Optimized cold chain to save food

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Chapter Outline

7.1 Introduction

Perishable foods, such as fruits and vegetables, dairy, fish, and meat products, have a limited shelf life after harvest or production. The delay before they become unmarketable or inedible depends on the food product itself and a number of environmental factors. These environmental factors include the storage temperature, pressure and relative humidity, and composition and velocity of surrounding gas.

The temperature generally has the greatest impact on the shelf life of perishable food (Hertog et al., 2014; Nunes et al., 2014). A temperature too high increases the rate of respiration and the growth of microorganisms, which can spoil some food

Saving Food. DOI: https://doi.org/10.1016/B978-0-12-815357-4.00007-9
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products in a few hours or days (Giannakourou and Taoukis, 2003; Hertog et al., 2014; Gwanpua et al., 2015). A temperature too low can create cold injuries and render the food product unmarketable (Heap, 2006; Aghdam and Bodbodak, 2014). In contrast, perishable food products kept at the proper temperature can generally remain of high quality for multiple days or weeks, or even multiple months or years in the case of frozen food (Mercier et al., 2017).

Therefore, refrigeration plays a critical role in food loss. This is especially true in this current state of globalization, with fresh produce continuously traveling long distances between countries and continents to meet consumers' expectation of a having a wide range of fresh produces available year-round. As an example, the supply of Mexico-grown blackberries to the United States, which includes stages of precooling, transportation to the distribution center (DC), storage at the DC, transportation to retail, and storage at retail, can typically take from 5 to 15 days (Nunes et al., 2014). Yet, the shelf life of berries can be below 1 day when field heat is not removed and below 1 week when kept at 10°C (Hertog et al., 1999). As such, it is critical that the perishable food remains at the proper storage temperature during all stages of the supply chain, to prevent decay at a rate that would make the product unmarketable before retail and create food loss.

A range of refrigeration technologies, of varying efficiency, cost, and environmental impact, is available to preserve the temperature of the food in the desired range during each stage of the supply chain. When refrigeration is applied along the supply chain to improve food preservation, the supply chain is called a cold chain. This chapter first provides a high-level overview of the different stages found along a typical cold chain. In the following sections, the different refrigeration technologies available at each stage of the cold chain are discussed, along with their impact on food loss and waste. A section will then be dedicated to the optimization of the cold chain, that is, how we can identify the proper refrigeration technology and operating conditions to reduce food loss and waste, while also limiting cost and environmental impact. Finally, notable differences between cold chains in different regions of the world are discussed, notably regarding the refrigeration capacities and reported food loss, waste, safety, and security.

7.2 Overview of the cold chain

The stages found along a typical cold chain of a chilled product are presented in Fig. 7.1. When the product is harvested (for fresh fruits and vegetables, FFVs) or processed (for processed fruit, vegetable, meat, and dairy products), its temperature is generally above the optimal range for the preservation of its quality and safety. As such, the food is first cooled to the desired range in a precooling facility, or in some cases, directly within a refrigerated container or vessel. The food product is then transported by land to one or a series of DCs, where pallets are sorted and sent to the proper client based on product demand and a predetermined management system. The food product can also transit through a number of cross-docking sites,

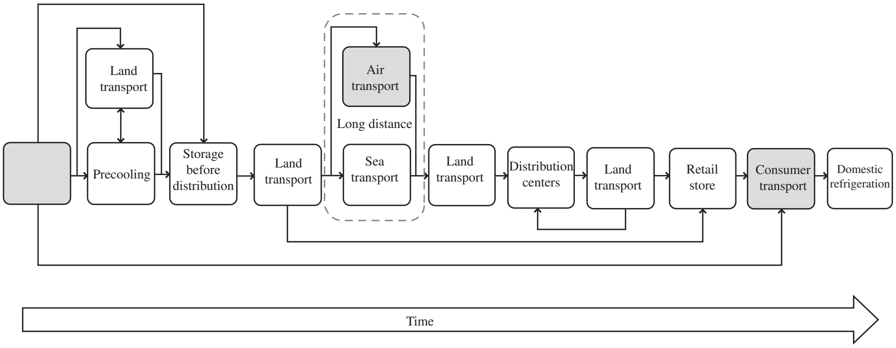

Figure 7.1 Overview of the main stages along a typical cold chain. Shaded area denote stages where no refrigeration is generally applied.

to combine shipments of small suppliers and reduce transportation cost (Mack et al., 2014). Depending on the distance-to-market, transportation can be by land or a combination of land and sea or air transportation. After transiting through the last DC, the food product is transported to a retailer, where it is stored in a backroom or in a refrigerated display cabinet until it is sold to consumers. For small growers in developing countries, the food product can often bypass the distribution stages of the cold chain and be sent directly from harvest to retail, generally nearby farmers' markets (Sibomana et al., 2016). Once the food product has been bought by consumers, it is transported home and stored in a domestic refrigerator until consumption.

7.2.1 Precooling

Precooling is commonly defined as the critical postharvest procedure that immediately follows harvest to quickly lower the temperature of FFVs to minimize spoilage and maximize shelf life and product quality. Poor precooling after harvest creates food waste and loss, endangers food safety, and represents a major economic problem to the produce industry. Delaying precooling by 6 hours at ambient temperatures can increase decay incidence by more than 25%, while a 50% increase in water loss upon arrival at the DC can be induced by a simple 4-hour delay between harvest and precooling (Nunes et al., 2005; Pelletier et al., 2011). The consequences of poor precooling are usually not apparent until later during distribution, and only a fraction of the decay or water loss demonstrated above will result in rejected loads, lost sales, and consumer dissatisfaction, resulting in wasted food (Mercier et al., 2017).

Mainly there are five different ways for precooling fresh produce—room cooling, forced-air cooling, water or hydrocooling, ice cooling, and vacuum cooling—specifically recommended based on the characteristics of the product. These characteristics include the sensitivity to chilling injuries, scale of the harvest, the minimum/maximum time required for precooling as well as product packaging. Each method has its own advantages and disadvantages with a detailed comparative analysis provided by Kader and Rolle in their book titled *The Role of Post-Harvest Management in Assuring the Quality and Safety of Horticultural Produce* (Kader and Rolle, 2004).

Room cooling is a relatively slow procedure suitable for products that generally do not decay rapidly and may be more sensitive to moisture (Thompson, 2004). As the name implies, the products are placed in a refrigerated room (which can either be a storage facility or a temperature-controlled transportation container) where there is constant circulation of cold air with the help of cooling fans. It is important to note that the air circulation in room cooling is mild and occurs around the produce instead of going through them. Room cooling is generally recommended for produce such as zucchini and squash, as well as potatoes, tomatoes, and cabbage. Among the five different precooling techniques, room cooling is both the most energy efficient and the slowest one and also requires careful placement and stacking of produce to maximize airflow between pallets.

Forced-air cooling is similar to room cooling except the cold air is "forced" to circulate through the produce instead of the ambience as in the former (Ferrua and Singh, 2009). It is by far the most effective and widely used precooling technique as it is used to cool palletized produce at industrial scales. The airflow can be horizontal or vertical depending on the placement of pallets and cooling equipment. Rows of pallets of fresh produce are covered with a plastic tarp to ensure controlled airflow from one side to the other. A cooling tunnel consists of two or more rows of produce pallets with an air intake fan in the middle that draws colder ambient air outside the tunnel through the warm produce to cool them down quickly. This air is recirculated back to the room after it goes through thermal equipment to bring it back down to desired product temperatures. Challenges remain, however, especially in regard to the uniformity of product temperature distribution as well as over cooling (freeze damage) and under cooling (loss of shelf life) of produce. Forced-air cooling is generally recommended for produce such as beans, berries (including strawberries, blueberries, and raspberries), carrots. and leafy greens.

In water or hydrocooling, cold water is applied to produce in a variety of ways such as submersion in a tank to sprinkling/spraying or passing the palletized products through constant streaming water. Additionally, the water can be treated with chemicals to control bacteria, which can cause spoilage (Reina et al., 1995). Hydrocooling is desired for situations where faster cooling is necessary to preserve product quality as water possesses a higher cooling capacity than air. However, it is also important to note that not all products can be cooled with water, which causes more spoilage in sensitive produce such as berries. Hydrocooling is typically recommended for products such as oranges, peaches, sweet corn, and cucumbers.

Ice cooling is similar to hydrocooling in that instead of cooled water, crushed, slurry ice is used to rapidly cool down the produce (Siegel et al., 2012). Ice is injected into the produce package to provide not only faster precooling times but also to extend the amount of time the product stays cooled down. It is important that ice is neither contaminated with bacteria, nor includes any chemical that might be harmful to the produce or human consumption. Ice cooling is typically recommended for products such as broccoli, onions, and parsnips.

Finally, in vacuum precooling the produced is placed in a chamber where the air is pumped out to create an environment where the atmospheric pressure is reduced immensely compared with normal atmospheric pressure (Dongquan et al., 2002). Hence, the boiling point of water is lowered, which results in significantly faster evaporation and ultimately cooling down of the produce. While, vacuum cooling is one of the fastest ways to lower produce temperature, it has its own challenges mainly in controlling the increased water loss and energy costs in running the vacuum chambers. Vacuum cooling is mostly recommended for leafy vegetables like lettuce and creates the most uniform temperature distribution among all precooling techniques.

7.2.2 Commercial transportation

7.2.2.1 Sea transportation

Refrigerated sea transportation is an important link in the food supply chain and is an important mode of transportation for dairy products, fish products, fruits, meats, vegetables, and other food products. The two most commonly used sea transportation methods for refrigerated shipments are transport in specialized refrigerated containers (also known as reefers) incorporating a mechanical vapor compression refrigeration unit into an insulated container, or in the bulk holds of dedicated refrigerated cargo ships. Wild (2009) reported that in 2000 each transportation method was accounting for approximately 50% of the world's sea refrigerated cargo transportation. Refrigerated ships were mainly dedicated to the transportation of frozen meat and bananas. Today, these ships have been partially replaced by refrigerated containers that only require an external source of electricity to operate the refrigeration system and remove heat from the container's internal environment (Fitzgerald et al., 2011). The shift from bulk to refrigerated containers is in large part due to the longer shelf life that is made possible by faster delivery for refrigerated containers, which results in greater cost-efficiency, especially for small shipments (Jedermann et al., 2014; Arduino et al., 2015). For both specialized refrigerated ships and refrigerated containers, the delivery of cold air through floor gratings is the most typical airflow pattern. The air then passes vertically through the produce and returns to the cooling unit along the ceiling (Smale, 2004). In addition to the airflow pattern, factors that will significantly influence the temperature distribution inside ships and refrigerated containers are the operation and design of the container or the ships, packaging, stacking mode, and the properties of the food product (Tanner and Smale, 2005). During the shipment of kiwis from New Zealand to Belgium, Tanner and Amos (2003) monitored the temperature inside a specialized ship and a refrigerated container. They observed significant temperature variability both spatially across the width of the container and temporally making the temperature control system inefficient since it was operated based on the basis of single-position temperature measurement in the container. A decrease of the delivery air temperature down to as low as −5°C for short periods and −2.5°C for extended periods was observed in response to a temperature measured by the sensor

0.5°C above the set point, increasing the likelihood of fruit freezing injuries. Although the number of kiwis outside the recommended temperature range was significant, they reported a more uniform temperature for the transport inside the cargo of the ship than for refrigerated containers. Amador et al. (2009) performed the temperature mapping of a load of crownless pineapples inside a refrigerated container shipped from Costa Rica to the United States (Florida). Their results suggest that the pineapples near the bottom of the pallets were more at risk of chilling injuries since the temperature was lower by as much as 3°C−4°C than near the top of the pallets. This difference was explained by the vertical airflow pattern inside the refrigerated containers. Defraeye et al. (2016) simulated an ambient loading protocol for sea transportation of oranges in refrigerated containers. A cooling period of 21 days was selected to mimic a period of forced-air precooling of 3 days followed by an 18-day transportation period. Performance of the standard ambient loading method was compared with that of the channeling configuration, which reduced airflow bypass between pallets, and the horizontal configuration, which forced the air horizontally across the pallets. Results indicated that the standard ambient loading protocol and the channeling configuration exhibited similar cooling behavior and were able to cool the produce within about 3 days to the seven-eighths cooling time. However, the oranges were of better quality and lasted longer in shelf life conditions for the channeling configuration due to less moisture loss. The horizontal configuration performed worse on all aspects. Mai et al. (2012) performed the temperature mapping for three air and three sea shipments of fresh fish transported from Iceland to the United Kingdom or France. They observed that the temperature was less stable during air transport than during sea transport, as transportation by sea using refrigerated containers reduced the number of handling operations during which the pallets could be exposed to high ambient temperatures. However, they also observed that the predicted remaining shelf life is shorter for sea transport than for an air shipment with precooled product due to the long transportation time required for the sea shipment. This indicates that several factors are to be considered when selecting the transportation mode including quality and safety of the produce, time to reach destination, as well as transportation cost. In their work, Kan et al. (2017) have employed computational fluid dynamics (CFD) technique to model and simulate the influence of cargo stacking on temperature distribution of a 20-ft. THERO-KING standard reefer container commonly used for sea transportation. They studied the impact of the height and length of the cargo stack, as well as of the space between cargo stack and the sidewall surface. They found that with the increase of the stack's height, the return air channel gradually narrows down resulting in an increase of the uneven temperature inside the containers. They also observed that an increase in the stack's length results in the apparition of enlarging high-temperature zone near the door, which also results in an increase of the uneven temperature inside the containers. Concerning the impact of the space between cargo stack and the sidewall surface, they observed that the heat transfer between the air and the cargo in the container improves with an increase of this space reducing the presence of uneven temperature profile inside the containers. They conclude that CFD technique can provide useful information in making a decision on the dimensions and stacking of the cargo to optimize the temperature distribution in the sea refrigerated containers.

7.2.2.2 Rail transportation

Transportation of containers by rail is a natural extension of sea container transport and a link of intermodal transport, it may also be an independent transportation mode. While rail transport carries huge amounts of corn syrup, French fries, canned goods, FFVs, corn and soybean oil, frozen chickens, sugar, and pasta (Foodlogistics.com), it is far from being the preferred mode of transport for the food industry because it takes a lot of time compared with all-road transport for the transportation of perishable goods (Sommar and Woxenius, 2007). As such, documentation on the temperature conditions observed during rail transport is scarce. However, there is significant growth potential owing to some current developments including high-speed trains reserved for medium-sized loads transportation, with maximum reduction of intermediate times (Fronda, 2013), and the promotion and development of fast intermodal transport solutions (Inbound Logistics, 2010; Sandberg Hanssen and Mathisen, 2011). Rail transportation also has low external costs (cost of accidents, congestion, air pollution, greenhouse gases, and noise), when compared with those of a general freight truck (Forkenbrock, 2001).

7.2.2.3 Intermodal transportation

Intermodal transportation is defined as the movement of goods in a single loading unit by a sequence of at least two transportation modes (road, sea, rail or air), the transfer from one mode to the next being performed at an intermodal terminal. Many varieties of intermodal containers are in use along the food supply chain but the standard dry-freight containers (20′, 40′, 45′ length; 8′6″ height) are the most common, while refrigerated containers (reefers) used for transportation of perishable goods (5%) represent a growing segment (Rodrigue, 2013). The main advantage of intermodal transportation is its low transportation costs compared with transportation by freight truck since usually the most suitable transport mode is used along the food supply chain (Sandberg Hanssen and Mathisen, 2011). On the other hand, intermodal transportation requires movements that may damage fragile goods, and it relies on time-consuming transshipment compared with all-road transportation, which may result in a decrease in the remaining shelf life of perishable food products and thus a decrease of its value. For example, Lervåg et al. (2001) reported that a delay of 48 hours in the transportation of fresh fish results in a price reduction of between 20% and 25%. In addition, even if the refrigerated containers slow down the decay of perishable food products, they do not completely eliminate it. As it is the case for other loading units, they can also be subject to potential temperature abuses that impact the remaining shelf life of the products. For bananas, Haass et al. (2015) reported that an increase in the reefer temperature from 15°C to 20°C may increase the daily ripening rate of bananas by as much as 75%.

In their work, Dulebenets et al. (2016) proposed a novel optimization model to minimize the total cost associated with the transportation and decay of perishable food products during intermodal transportation. The intermodal freight network for the import of seafood perishable products to the United States has been used to conduct comprehensive numerical experiments to identify important managerial insights. The numerical cases show that product decay cost significantly affects the transportation modes and the associated total transportation time and distribution costs. For example, an increase in the product decay cost was found to reduce the total miles traveled by rail while increasing the use of road transportation, which provides faster delivery and decreases the total product decay. However, the use of road transportation is more costly in terms of distribution costs. They also showed that the total miles traveled by sea was reduced with increasing product decay cost. This type of model can help in making a decision on the transportation modes to be used to minimize the total cost associated with intermodal transportation.

7.2.3 Storage at the distribution center

In the late 19th and early 20th centuries the introduction of cold chain principles across food systems was slowly being adopted. At the time this was not a fully welcomed development and it received much negative attention. This, in part, was due to a lack of trust on the part of the consumer given the fact that they were now being offered food stuffs that traditionally were only available at selected times of the year (due to local harvest seasons). This, new, year-round offering challenged social thinking at the time both locally and nationally and was a topic of many negative conversations (Freidberg, 2015). It also presented a number of new unforeseen challenges to existing legislation and know-how governing logistics at the time. The adoption of cold chain at that time in history would undoubtedly have required significant fundamental social and operational restructuring as well as all the associated financial investment.

Nowadays cold chain is widely adopted and it is difficult to present a counter argument against it. Social attitudes have evolved and people do not have the same negative views or distrust for refrigerated food supply chains once held. In fact one of the key issues causing distrust of the traditional cold chain (the year round product offering) is now a basic requirement of the modern day consumer. Cold chain, as a direct result of this year round offering, has also helped provide a more sustainable business case for produce as these business cases are generally harder to build (Liu et al., 2018). Cold chain adoption has also had direct positive implications on food security and waste and loss (McCarthy et al., 2018). Cold chain adoption has undoubtedly transformed the “food lives” of the modern day consumer, given the fact that it, in partnership with other advances, has transformed food supply chains from adopting a localized “narrow” trading span to now offering product and services across geographies, time zones, language zones, and cultures. By virtue of its name the cold chain is regulated and audited through its ability to maintain a specific temperature at which food stuff must be transported and stored to avoid premature spoilage.

Modern day DCs are central to cold chain applications and play a crucial role in the safe, efficient, and responsible carriage and storage of food stuffs and it is for this reason alone their importance cannot be overlooked. Food DCs serve as a point in time where the food can be visually inspected, assessed, and accounted for through human contact/visualization. Modern day organizations use food DCs as a hub for central/regional storage and holding sites that are strategically located at equally distance between food stores to facilitate timely and cost effective store replenishment. In theory this means that carefully placed DCs allow for all types of product (produce, dried, canned, apparel, etc.) to be within a set distance of each store nationally, and even globally, thereby reducing shelf replenishment time and out of stock occurrences. Such careful placement of DCs also helps reduce the occurrence of product loss and waste during transport. With respect to product loss and waste there is an important distinction to be made between loss and waste. Food loss is the loss of food before it reaches retail, that is, food that gets spilled or spoilt before it reaches its final product or retail stage. Food waste is considered to be food that is fit for human consumption but is not consumed and left to spoil, that is, food that is left to spoil or discarded by retailers or consumers (FAO, 2011). Collectively food waste and food loss have been reported to amount to about 1.3 billion tons per year or one-third of food produced for human consumption. While DCs alone cannot be held accountable for this 1.3 billion tones, the correct and efficient operation of DCs will certainly help reduce this figure.

To further represent the challenges faced by DC managers it is a well-established fact that not all foods have the same optimum storage temperature. As a consequence, modern day cold chain trading between DCs has been carefully tailored to the product as opposed to the process, that is, each product is and should be handled in accordance with its best practice (optimum temperature). It is no longer acceptable to simply establish trading links, and distribute food at any given temperature without considering the type and nature of the product being shipped. Improving global food supply chain and food handling processes can help address current levels of food waste, which have far-reaching impacts on global food security, resource efficiency, conservation, and climate change. The increasingly detailed regulations established in developed countries over the last few years reflect these product-specific handling requirements (Fig. 7.2). The product-specific optimal handling and storage conditions undoubtedly add complexity when it comes to food distribution and DC management and have resulted in modern day DCs being designed to accommodate a large variety of food types, shapes, sizes and weights with each requiring different storage requirements. Therein lies the cold chain challenge, that is, the development of an efficient supply network that will base decisions on product-specific information and distribute this information across the complete producer/consumer supply axis in real time (McMurray et al., 2013).

There are currently a large variety of technologies available to help improve the cold chain management each with the primary aim of reducing product losses and increasing profitability (Badia-Melis et al., 2018). Such systems, to function correctly, must consider both the incoming and outgoing flow of goods. Irrespective of

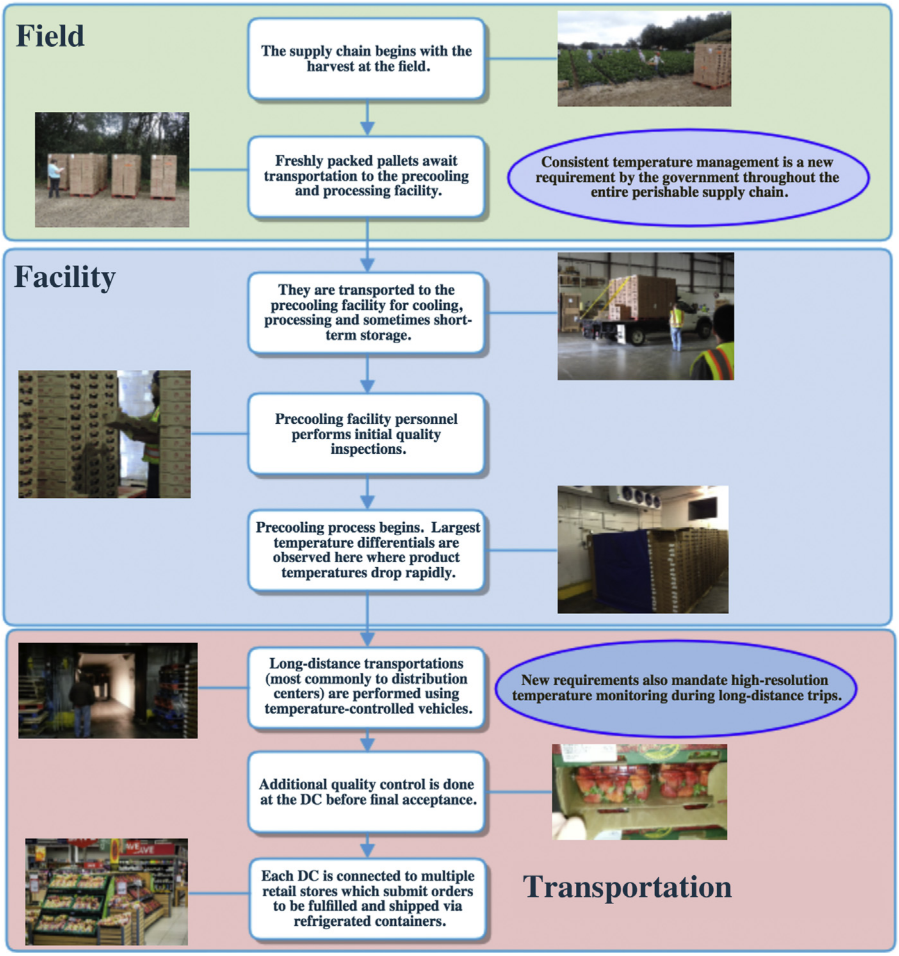

Figure 7.2 Stages along the strawberry cold chain where good practices need to be improved to comply with recent United States Food and Drug Administration (FDA) regulations.

function, form factor, functionality, cost, and level of integration these systems have the primary aim of increasing transparency of the food product during transport and storage. These systems essentially have the ability to act as custodians of the product. To be in a position to do this the systems must be able to facilitate and monitor the transit of physical product, with cyber (business/product) information (Smith, 2008). This complexity of carriage combined with where the product has been sourced in addition to where it is going relative to its current state of freshness is not a trivial task and not one that can be made in autonomy as, every decision, no matter how local, can have significant effect on the product, retailer, and the profitability of the company. Therefore there is a strong requirement that these systems function in totality across supply chains, DCs, products, time zones, and geographies.

As previously mentioned varying food types possess different ideal storage temperatures, which, as a general rule, may be grouped into three common commercial groupings, that is, frozen, chilled, and/or ambient, with each group having internal variation (i.e., ambient storage temperature may vary for different product types). In an ideal theoretical supply chain all foods (irrespective of grouping) being transported from DC-A to DC-B are loaded onto a single transport unit (truck, plane, ship, etc.) and delivered from DC-A to destination DC-B. The reality is however that many transporting units do not have an ability to mix groupings (i.e., frozen and ambient); requiring the use of a second transport (truck, plane, ship, etc.) unit traveling in unison with the first, thus doubling transport costs between DC-A and DC-B.

The science of cold chain management requires an understanding of the chemical process of food spoilage, its environmental triggers and inhibitors, its technological guardianship, and monitoring driven by business process compatibility. As a result of this decision making requires a multidisciplinary approach in a dynamic environment. DC and food logistics managers must consider a number of critical influencers prior to execution that individually and collectively are designed to reduce food waste and/or loss during transit and/or immediately on arrival at destination. Some of these decision influencers include:

1. the deterioration rate of the product at optimum conditions;
2. the state in which the food has arrived to the DC (has any negative occurrence taken place that may reduce the expected shelf life);
3. the conditions under which it must be kept at your DC;
4. product demand local and nationally;
5. the remaining shelf life of the product;
6. travel time to destination; and
7. the distance it has to travel to retail relative to remaining shelf life (Hertog et al., 2014).

Also, many food DC managers are faced with the challenge of making these decisions in the context of business process efficiency. This is due to the fact that the unfortunate reality is that, in either scenario, the negative effects of product spoilage are significant given the fact that product that spoils during transit is money wasted on transit costs and secondly product that spoils on DC arrival is, again, money wasted on transport costs, and also storage and disposal costs.

The role and importance of food DCs cannot and must not be overlooked. As food companies modernize and tend towards vertical ownership of their value chains, combined with advances in communication technologies, there are obvious efficiencies being achieved at DCs year on year. Within each company correct DC placement and management can have a direct positive impact on the social, financial, and security elements of food supply thus reducing food loss and waste across our supply networks. It is also important to note that efficient management of food DCs cannot be done in autonomy and decision making must account for the full supply network as opposed to being made at the local level.

7.2.4 Display at retail

After transiting through the last DC, the food products are transported to a retailer, where they are stored in a backroom or in a refrigerated display cabinet until they are sold to consumers. Different types of refrigerated display cabinet are used worldwide, including vertical open cabinets, vertical reach-in cabinets, tub-type cabinets, and service deli cabinets. The most common type is the vertical open-refrigerated display cabinet. This type of cabinet is equipped with a recirculating air curtain, which provides a barrier between the interior conditioned area of the cabinet and the ambient air in the retail space, with concomitant easy access to the food products by the consumers (Jouhara et al., 2017). However, they often fail to provide the temperature necessary for proper storage of the food products and they are not energy efficient. Numerous research works have been carried out to identify and optimize the variables involved in the effective design of air curtains (Bhattacharjee and Loth, 2004; Navaz et al., 2005; Yu et al., 2009).

In their work, Willcox et al. (1994) reported temperature performance for a vertical three-deck cabinet and for an horizontal one-deck cabinet used to display minimally processed, modified atmosphere packed vegetables. Both cabinets were cooled by fan-assisted cold air. For the vertical cabinet, the mean temperature measured during 1 week varied between 6.9°C and 12.3°C for the deck 1 and 3 located at the bottom and at the top of the display cabinet, respectively. Only the temperature performance of deck 1 complied with the Belgian legal requirement. For the horizontal display cabinet, the temperature distribution was more uniform and in average at 7.0°C or less, which complied with the requirement. Temperature performance of both display cabinets was influenced by the ambient air temperature as well as by the day/night regime. Nunes et al. (2009) have monitored the temperature inside 27 refrigerated and nonrefrigerated retail display cabinets. Refrigerated display cabinets were open stand-up or low cases, and were not movable, while the nonrefrigerated cabinets were also open but in some stores they were movable allowing for their positioning with the department. For the refrigerated cabinets, temperature setting was between 2°C and 4°C. The temperatures varied from −1.2°C to 19.2°C inside refrigerated retail displays, for middle shelves and "before" lower shelves, respectively, while it varied between 7.6°C and 27.7°C inside nonrefrigerated retail displays for bottom shelves and upper shelves, respectively. Maximum temperature performance reported for the refrigerated retail display cabinets was too high for produce requiring low temperature, and the minimum temperature performance too low for chilling-sensitive produce. For most of the produce stored in nonrefrigerated displays, the temperatures were too high. This was particularly problematic at the middle and top of the display. Morelli et al. (2012) studied the performance of open horizontal refrigerated display cabinets used for bakeries, pork butchers/delicatessens, and cheese/dairy products. They monitored the temperature of both food products and air in the refrigerated retail display cabinets and reported that 70% of time/temperature food product profiles were above 7°C and were thus unsatisfactory. These unsatisfactory results were attributable in equal part to poor refrigerated retail display design and poor professional practices. Zeng et al. (2014) monitored the temperature profiles of bagged salads in display cases at nine supermarkets for 2 months during summer (July to September) and for 2 months during the subsequent winter (January to March). The bagged salads were typically held for 1−3 days and were displayed for a maximum of 3 days. A total of 3799 temperature profiles were obtained. Temperature profiles indicated minimum and maximum temperature peaks ranging from 1.0°C to 14.1°C and a distribution of mean measured temperatures ranging between −1.1°C and 9.7°C. This demonstrates that temperature abuse is likely to occur during retail display. In the same work, Zeng et al. (2014) demonstrated that such abuse increased the growth probabilities for both *Escherichia coli* O157:H7 and *Listeria monocytogenes* used to inoculate bagged salads. Kou et al. (2015) monitored the spatial and temporal temperature variations within two commercial open-refrigerated display cases, consisting in three 4-ft. sections and five modular shelves that are with flexible placement, filled with a total of 72 spinach packages. Temperature was found to be the highest (average 6.5°C) in the front rows of the display cabinet while temperature in the back was the lowest (average −0.8°C), and was below freezing, which resulted in spinach damage. To solve this problem, insulating foam boards were installed. Temperature variation between the front rows and the ones in the back was successfully reduced by 3.5°C and enabled spinach packages in the front rows to remain at temperature below 5°C as recommended by the FDA. Brown et al. (2016) have monitored the temperature in nine 8-ft. display cases containing fresh-cut leafy greens. Monitors were placed in the lower bin and at the front and back of shelves. High-temperature abuse was recorded in all display cases while low-temperature abuse was recorded in five of the nine display cases. For at least 5% of the time, 40.2% of the sensors recorded temperature above 7.22°C while 17.2% of the sensors recorded temperature below −0.17°C. Temperatures were often too high at the top and too low at the bottom of the display cases. As reported in the aforementioned works, a wide range of temperature during display at retail has been observed. It can be due to several factors but the heterogeneity of temperature according to the position inside the display cabinet is certainly one of the main factors.

7.2.5 Transportation and storage by consumers

The last stages of the cold chain are under the control of consumers. Once the food product has been bought, it is generally transported home without any refrigeration, and thus at a temperature too high for proper preservation. Derens et al. (2006) measured the temperature of yogurt and meat products during transportation by consumers and reported that 85% of the products reached a temperature above 6.0°C. Morelli and Derens-Bertheau (2009) and Gogou et al. (2015) reported that the average temperature of smoked salmon and meat products during transportation by consumers was of 13.0°C and 9.8°C, respectively. The aforementioned studies reported an average duration of transportation by consumers between 40 and 75 minutes. Although it is hard to accurately quantify the impact of transportation by consumers on the amount of food waste, 1 hour at a temperature above 10°C can be sufficient to impact food quality and safety. As an example, for strawberries, 1 hour at 12°C is equivalent to nearly 4 hours in shelf life loss (Hertog et al., 1999). Similarly, James and Evans (1992) estimated that *Pseudomonas* can grow by up to two generations on a variety of perishable food products during domestic transportation in summer conditions. However, the growth can be maintained below 0.5 generation using an insulated box. As such, protecting perishable food products using insulated bags or containers is a sound practice to adopt when the ambient temperature is warm or the delay between retail and storage in the domestic refrigerator is significant.

Before the perishable food is consumed, it is generally stored in a domestic refrigerator. Three main types of domestic refrigerators are used: icebox refrigerators containing a box-plate evaporator, larder refrigerators with a backplate evaporator, and fridge-freezers with a backplate evaporator (James et al., 2017). Many studies have investigated the average temperature and the temperature distribution inside domestic refrigerators (Mercier et al., 2017). Some studies suggest that icebox refrigerators (Evans et al., 1991; Janjić et al., 2016) and refrigerators of smaller size (Laguerre et al., 2002) have a better performance and a more uniform temperature, while other studies have not found a significant difference in performance between refrigerator types (James et al., 2017). Most studies have reported the presence of significant temperature heterogeneity inside domestic refrigerators, regardless of the type. James and Evans (1992) and Bakalis et al. (2003) reported that the temperature difference between the warmest and coldest locations was above 5°C in most refrigerators. The warmest region is generally located inside the door: as an example, Janjić et al. (2016) reported that the temperature inside refrigerators in Serbia was on average 2.0°C higher when it was measured inside the door in comparison to the bottom shelf. However, conflicting results have been obtained regarding the temperature distribution along the height of refrigerators. Some studies have reported that the temperature is generally higher at the top shelf (Evans et al., 1991; New Zealand Foodsafe Partnership, 2004), while other studies have found that the temperature is generally higher at the bottom shelf (Godwin et al., 2007). Laguerre and Flick (2004) have also reported that the shelf with the highest temperature can change over time.

Nearly every study investigating domestic refrigerators has reported that the temperature inside the majority of refrigerators is too high. The recommended temperature inside refrigerators varies between countries, but is generally below 5°C (James et al., 2017). Yet, the majority of studies suggest that the average temperature inside domestic refrigerators is between 6°C and 7°C (Mercier et al., 2017). Brown et al. (2014) estimated the impact of the high temperature in domestic refrigerators on the amount of food waste in the United Kingdom. The authors assumed that the average temperature inside domestic refrigerators is currently of 7°C and that the amount of food saved would be proportional (the proportionality constant depending on the food product) to the increase in shelf life achieved from operating the refrigerators at a lower temperature. Based on these hypotheses, the authors estimated that maintaining refrigerators at a temperature of 4°C would save in the United Kingdom about 71,000 tons, or £162.9 million, of food annually. The authors also confirmed that the amount of energy and CO_2 saved from the consumption of these 71,000 tons of food would significantly exceed the amount of energy and CO_2 required to operate refrigerators 3°C below their current average temperature.

7.3 The cold chain around the world

7.3.1 Refrigeration capacities

The availability of proper infrastructure to preserve perishable food within the desired temperature range along the cold chain varies significantly across regions of the world. Table 7.1 presents the refrigerated warehouse capacity for the top 12 countries in 2014. While developing countries such as India, China, Brazil, and Indonesia have some of the largest refrigerated warehouse capacities in the world, their capacities are much smaller than most developed countries when considering the size of their population. On a per capita basis, the refrigerated warehouse capacity in India, China, Brazil, and Indonesia is below one-third of the capacity in most developed countries. In accordance with the difference in refrigerated warehouse capacity between developing and developed countries on a per capita basis, Bresolin et al. (2018) estimated that, for instance, current refrigerated warehouse capacities in Brazil only meet 29% of the country's cold chain needs.

While breaks along cold chains in developed countries are generally only observed during waiting times and transfer between stages of the cold chain, entire stages can be performed without refrigeration in developing countries, with great consequences on food loss and safety. In Africa and China, many small or medium size dairy or fruit and vegetable farms do not have access to precooling facilities because of their high capital and operating costs (Torres-Toledo et al., 2018;

Table 7.1 Refrigerated warehouse capacity (total and per capita) for the top 15 countries in 2014 (GCCA, 2014)

Country	**Total refrigerated warehouse capacity (Mm^3)**	**Refrigerated warehouse capacity per capita (m^3 per habitant)**
India	130.7	0.1
United States	114.8	0.4
China	76.1	0.1
Japan	32.7	0.3
Great Britain	25.0	0.4
Germany	24.0	0.3
Brazil	16.1	0.1
Netherlands	16.0	0.9
France	15.5	0.2
Iran	14.0	0.2
Indonesia	12.3	0.1
Canada	8.9	0.3

Zhao et al., 2018). The absence of precooling accelerates food decay, can trigger pathogens growth, and can result in the rejection of the food at the collection center, leading to substantial food and income losses (Torres-Toledo et al., 2018). Perishable food products are also frequently transported without refrigeration because of a deficit in refrigerated truck capacities. In India, it is estimated that more than five times the current number of refrigerated trucks would be required to meet cold chain needs (NCDD, 2016). In China, it is estimated that 85% of perishable food is transported in regular trucks, without refrigeration (USDA, 2008; Zhao et al., 2018). In contrast, about 90% of perishable food is transported in refrigerated trucks in developed countries (USDA, 2008). Significant differences can also be observed between the locations were fresh produce is bought by consumers in developed and developing countries. In developing countries, a large fraction of food products is sold in farmers' markets: as an example, more than 70% of agricultural products are sold in farmers' markets in China (Zhao et al., 2018). Farmer's markets have significant advantages, notably by removing intermediaries between the producers and the buyers and improving the accessibility to locally grown and low-cost fresh produce. However, the absence of proper refrigeration equipment, poor sanitation practices, and limited food quality inspection can create a significant amount of food waste at the retail level in developing countries (Torres-Toledo et al., 2018; Zhao et al., 2018).

Within developing countries, substantial differences can also be observed between small-scale and large-scale growers. Refrigeration can be completely absent along supply chains from small-scale growers to retail (Torres-Toledo et al., 2018). The absence of refrigeration creates food safety risks, and increases product rejection rate and food loss. The shorter shelf life in the absence of refrigeration also limits selling opportunities to markets located close to the production site, which can substantially reduce profit. In contrast, more modern infrastructure, closer to the infrastructure found along cold chains in developed countries, is often observed for large-scale growers selling their products to supermarkets (Torres-Toledo et al., 2018). The improved postharvest management observed for large-scale growers is stimulated by the stricter food quality requirements of supermarkets, and the postharvest management practices required by international standards when food products are exported (Torres-Toledo et al., 2018).

Another significant problem observed in some regions is the inability of consumers to preserve perishable food in the desired temperature range at home. In developed countries, nearly every household has a refrigerator. In North America, about 25% of households even have two or more (EIA, 2009; Statistics Canada, 2009). However, the household penetration rate of refrigerators is much smaller in many developing countries. In China, 91.7% of households have a refrigerator in urban areas, but the figure drops to 77.6% in rural areas (Zhao et al., 2018). In South Africa, 68.4% of households have a refrigerator (Lesame, 2014). In Indonesia, the percentage of households with a refrigerator is of 55.5% in urban areas, and only of 24.7% in rural areas (Statistics Indonesia, 2012). The major reasons for the absence of a refrigerator are the high capital cost and the absence of a reliable electricity source (Aste et al., 2017).

It is, however, important to note that progress is seen in many developing countries. The total refrigerated warehouse capacity in the world increased by 8.6% from 2014 to 2016 (GCCA, 2016). The most significant increases are observed in developing countries: for instance, the refrigerated warehouse capacity in Brazil, China, Mexico, and India increased by more than 25% annually from 2008 to 2014 (ITA, 2016). New technological developments also represent a key driver for the improvement of the cold chain in developing countries. Examples of promising technological developments include low-cost and sustainable refrigeration technologies powered by renewable energy sources, such as on-farm precooling and refrigeration systems powered by biogas or solar energy (Islam and Morimoto, 2014; Aste et al., 2017; Torres-Toledo et al., 2018). The development of accessible refrigeration technologies based on renewable energy sources is critical to the improvement of the cold chain, especially given that more than a quarter of the population living in rural regions still does not have access to electricity (The World Bank, 2014).

7.3.2 Food loss and waste in different countries

Given the larger refrigeration capacities found in developed countries, one could expect the proportion of food lost and wasted to be smaller than in developing countries. However, the opposite is actually observed: according to the 2011 report from the Food and Agriculture Organization of the United Nations (FAO, 2011), the annual mass of food loss and waste is approximately 280—300 kg per habitant in North America and Europe, in comparison to 120—170 kg per habitant in Sub-Saharan Africa and South/Southeast Asia. Differences in consumer behavior is a major factor explaining the higher amount of food loss and waste in North America and Europe. In North America and Europe, consumers waste annually, on average, 95—115 kg of food, about 10 times the amount of food wasted by consumers in Sub-Saharan Africa and South/Southeast Asia. Another factor is the higher rejection rate of food in developed countries resulting from stricter quality standards. For instance, approximately 20% of FFVs are lost at the agricultural level in North America and Europe. A large portion of these fruits and vegetables are discarded right after harvest, often only because of small defects in appearance or shape (FAO, 2011).

Nevertheless, the impact of inadequate refrigeration infrastructure in developing countries on food loss and waste is significant. More than 25% of fruits and vegetables are lost at the postharvest and processing stages in Sub-Saharan Africa and South/Southeast Asia, in large part because of insufficient refrigeration capacities and technical knowledge (FAO, 2011). In contrast, the amount of fruits and vegetables lost at these stages is less than 5% in North America and Europe. For dairy products, the amount of food lost during the postharvest and processing stages is approximately 10% in Sub-Saharan Africa and South/Southeast Asia, about twice the amount observed in North America and Europe (FAO, 2011). The International Institute of Refrigeration estimated in 2009 that, if the level of refrigeration used in developed countries was applied in developing countries, more than 200 million tons of perishable food would be saved annually, corresponding to approximately 14% of their annual consumption (IIR, 2009).

As such, the amount of food loss and waste in developed and developing countries represent two problems with distinct primary causes and solutions. In developed countries, major reduction of food loss and waste will require an increased awareness of the value of food and of the substantial consequences that poor food management at the consumer scale has at the global scale. In developing countries, supporting the cold chain with proper refrigeration infrastructure and improving technical knowledge are critical to the reduction of food loss and waste.

7.4 The cold chain in northern communities

While the improvement of refrigeration technologies and practices to decrease the temperature of food below the environmental temperature has been an issue actively researched and discussed, the problem of temperature management of food along the cold chain in cold climates has not received the same level of attention. Communities located in cold climates generally share a number features affecting the accessibility to fresh and high-quality food: many of these communities are located far from major cities, ports and DCs, have a low density and a high poverty level, face extreme environmental conditions, and have limited possibilities for local food production (Mercier et al., 2018). As an example, Emond et al. (2003) monitored the temperature and the quality of a mixed shipment of perishable food products from Montreal to Nain, a community located in the northern part of Labrador. The shipment was first transported for approximately 60 hours in a refrigerated truck from Montreal to a first community in Labrador. The shipment was then unloaded at the airport and stored overnight. The following day, the shipment was loaded inside a small airplane, and placed on a 2-hour flight to Nain. The shipment was finally unloaded and delivered to retailers using sleighs driven by snowmobiles. The delivery took from 10 to 40 minutes, during which no temperature control was applied and the food was exposed to environmental conditions such as wind, snow, and rain. The total duration of the cold chain from Montreal to Nain was between 3 and 4 days. Inspection of the shipment at arrival revealed that multiple products had become unmarketable because of chilling injuries, water loss, bruises, and browning. The low quality of the shipment was attributed to poor temperature management during storage and transportation, mechanical damages due to vibrations, and the exposure of the food to harsh weather conditions.

The cold chain delivering food to northern communities thus faces several challenges, notably:

1. the preservation for multiple days of mixed loads of fresh produce with different optimal temperatures;
2. limiting cold injuries during land transportation using vehicles without temperature control or protection against environmental conditions;
3. supplying communities at a sufficient rate to promote year-round accessibility to a range of fresh and healthy produce; and

4. reducing the cost of the cold chain, to provide affordable food reflecting the income level of the communities. The establishment of cold chains delivering high-quality food to northern communities with limited food loss requires a concerted effort to improve refrigeration of food after harvest and processing, develop low-cost and product-specific packaging protecting food against a range of environmental conditions, and establish management strategies reflecting each communities' specific needs and characteristics (Mercier et al., 2018).

Temperature management of food along cold chains in northern communities is a topic that should not be overlooked, given the major food security issues observed in many of these communities (Rosol et al., 2011; Skinner, 2013; Council of Canadian Academies, 2014).

7.5 Conclusion

Refrigeration plays a key role in the preservation of perishable food. The literature review revealed the consistent amount of food wasted or lost across regions of the world, although for different reasons: waste and loss in developed countries can be traced back in majority to poor handling of the food, while waste and loss in developing countries can be attributed to lack of refrigeration capacities, absence of electricity, and poor food handling. The review also highlighted the concerning stability of food waste and loss figures over the last two decades, despite the significant improvements in refrigeration technologies.

It is acknowledged that significant reduction of food loss and waste is required given the consistent increase of the world population and the saturation of land resources. Some of the main paths towards that objective are:

1. building a precise knowledge of food loss and waste for all categories of food products and regions of the world, to enable a proper comparison of the improvements against the reduction targets;
2. influencing a change of behavior at the microscale (households, restaurants, retailers), given that poor food management at these stages sums up to massive amount of food loss and waste, especially in developed countries; and
3. increasing refrigeration capacities in developing countries and remove/northern communities, to enable the year-round accessibility to healthy and fresh food in a sustainable manner.

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