. In addition to that, it can be noticed that there are a few studies that investigate the effect of multiscale packaging, especially internal packaging like liner bags and clamshells, due to the complexity of this type of assessment. O'Sullivan, et al. [40] were able to predict the effect of the airflow behavior inside palletized, polylined kiwifruit packages on the temperature of the fruits. The authors included the natural convection inside the polyliner. They observed that the fruit near the polyliner or in contact with it cool faster than the kiwifruit in the middle, which is subjected to natural convection heat transfer mechanisms.

A multi-scale modeling approach can be an effective strategy to overcome these challenges. Different models at different scales can be developed to describe a system in which information is shared between different scales [116,124]. Figure 10 illustrates an example of this strategy being used to evaluate different tray designs filled with strawberries MAP. A detailed model (M1) can be implemented at the scale of one level of a pallet, where the effect of different physical phenomena can be incorporated (respiration, transpiration, and condensation), and the CFD direct method applied. At this scale, the airflow behavior between the MAP can be described for given boundary conditions. The Darcy-Focheimer coefficients related to airflow resistance induced by the pallet stacking patterns and its internal packaging and convective heat transfer coefficients, obtained in a wind tunnel test with model M1, are transferred to a macroscale model (M2). This allows to build a simplified airflow model (M2) for the whole refrigerated room by assuming a porous medium approach for pallets, where less detail is included because of numerical resources, and thus to predict the global airflow patterns outside pallets. Using M2, factors such as cooling conditions, gaps between pallets, and pallet stacking patterns can be investigated. Different combinations of different factors will be obtained and evaluated. Air temperature and velocity profiles around pallets located in the critical regions, like stagnant zones, or that have the higher velocity for each configuration tested will be identified and incorporated as boundary conditions in the third model (M3), scale of a pallet. The model M3, based on direct CFD numerical modelling, will serve to investigate the local aspects related to the interactions between the airflow and the produce within cardboards and to predict the heterogeneity of product temperature evolution, thus evaluating the cooling performance for the studied pallet with respect to its location in the refrigerated room. To complete the analysis, a quality model can be integrated in M3 to evaluate the impact of the temperature heterogeneity on product quality. Indeed, it is difficult to evaluate the critical aspect of the temperature heterogeneity without integrating quality evolution into the analysis, as it depends on the type of product. The same steps will be applied to different tray designs to compare the performance of the different alternatives and optimize the configuration.



Model	Model 1	Model 2	Model 3
Scale	One level of a pallet	Refrigerated room	Pallet
CFD method	Direct	Porous medium	Direct
Factors to be studied	Package design		
		Gaps between pallets Cooling conditions Stacking pattern	
Functionalities	Tray ventilation	Environmental impact Logistical factors Energy consumption Cost	Product cooling Product quality

Figure 10. Schematic example of the multi-scale modeling approach.

The high quality of horticultural products at the final stage of the cold chain is not the only criterion taken into account when studying the performance of a new solution. Because the overall purpose of those studies is the sustainability of the food chain, other objectives such as, but not limited to, energy consumption, the environmental impact of the packages, cost, logistics feasibility, and consumer perception may be considered. To evaluate the effect of a new solution on those numerous criteria, the "ideal" solution would be to conduct a large-scale field experiment to test different packaging alternatives or refrigerated conditions by tracking horticultural products from harvest to consumption and reporting on the conditions under which the cold chain operates. However, feasibility, ethics, and cost limitations put this approach out of consideration. The use of integrative and multi-scale approaches to model those aspects offers an alternative solution in this situation. This multi-parametric and multi-scale approach will help: (1) researchers to quantify and visualize the quality deterioration and the influence of different parameters over time; and (2) decision-makers to determine the action presenting the best compromise.

A significant limitation of this type of approach can be represented by the fact that this study must include all links of the cold chain, hence the need to collect data on the chain, the complexity, the specifications, and the high variability of the chain characteristics such as the transport distance, the number of pieces equipment, the characteristics of the equipment (air velocity, temperature, etc.).

To develop a new package design or a new cold chain scenario, it is necessary to account for all the phenomena and associated variables to optimize the chain and reduce food waste significantly. For example, a MAP package might be developed under different controlled temperature conditions but subjected to high-temperature fluctuation in the chain due to the compressor cycle and transfer from one piece of equipment to another, leading to condensation inside the packaging that might affect both quality and consumer perceptions. Moreover, to include such variability and properly evaluate the feasibility of new solutions, it is essential to account for various multi-disciplinary phenomena (heat and mass transfer, food engineering, mechanical engineering). For example, to evaluate the product quality in a multi-parametric approach, different physical phenomena like transpiration, respiration, and condensation, which affect microbial growth, should be introduced into the model. However, this will make the model more complex in terms of development, numerical resource limitations, and its application; for example, on a macro scale, it would be more challenging (scale of a refrigerated room filled with pallets). Hence, as modelers, a compromise should be found between the relevance and accuracy of the phenomenon that is being accounted for and the feasibility of the model's development and interpretation of the results. The multiscale modeling approach can play an important role in tackling this problem. Another limitation associated with this issue is raised, such as the compatibility of this approach in terms of model integration and validation. Such models are very difficult to validate; however, the different modules of such an integrated approach are validated, and one could expect that the global model represents something close to real-life conditions.

This is a highly diversified and multidisciplinary topic, thus industrial stakeholders in the cold chain and the scientific community from different disciplines should collaborate to implement new solutions, manage the product temperature and quality, and obtain an efficient cold chain [22].

6. Conclusions

Packaging and cooling facility conditions are considered two critical factors that negatively or positively affect the temperature of fresh products and, thus, their quality in the cold chain. The ultimate solution to compare different cold chain scenarios or packaging design alternatives is to conduct a field study to monitor all products' temperatures throughout the cold chain, which can help researchers discover the position of temperature abuse. This solution is logistically unfeasible. However, a heat transfer and airflow study can offer a better understanding of the physical phenomena inside a cooling unit and the interaction between the airflow around and inside the pallets, as well as a detailed cartography of temperature.

Airflow and heat transfer studies have been conducted to comprehend the contribution of each factor on the cooling performance and to find the optimal solution that can improve the homogeneity of cooling, diminish the cooling time, and thus preserve the quality of the horticultural products. These studies are based on the use of two approaches: experimental and numerical. Each approach applied has its limitations in calculation time and logistics constraints.

This work dealt with the different scales for the experimental setup and numerical model that are used by researchers in order to study the ventilation and cooling performance. The choice of the appropriate scale is challenging and is a function of many considerations, such as available resources, computational power, and factors to be assessed. All these variables will influence the simplifications and assumptions to be made, the material to use for the measurements, and the numerical methods to apply, whether porous medium or the direct CFD method.

This review explored other criteria to be included in the analysis, including not only product cooling but also product quality, the mechanical strength of a package, energy consumption, environmental impact, cost, and logistics. A multi-parametric approach is a recommended method that can be employed in this case to evaluate packaging alternatives or a new cold chain scenario based on a compromise between the different objectives in order to achieve an efficient cold chain. Future work should focus more on this method and improve it to be adapted to actual industrial conditions. Researchers from different disciplines and the decision makers themselves should participate in these investigations in order to recommend new solutions.

A novel strategy was proposed based on implementing a multi-scale approach. This technique can be developed to deal with complex systems, and it is able to tackle the different challenges encountered by researchers such as multi-layer packaging, the different physical phenomena incorporated, and the computations and resources required.

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Nomenclature

WHO	World health organization
CFD	Computational fluid dynamics
CSD	Computational structural dynamics
LDV	Laser-Doppler Velocitymeter
PIV	Particle Image Velocimetry
ASL	Air speed logger
RANS	Reynolds Averaged Navier-Stokes
NS	Navier-Stokes
HCT	Half cooling Time
SECT	Seven-eighths Cooling Time
CHTC	Convective heat transfer coefficient
FAC	Forced air cooling
MAP	Modified Atmosphere Packaging
TVA	Total vent area
CHT	Computational heat transfer
VCC	Virtual Cold Chain
RH	Relative humidity
$\overline{u}$	mean velocity $\left(\mathrm{m \cdot s^{-1}}\right)$
u'	velocity fluctuation $\left(\mathrm{m \cdot s^{-1}}\right)$
t	time (s)
ρ_f	density of the fluid $\left(\mathrm{kg \cdot m^{-3}}\right)$
Cp_f	heat capacity of the fluid $\left(\mathrm{J \cdot Kg^{-1} \cdot K^{-1}}\right)$
μ	dynamic viscosity of air $\left(\mathrm{kg \cdot m^{-1} \cdot s^{-1}}\right)$
$\overline{p}$	mean pressure (Pa)
Pr_t	turbulent Prandtl number
μ_t	turbulence viscosity $\left(\mathrm{kg \cdot m^{-1} \cdot s^{-1}}\right)$

$\overline{T_f}$	mean fluid temperature (K)
k	turbulence kinetic energy
λ_f	thermal conductivity of the fluid $\left(W{\cdot}m^{-1}{\cdot}K^{-1}\right)$
λ_{eff}	effective thermal conductivity $\left(W{\cdot}m^{-1}{\cdot}K^{-1}\right)$
K	Darcy permeability
F	Forchheimer coefficient
A_{box}	box face area $\left(m^2\right)$
A_{hole}	vent hole area $\left(m^2\right)$
D_h	package hydraulic diameter (m)
d_p	effective product diameter (m)
Pr	Prandtl number
Re	Reynold number
Nu	Nusselt number
Re_t	Turbulent Reynolds number
Tu	Turbulence intensity

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