AN ANALYSIS OF THE FEASIBILITY OF A SMART OUTDOOR COMPACT REFRIGERATOR FOR RECEPTION OF GROCERY DELIVERIES

by

YI-ZHENG ETHAN HUANG

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CASE WESTERN RESERVE UNIVERSITY

SCHOOL OF GRADUATE STUDIES

We hereby approve the thesis of

Yi-Zheng Ethan Huang

candidate for the degree of Master of Science *.

Committee Chair

Edward Caner

Committee Member

Robert Brown

Committee Member

Michael Martens

Date of Defense

May 22, 2019

*We also certify that written approval has been obtained

for any proprietary material contained therein.

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Preface

The ability for a consumer to order groceries online and have them delivered to his/her home is not a new service. Webvan, founded in 1996, was one of the earliest online grocery delivery companies, even though it soon filed for bankruptcy in 2001 in one of the biggest dot-com flops in history. Peapod, which was founded in 1989, is still in business today, although it was bought out in 2001 by global grocery company Royal Ahold.

Grocery delivery gained new life in the early 2010's when Instacart, a Silicon Valley unicorn, came into existence. Unlike Peapod, which sold groceries and delivered them out of their own fulfillment centers using their own delivery fleet, Instacart does not sell groceries. Instacart is what is known as a third-party grocery delivery service, where the consumer will order groceries from a grocery store that is partnered with Instacart, and Instacart will pick up and deliver the groceries to the consumer. This enabled any grocery store to offer online ordering of groceries and subsequent delivery services, without needing to hire their own delivery drivers. Soon, other third-party grocery delivery services, like Shipt, were founded.

Then, in 2017, Amazon acquired Whole Foods, which sent a ripple through the grocery retail market. Amazon is an online retail giant, and seemed intent on using the acquisition of a physical grocery store to lean heavily into the online grocery shopping market. This caused grocery delivery companies and other grocery stores to respond in kind; Target would acquire Shipt later that year, Instacart would begin to engage in a price war with Amazon, while Walmart and Kroger pursued other avenues of attack. Grocery delivery and online grocery shopping seem poised to become the next big thing.

Acknowledgements

I would like to thank my program advisor Edward Caner for invaluable advice, guidance, and support. I would also like to thank the defense committee members Robert Brown and Michael Martens for assistance in reviewing and revising my thesis. Finally, I would like to thank the Kelvin Smith Library and Case Western Reserve University for access to marketing databases.

An Analysis of the Feasibility of a Smart Outdoor Compact Refrigerator for Reception of Grocery Deliveries

Abstract

by

YI-ZHENG ETHAN HUANG

A design for a device that is able to maintain refrigeration temperatures outdoors for up to eight hours was sought, in order to allow for delivered groceries that require refrigeration to be received without the consumer being present. An analysis of the rate of heat transfer into an insulated container, taking into account the efficiencies of various refrigeration mechanisms and power sources, concluded that the optimal design would be powered by an electrical outlet, and use vapor-compression refrigeration to maintain interior temperatures; an outdoor compact refrigerator. An analysis conducted on the grocery reception market showed that demand for a grocery-receiving device is currently low, but should increase as the online grocery shopping market grows at an annual rate of 13%. Marketing the device as a smart compact refrigerator was also explored as a possibility. However, potential lack of patentable intellectual property may prove to be an obstacle for both applications.

1. Introduction

The online grocery sales market is growing and is expected to grow at a significant pace. A 2012 forecast of online grocery sales revenue predicted that the 2018 revenue would be $17.5bn (PitchBook, 2017), but the actual revenue in 2018 was $26bn (IBISWorld, 2018a), an almost 50% increase over predictions. Meanwhile, online grocery sales revenue is expected to reach $100bn in 2022 (FMI-Nielsen, n.d.), which would mean a compounded annual growth rate of 40%.

However, an issue with the current paradigm for grocery delivery is that the consumer is required to be present to receive deliveries. For consumers who are not able or willing to change their schedule to be present for the delivery, this represents a major source of inconvenience and an obstacle to adoption: 13.7% of consumers who did not expect to shop for groceries online over the next year found it “inconvenient to remain home for a delivery” (Coresight, 2018). This is where the author’s idea of a grocery-receiving device started. Ordering groceries online and having them delivered to his/her front door should be convenient for the consumer; that is, after all, the value of the service.

The device would be placed outside when the consumer leaves his/her home, who upon return would find the delivered groceries in the device. Naturally, the device would need to be temperature-controlled, to prevent spoilage. The device would also need to be able to lock, to control access, so that only the delivery person and the consumer could open the device. To do this, the device would need to be connected to the internet, where a mobile app would allow only authorized people to open the device. Finally, the device would need to have some sort of method of confirming that all of what was ordered was delivered, and to check that nothing unwanted was placed inside; a simple solution would be interior cameras, which could send the photos to the consumer to verify delivery.

In this paper, I will determine the best design for the temperature-controlling system of this device, as well as determine whether consumers would purchase a device like this for the purpose of receiving grocery deliveries – or if this device would be better used elsewhere. Other aspects of the design, such as the electronic lock, internet connectivity, and interior cameras, will not be scrutinized. As such, the paper will be divided into two sections: a Scientific Analysis section, which will determine the optimal design, and a Market/Business Analysis section, which will determine the optimal market.

2. Scientific Analysis

2.1 Introduction:

In this section, I will describe the process I took to determine the most optimal, but scientifically sound, design for a device that will provide refrigeration for delivered groceries while the consumer is away. I determined that such a device must be able to maintain internal temperatures below 4°C (40°F) – the FDA recommended refrigeration temperature (FDA, 2018) – for at least eight hours – the average workday – when used in an outdoor environment. Of secondary interest was whether a design existed where the device would also be easily portable. I will start by introducing the relevant thermodynamic and heat transfer equations and concepts, then use these equations and concepts to explore the feasibility of various models.

2.2 Background and Theory:

2.2.1 Heat Transfer

Conduction is one of three mechanisms for heat transfer, the other two being convection and radiation. Conduction is the transfer of heat between molecules in continuous physical contact with one another, which includes heat transfer through an object and heat transfer between objects. For the following cases of heat transfer via conduction, the heat flow will be assumed to be one-dimensional and in a direction normal to the temperature gradient, and each object will be of uniform composition.

Consider a planar wall of thickness L and cross-sectional area A, with the surfaces at temperatures T_1 and T_2, aligned such that the normal direction of the surfaces lies along the x-axis. The rate of heat transfer due to conduction through the wall can be expressed using Fourier's law of heat conduction.

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \tag{1a}$$

where dQ/dt is the rate of heat transfer and the temperature T is a function of distance along the x-axis, parallel to the direction of heat transfer. In steady-state conditions, dQ/dt is constant; since k and A are constants, dT/dx must also be constant, meaning that $T(x)$ is linear. This linearity allows for integration from $x = 0$, $T(0) = T_1$, to $x = L$, $T(L) = T_2$ after multiplying both sides of eq. (1a) by dx, which yields

$$\frac{dQ}{dt} = \frac{kA}{L}(T_1 - T_2) \tag{1b}$$

where k is a proportionality constant known as the thermal conductivity and is determined experimentally. The quantity kA/L, which has units of W/K, is known as the thermal conductance. The inverse of the thermal conductance is the thermal resistance R, with units of K/W.

$$R = \frac{L}{kA} \tag{2}$$

Thermal resistance is important because it can be used to calculate the rate of heat transfer between multiple materials and objects in the same manner that electrical resistance is used when calculating current. The electrical analogue of temperature is voltage (Cengel, Cimbala, & Turner, 2012).

$$\frac{dQ}{dt} = \frac{T_1 - T_2}{R}\ ; I = \frac{V_1 - V_2}{R} \tag{3}$$

Thermal contact conductance describes the rate of heat transfer between two objects through the shared interface surface. Thermal contact conductance is not a property of either material, but rather of the interface between two materials. If the interface was perfectly smooth and heat was easily transferred from one surface to the other, the thermal contact conductance would be infinite; in reality, however, the interface is always microscopically rough, leading to air gaps that effectively serve as insulation. The thermal contact conductance thus depends on the surface roughness and the properties of the fluid in the gaps, as well as the temperature and pressure at the interface and the properties of the two materials in contact (Cengel, Cimbala, & Turner, 2012).

Thermal contact conductance is given as a constant per unit area of and temperature difference across the interface between the objects, and has units of $W/m^2 \cdot K$. The inverse of the thermal contact conductance is the thermal contact resistance, which naturally has units of $m^2 \cdot K/W$. Note that these are not the same units as for the similarly named thermal resistance; the thermal contact resistance needs to be divided by the relevant surface area to be used with thermal resistance. Due to the various dependencies of the thermal contact conductance, the values of the thermal contact resistance are determined experimentally for specific pairs of materials at specific surface roughness, temperature, and pressure, with a specific gap fluid, meaning that the thermal contact resistance for a desired interface is not usually readily available; fortunately, however, the thermal contact resistance generally falls between 0.000005 and 0.0005 m^2•K/W (Cengel, Cimbala, & Turner, 2012).

Heat transfer to or from an object will cause the object to increase or decrease in temperature. Let the ratio between the amount of heat transferred and the corresponding change in the temperature of the object be given by the heat capacity *C*, defined as

$$C = \frac{\Delta Q}{\Delta T} \tag{4}$$

where ΔQ is the amount of heat transferred to or from the system and ΔT is the resultant change in temperature.

Heat capacity is an extensive property, meaning that the value of the property will vary with the amount of mass present in the system. A better measurement to use would be the specific heat capacity C_S, which is an intensive property that does not vary with the amount of mass present. The specific heat capacity can be calculated from the heat capacity by dividing by the mass *m* of the system.

$$C_S = C/m \tag{5}$$

Thus, combining eqs. (4) and (5), and rearranging,

$$\Delta Q = mC_S \Delta T \tag{6}$$

Caution should be taken when using this equation because the heat capacity, and thus the specific heat capacity, varies with temperature, so the range over with the temperature changes cannot be too large.

2.2.2 Refrigeration Systems

Three kinds of refrigeration systems that are available to consumers for refrigeration down to near 0°C are vapor-compression, absorption, and thermoelectric. Vapor-compression and absorption refrigeration both achieve cooling by circulating a refrigerant that absorbs heat from the cooled interior and expels heat to the surroundings using thermodynamic effects, while thermoelectric cooling makes use of the Peltier effect to remove heat from the cooled interior.

Vapor-Compression Refrigeration:

Vapor-compression refrigeration achieves cooling by circulating a refrigerant in a closed system through the vapor-compression refrigeration cycle, which consists of four distinct stages: compression, condensation, expansion, and vaporization.

Compression:

The refrigerant starts as a gas at relatively low pressure and low temperature, while occupying a high volume. The refrigerant is mechanically compressed, which results in a gas at higher pressure and occupying lower volume, while also raising the temperature of the refrigerant. Ideally, this process is isentropic, so that the pressure, volume, and temperature of the gas before and after the process are related by

$$P_1{V_1}^{\gamma} = P_2{V_2}^{\gamma} \quad (7a)$$

$$T_1{V_1}^{\gamma-1} = T_2{V_2}^{\gamma-1} \quad (7b)$$

$$T_1{P_1}^{\frac{1-\gamma}{\gamma}} = T_2{P_2}^{\frac{1-\gamma}{\gamma}} \quad (7c)$$

where γ is the heat capacity ratio and is strictly greater than 1. (See Appendix for a discussion on the heat capacity ratio.)

If the pressure of the gas is increased by some factor A, then the volume of the gas gains a multiplier of $A^{-1/\gamma}$. That is,

$$If\ P_2 = AP_1\ , \qquad then\ V_2 = A^{-\frac{1}{\gamma}}V_1$$

$$P_2{V_2}^{\gamma} = AP_1\left(A^{-\frac{1}{\gamma}}V_1\right)^{\gamma} = AP_1A^{-1}{V_1}^{\gamma} = P_1{V_1}^{\gamma}$$

and eq. (7a) is recovered. If the pressure of the gas is increased by some factor A, then the temperature of the gas gains a multiplier of $A^{(1-1/\gamma)}$.

$$If\ P_2 = AP_1\ , \qquad then\ T_2 = A^{\left(1-\frac{1}{\gamma}\right)}T_1$$

$$T_2{P_2}^{\frac{1-\gamma}{\gamma}} = A^{\left(1-\frac{1}{\gamma}\right)}T_1(AP_1)^{\frac{1-\gamma}{\gamma}} = A^{\left(\frac{\gamma-1}{\gamma}\right)}T_1A^{\frac{1-\gamma}{\gamma}}{P_1}^{\frac{1-\gamma}{\gamma}} = T_1{P_1}^{\frac{1-\gamma}{\gamma}}$$

and eq. (7c) is recovered. Note that because the heat capacity ratio γ is strictly greater 1, as long as the pressure increase factor A is greater than unity, the volume multiplier $A^{-1/\gamma}$ must be less than unity, and the temperature multiplier $A^{(1-1/\gamma)}$ must be greater than unity.

The compression stage increases the pressure and temperature of the gaseous refrigerant, while decreasing its volume.

Condensation:

The refrigerant enters the condensation stage with high pressure and very high temperature, while occupying a low volume. In the condensation stage, the refrigerant dissipates heat into the surroundings; it is able to do this because its temperature has been raised above ambient temperature by the previous compression stage. The pressure during this phase is constant, and is high enough that the saturation temperature of the refrigerant is raised to above ambient temperature. This saturation temperature manipulation is done so that by the end of the condensation stage, when the refrigerant is at a temperature equal to the ambient temperature, the refrigerant will have condensed from a gaseous state to a liquid state. This phase change is significant because the latent heat of vaporization of a fluid is much greater than the specific heat capacity of the fluid for any temperature change, so more heat will be transferred to the surroundings when the refrigerant is made to condense than if it just cooled but stayed in the gaseous phase. The amount of heat transferred to the surroundings due to the condensation phase change can be calculated by multiplying the latent heat of vaporization of the refrigerant by the mass of the sample. (See Appendix for a discussion on phase transitions.)

The condensation stage expels heat from the refrigerant to the surroundings, causing the initially gaseous refrigerant to condense into a liquid that is at the same initial pressure, but is at a lower temperature.

Expansion:

The refrigerant enters the expansion stage as a high pressure but low temperature liquid. The refrigerant passes through an expansion valve, which demarcates the boundary between the high pressure condensation stage and the low pressure vaporization stage, and undergoes Joule-Thomson expansion. The Joule-Thomson coefficient μ_{JT}, which governs whether the refrigerant will increase or decrease in temperature when passing from a high pressure to low pressure region, is given by

$$\mu_{JT} = \frac{V}{C_P}(\alpha T - 1) \tag{8}$$

where V is the initial volume, C_P is the heat capacity at constant pressure, α is the volumetric coefficient of thermal expansion, and T is the initial temperature of the gas. (See Appendix for a discussion on Joule-Thomson expansion.) With an appropriate choice of refrigerant and initial conditions, such that the Joule-Thomson coefficient is positive, the refrigerant will experience a decrease in temperature as the pressure decreases across the expansion valve. The refrigerant will leave the expansion stage as a liquid at even lower temperature and low pressure.

Vaporization:

The refrigerant enters the vaporization stage as a liquid at low pressure and very low temperature. The refrigerant is at a lower temperature than the cooled region, so heat will be transferred from the cooled region to the liquid refrigerant. The low pressure in this stage is maintained at a value such that the saturation temperature of the refrigerant is lowered to less than the temperature of the cooled region. The refrigerant will thus continue to absorb heat from the cooled region until the refrigerant has enough energy to vaporize. As in the condensation stage, because the latent heat of vaporization of most fluids is significantly greater than their specific heat capacity, the refrigerant will absorb more heat if it has to undergo a phase transition than if it were to only heat up but remain in the liquid phase. The refrigerant leaves the vaporization stage as a low pressure and low temperature gas and enters the compression stage, ready to repeat the cycle.

Absorption Refrigeration:

Absorption refrigeration, similar to vapor-compression refrigeration, circulates a refrigerant that is vaporized by heat transfer from the cooled region and uses a condensation stage to transfer heat out of the system into the surroundings. However, where vapor-compression refrigeration increases the internal energy of the refrigerant prior to the condensation stage by doing mechanical work on the system with a compressor, absorption refrigeration increases the internal energy by using a heat source to transfer heat to the system. Absorption refrigeration also requires an absorbent, which undergoes a cycle of its own.

In total, the refrigerant in absorption refrigeration is circulated through four stages: vaporization, absorption, separation, and condensation. The absorbent cycle has two stages – absorption and regeneration – which generally line up with the absorption and separation stages in the refrigerant cycle, respectively, although additional processing may be needed. Two different designs for the absorption refrigeration system will be described below, corresponding to two common refrigerants: water and ammonia.

Water-Based Absorption Refrigerator:

In this model, water acts as the refrigerant and lithium bromide (LiBr), or rather, a solution of LiBr in water, is the absorbent.

Vaporization:

The water starts as a liquid at a temperature which is below that of the cooled region; e.g. 5°C and 7°C, respectively. Heat is thus transferred from the cooled region to the colder water. Meanwhile, the pressure inside the vaporization chamber is maintained at 0.87 kPa. At this pressure, the saturation temperature of water is precisely 5°C, so that any heat transferred to the water will cause water molecules to vaporize, which cools the remaining liquid water because the now gaseous molecule is carrying energy away. The amount of energy the evaporated molecule carries away is equivalent to the latent heat of vaporization.

Absorption:

Gaseous water vapor leaves the vaporization stage and enters the absorption stage. Here, the water vapor condenses into an aqueous solution of lithium bromide (LiBr). This LiBr solution is actually what causes the pressure in the previous vaporization stage to be a constant 0.87 kPa. Aqueous LiBr has a saturation pressure that is dependent on concentration and temperature. At 50% concentration and 25°C, the LiBr solution has a saturation pressure of 0.87 kPa, which means the solution will be in phase equilibrium with water vapor with a vapor pressure of 0.87 kPa. Water that vaporizes in the vaporization stage will increase the water vapor vapor pressure, which causes the water vapor to condense into the LiBr solution. If more or less water vapor than steady-state operation is vaporized, the LiBr solution will correspondingly absorb more or less water vapor such that the water vapor pressure equals its saturation pressure.

Of course, the condensation of water vapor into the LiBr solution will tend to dilute and heat up the solution, causing the saturation pressure to vary. However, in the absorption refrigerator, “fresh” LiBr solution at the correct concentration and temperature is continually being added to the LiBr chamber, and the warmer, diluted LiBr solution is pumped away, meaning that the LiBr solution will maintain the constant saturation pressure of 0.87kPa.

In summary of the vaporization and absorption stages, water enters the vaporization chamber at 5°C, where heat transferred from the cooled region causes the water to vaporize. The water vapor travels to the absorption chamber, where the water vapor condenses into the LiBr solution. The diluted and heated-up LiBr absorbent solution is pumped away to the separation stage, while LiBr solution at correct concentration and temperature is pumped in simultaneously.

Separation and Regeneration:

The diluted LiBr solution enters this stage from a pump, which is necessary because the pressure in this stage is greater than the pressure in the previous absorption stage. Heat is applied to the diluted LiBr solution, which causes a portion of the water to vaporize, restoring the LiBr solution to correct concentration. Thus, the cycling water refrigerant is separated from the water that is part of the LiBr absorbent solution, and leaves the separation stage as water vapor.

Meanwhile, to complete the regeneration stage of the absorbent, the LiBr solution passes through an expansion valve and undergoes Joule-Thomson expansion, where the pressure decrease from the higher pressure separation stage to the lower pressure absorption stage causes the temperature of the LiBr solution to decrease. The LiBr absorbent solution, now at both correct concentration and temperature, reenters the absorption stage.

Condensation:

The water vapor from the separation stage enters the condensation stage at a relatively high temperature, while maintaining the pressure from the separation stage. Heat is transferred to the surrounding ambient air because the temperature of the water vapor is greater than the ambient air temperature. As with the condensation stage for vapor-compression refrigeration, the saturation temperature of the water vapor has been manipulated so that it is below the ambient air temperature, so that the water vapor will have condensed into liquid water by the end of the condensation stage and given off heat equal to the latent heat of vaporization times the sample mass. Note that because the saturation temperature of water is 100°C at 1 atmosphere (atm) of pressure, the pressure in the condensation stage must be lower than 1 atm so that the saturation temperature is near room temperature – i.e. lower than 100°C – despite being the relatively high pressure in the refrigerant cycle.

The refrigerant water is now in a liquid state, but is still at room temperature and at a higher pressure than the vaporization stage. The liquid water thus also goes through an expansion valve and undergoes Joule-Thompson expansion, where the decrease in pressure from the condensation stage to the vaporization stage causes a decrease in the temperature of the liquid water. The refrigerant water has now been restored to 5°C and 0.87 kPa again and completes the refrigerant cycle by reentering the vaporization stage.

Ammonia-Based Absorption Refrigerator:

In this model, ammonia is the refrigerant and water is the absorbent. The entire cycle is operated at a constant pressure, which precludes the inclusion of pumps and expansion valves. In addition, hydrogen gas plays an important role in the vaporization stage.

Vaporization:

Ammonia enters the vaporization stage as a room temperature liquid, which will cool to the desired temperature through evaporative cooling. This is achieved by manipulating the partial pressure of the ammonia gas in the vaporization chamber so that the partial pressure is lower than the saturation pressure of the incoming liquid ammonia. In an isolated system, this would cause liquid ammonia to vaporize and cool until the partial pressure of the gaseous ammonia has been raised to be equal to the saturation pressure of the cooling liquid ammonia. However, because the ammonia gas is constantly being absorbed out of the gas mixture, the partial pressure of ammonia gas will remain constant, so the liquid ammonia will continue to vaporize and cool until the rate of heat transfer into the liquid ammonia from the cooled region is equal to the rate of heat transfer out of the liquid ammonia due to vaporization. (See Appendix for a discussion on partial pressure and its relation to vaporization.)

Manipulation of the partial pressure of ammonia gas is accomplished by adding hydrogen gas to the vaporization chamber at construction. Hydrogen gas does not dissolve in liquid ammonia and thus forms a mixture with the ammonia gas in the space above the liquid, which causes the partial pressure of the ammonia gas to be some fraction of the total pressure. Meanwhile, the liquid ammonia entering the vaporization stage is in phase equilibrium with itself, meaning that its saturation pressure is equal to the total pressure. Thus, the partial pressure of ammonia gas must be less than the saturation pressure of the incoming liquid ammonia.

The gaseous ammonia leaves the vaporization stage in a mixture with the hydrogen gas.

Absorption:

The ammonia-hydrogen gas mixture travels to the absorption chamber, where a weak solution of ammonia in water acts as the absorbent. Ammonia gas dissolves in water, while hydrogen gas does not. The hydrogen gas is thus free to flow back to the vaporization chamber, while the now more concentrated ammonia solution flows to the separation stage.

Separation and Regeneration:

Heat is applied to the strong ammonia solution, which causes a portion of the ammonia in solution to vaporize. Meanwhile, the water does not vaporize, because it has a higher saturation temperature than ammonia, as can be seen from the fact that water is a liquid at room temperature and atmospheric pressure, but ammonia is a gas. The hot pure ammonia gas flows to the condensation stage, while the regenerated water absorbent returns to the absorption stage.

Condensation:

The ammonia gas from the separation stage enters the condensation stage at high temperature. Heat is transferred to the surrounding ambient air because the temperature of the ammonia gas is greater than the ambient air temperature. As with the previous condensation stages, the saturation temperature of the ammonia gas has been manipulated so that it is below the ambient air temperature, so that the ammonia gas will have condensed into liquid ammonia by the end of the condensation stage and given off heat equal to the latent heat of vaporization times the sample mass. Note that because ammonia is a gas at ambient temperature and 1 atm pressure, the pressure in the condensation stage must be greater than 1 atm so that the saturation temperature is near room temperature.

Thermoelectric Cooling:

Thermoelectric cooling uses the Peltier effect to transfer heat from the cooled region to the surroundings, rather than thermodynamic effects. The Peltier coefficients for a semiconducting material give the energy transported per unit charge. (See Appendix for a discussion on Peltier coefficients.)

$$\Pi_e = -\left(E_C - \mu + \tfrac{3}{2}k_B T\right)/e \tag{9a}$$

$$\Pi_h = \left(\mu - E_V + \tfrac{3}{2}k_B T\right)/e \tag{9b}$$

where Π_e is the Peltier coefficient for electrons and Π_h is the Peltier coefficient for holes. Note that Π_e is strictly negative so that negatively charged electrons carry positive energy. Thus, a simple thermoelectric cooler can be constructed by connecting an n-doped, electron-filled, semiconductor and a p-doped, hole-filled, semiconductor in series.

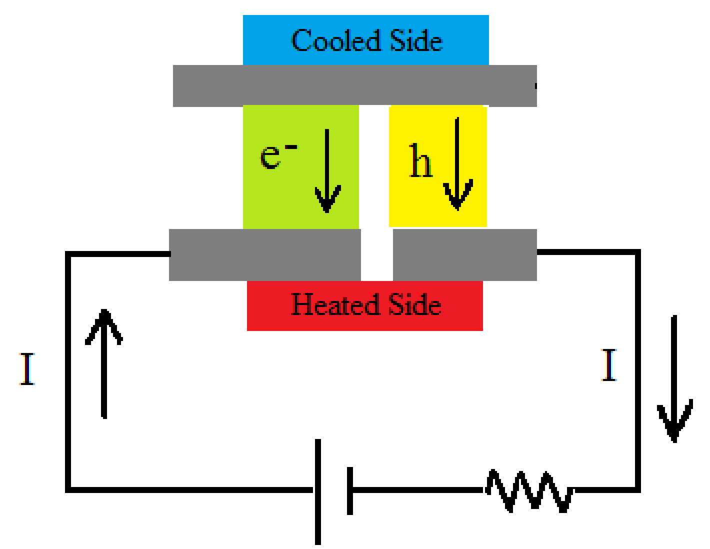


Figure 1: A simple thermoelectric cooling circuit. An applied voltage causes current to flow in a clockwise direction, as shown. The circuit is arranged so that the holes and electrons, which travel with and against the direction of current flow, both transport heat in the same direction.

The rate of heat transfer can be calculated by multiplying the Peltier coefficient of the charge carrier Π by the current I, since Π is energy per charge and I is charge per time.

$$\frac{dQ}{dt} = \Pi * I \tag{10}$$

The rate of heat transfer from the cooled side can be calculated by summing the rates of heat transfer due to current flowing in and current flowing out.

$$\frac{dQ}{dt} = (\Pi_e * I) - (\Pi_h * I) = (\Pi_e - \Pi_h) * I \tag{11a}$$

The same calculation can be done to determine the rate of heat transfer to the heated side

$$\frac{dQ}{dt} = (\Pi_h * I) - (\Pi_e * I) = (\Pi_h - \Pi_e) * I \tag{11b}$$

where the result is equal but opposite to eq. (11a), as it must. Thus, recalling that Π_e is strictly negative, the net rate of heat transfer from the cooled side to the heated side for a simple thermoelectric cooler is

$$\frac{dQ}{dt} = (|\Pi_e| + \Pi_h) * I \tag{11c}$$

2.3 Passive Temperature Control Analysis:

I started by determining the rate of conductive heat transfer into an insulated container, with the goal being to determine if a solution that did not require power to operate was feasible. A secondary objective was to see determine if such a design could be easily portable, as an added benefit of not needing to be plugged in to power to operate. The interior is taken to be a cold reservoir at some temperature and the air far away from the container is a hot reservoir at some higher temperature. A layer of insulation of variable thickness and an outer casing of some material separate the cold reservoir from the hot reservoir, while a layer of packaging prevents the insulation from directly touching the cold reservoir. Lastly, a buffer layer of air is assumed to exist on the exterior of the outer casing. (See Figure 2)

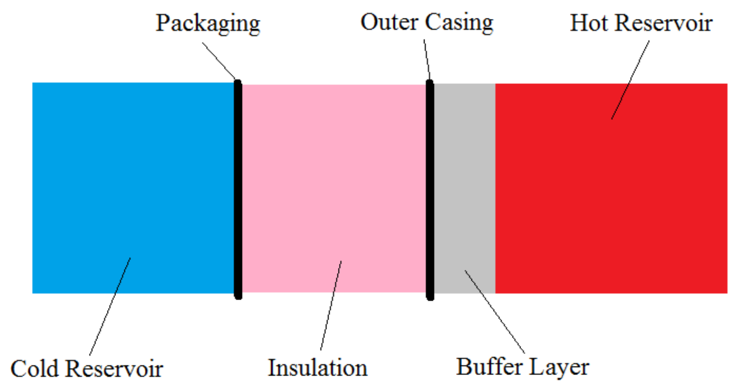


Figure 2: Heat conduction diagram showing the layers of the wall for the model insulated container. Not to scale.

There are four layers of interest, each with its own thermal resistance, as given by eq. (2). Since they are conducting heat in series with each other, the thermal resistances can simply be summed to obtain the total thermal resistance, then used with eq. (3) to solve for the net rate of heat transfer into the container.

$$R_{tot} = R_{pack} + R_{insulation} + R_{casing} + R_{buffer}$$

Determination of the thermal resistance of a layer requires the thermal conductivity for the material that makes up the layer, the thickness, and the area normal to the direction of heat transfer for the layer. In this particular model, high-density polyethylene (HDPE) was used for the packaging and outer casing layers, in order to simulate a standard compact refrigerator. The thicknesses of those two HDPE layers were estimated to be ~1 cm. Standard foam insulation was used for the insulation layer, where the thickness ℓ was intentionally left as a variable. The thickness of the buffer layer was also approximated to be ~1 cm. The thermal conductivities were found online on various engineering webpages. As for the area, the assumption was made that the container was a cube of side length 0.5 m. By summing up the five faces that are exposed to the air, a total area of 1.25 m^2 was obtained.

Material	Thermal Conductivity (k) (W/m•K)	Thickness (L) (m)	Area (A) (m^2)	Thermal Resistance (R) (K/W)
HDPE	0.45 [a]	0.01	1.25	0.018
Foam Insulation	0.029 [b]	ℓ x10^{-2}	1.25	0.28 ℓ
HDPE	0.45 [a]	0.01	1.25	0.018
Air	0.025 [c]	0.01	1.25	0.32
			Total Thermal Resistance	0.356 + 0.28 ℓ

Table 1: Calculation of the total thermal resistance of the model insulated container as a function of the insulation thickness ℓ, given in centimeters.
Thermal conductivity values retrieved from: HDPE (Goodfellow, n.d.); foam insulation (Owens Corning, 2011); air (Engineering Toolbox, The., n.d.).

Using this expression for the total thermal resistance, I was able to calculate the rate of heat transfer into the insulated container as a function of the thickness of the insulation layer using eq. (3), where T_1 = 22°C, the average summer temperature in Ohio (Current Results, n.d.), and T_2 = 2°C, in the middle of the range for FDA recommended refrigerator temperatures (FDA, 2018).

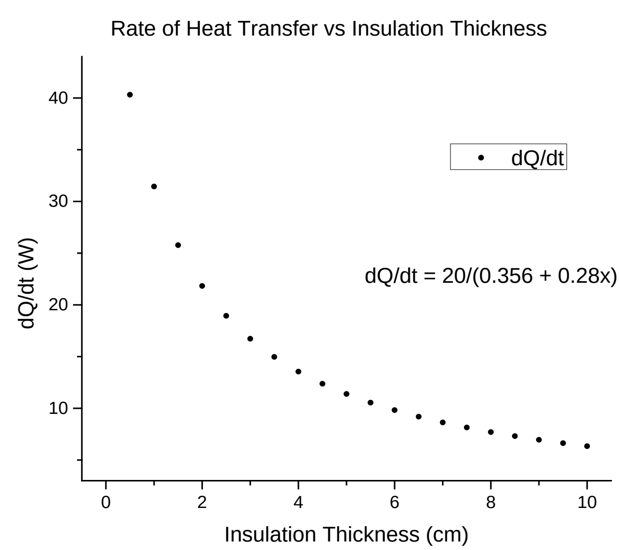


Figure 3: Graph showing the relationship between the rate of heat transfer and the insulation thickness. Note that due to the 1/ℓ behavior of the *dQ/dt* function, the first few centimeters of insulation have the most effect on reducing the rate of heat transfer.

Insulation Thickness (ℓ) (cm)	1	3	5	7	10
Rate of Heat Transfer (dQ/dt) (W)	31.4	16.7	11.4	8.6	6.3

Table 2: Rate of heat transfer into the model insulated container, calculated for various insulation thicknesses.

The thermal contact resistance was not taken into account in calculating the rate of heat transfer because average values for thermal contact resistance are on the order of 10^{-5} m^2•K/W, which when multiplied by the contact areas results in thermal resistances several orders of magnitude smaller than the existing thermal resistances.

Having determined the rate of heat transfer into the cold reservoir of an insulated container, the duration that the container could maintain that internal temperature can be calculated. Suppose that the cold reservoir was simply a layer of some cold fluid, such as water, a common fluid with a high specific heat capacity. The length of time the water could maintain a certain temperature can be approximated by treating the rate of heat transfer as roughly constant over the range of temperature change and using eq. (6).

$$\Delta Q = mC_S \Delta T \qquad (6)$$

The mass of the water can be determined simply by setting the thickness of the layer, then multiplying by the total area and density of water. A 1 cm thick layer of water of density 1000 kg/m^3 in the 0.5 m side length cubic insulated container would have a mass of 15 kg. The specific heat capacity of water is 4.22 kJ/kg•K at 2°C, so that the amount of heat required to raise the temperature of the 1 cm thick layer of water by 1°C is 63.3 kJ.

Insulation Thickness (cm)	Rate of Heat Transfer (W)	Time (hour)
1	31.4	0.56
3	16.7	1.05
5	11.4	1.54
7	8.6	2.04
10	6.3	2.79

Table 3: Time needed to raise the temperature of 15kg of water by 1°C, calculated using the rates of heat transfer, for various insulation thicknesses, into the model insulated container as described above at exterior and interior temperatures of 22°C and 2°C, respectively. Rates of heat transfer obtained from Table 2.

Since the recommended refrigeration range is from 0°C to 4°C, the water temperature can vary from 0°C to 4°C and still be within regulations. The rate of heat transfer would vary depending on the temperature of the water, but the average would be the rate of heat transfer for the water at 2°C, so the amount of time the water would stay within recommended temperatures can be calculated by simply multiplying the time values in Table 3 by four.

Thus, in order for an insulated container of side length 0.5 m with a 1 cm thick layer of cooling water to be able to stay within recommended temperatures for at least 8 hours, the insulation must be at 7cm thick. However, there are several issues with this approach that rule it out. First, 7 cm of insulation occupies a significant amount of space in a 0.5 m wide cubic container, taking up over 60% of the space inside. Second, 15 kg of cooling water would be comparable in weight to the average compact refrigerator, and significantly heavier than the bulkiest portable coolers. Moreover, the water would need to be chilled eventually to allow for reuse, which would require that the container be moved between desired placement and a location with power, or be kept in a location with power. If the former, then the weight is significant; if the latter, then there is little benefit to creating a solution that does not need power to operate.

Lastly, to address the impact of convection on the rate of heat transfer. The concept of the buffer layer of air comes from the concept of the thermal boundary layer, which is the layer of air that flows slower next to the surface of an object due to the "no-slip" condition. However, that thermal boundary layer does not seem to be separately taken into account when dealing with heat transfer via convection. The thermal resistance for convection is given by the inverse of the product of the heat transfer surface area and the convection heat transfer coefficient h_C. However, this quantity is dependent on the geometry of the surface. Fortunately, h_C can be calculated from the dimensionless Nusselt number, which describes how much convection increases heat transfer through a fluid layer over conduction. The Nusselt number itself is calculated as function of the Reynolds and Prandtl numbers, depending on whether the flow is laminar or turbulent.

$$Nu = \frac{h_C L}{k} = \begin{cases} 0.664\, {Re_L}^{0.5} Pr^{1/3}\,; & Re_L < 5 \times 10^5 \\ (0.037\, {Re_L}^{0.8} - 871) Pr^{1/3}\,; & 5 \times 10^5 < Re_L < 10^7 \end{cases} \qquad (12)$$

where the Prandtl number Pr is determined experimentally and can be found in the literature, and the Reynolds number Re_L is calculated by

$$Re_L = \frac{VL}{\nu} \qquad (13)$$

where V is the velocity of the fluid, L is the length of the flat surface, and ν is the kinematic viscosity. For air at 22°C, $\nu = 1.5 \times 10^{-5}$ m^2/s. Let the wind speed be 10mph, which corresponds to 4.5 m/s. L is 0.5 m for the 0.5 m side length container. The Reynolds number is then $Re_L = 1.5 \times 10^5$, which is less than 5×10^5, so the laminar equation is used. The Prandtl number for air at 20°C is 0.73, so the Nusselt number is then 232. The thermal conductivity of air is 0.025 W/m•K, from above, which allows for the calculation of h_C = 11.6 W/m^2•K. Since the thermal resistance for convection is 1/$h_C A$, R = 0.07 K/W. This thermal resistance would replace the thermal resistance for the buffer layer, causing the total thermal resistance to decrease to 0.105 + 0.28x. The rate of heat transfer for x = 1 cm would then be 52W, a 66% increase from 31.4W. The impact is less noticeable for greater insulation thickness, however; for x = 10cm, the rate of heat transfer is only 6.88W, a less than 10% increase.

2.4 Active Temperature Control Analysis:

After determining that an insulated container that did not require electricity to maintain cool temperatures did not work, I had to turn toward a powered container. However, I still wanted to maintain the portability, or at freedom of placement, for the container, so I looked into power sources that were not simply plugging the container into a wall outlet, such as batteries, super capacitors, or solar cells. Furthermore, since the container is now actively cooled, I also looked into the three refrigeration techniques: vapor-compression, absorption, and thermoelectric.

Initial research into the three refrigeration techniques turned up a value called the Coefficient of Performance (COP), which is defined as the ratio between the useful cooling energy and the work input; that is, the ratio of heat transferred away from the cooled region to the amount of energy input needed to transfer that amount of heat away (Cengel, Cimbala, & Turner, 2012).

$$COP = \frac{Q_{cooling}}{W_{input}}$$

although a more useful form can be derived by solving for W_{input} and differentiating both sides with respect to time.

$$P_{input} = \frac{dQ/dt}{COP} \tag{14}$$

where P_{input} is the power input required from the electrical power source to dissipate the rate of heat transfer into the cooled region through the walls *dQ/dt*. The COP varies between different refrigerator models, but average values for the COP of the three refrigeration techniques were discovered upon further research.

Figure 4: Graphic showing average coefficients of performance for vapor-compression and absorption refrigerators, and thermoelectric coolers, from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (as cited in Singh et al., 2015; Shaikh & Chopra, 2014)

Using the rate of heat transfer values calculated in the previous Passive Temperature Control Analysis section – specifically, the 11W value for 5 cm thick insulation – in conjunction with eq. (14), the average required power for each refrigeration technique was calculated.

Refrigeration Technique	Coefficient of Performance	Required Power Input (W)
Vapor Compression	1 – 3	3.7 – 11
Absorption	0.2 – 0.3	37 – 55
Thermoelectric	0.1 – 0.2	55 – 110

Table 4: Average power input required to dissipate 11W of heat, calculated for each of the three refrigeration techniques. Coefficients of performance obtained from Figure 4.

Of the three refrigeration techniques available, thermoelectric was almost instantly eliminated as a possibility, for several reasons, not the least of which being its poor coefficient of performance. Thermoelectric is also severely limited in terms of maximum rate of heat transfer; a survey of existing thermoelectric coolers showed that most could only cool 30 – 40°F (17 – 22°C) below ambient temperature, so the container would be unusable on even mildly hot days (TheCoolerZone, n.d.).

When researching possible power sources, whether the power source would be able to supply the necessary power was the first consideration, followed closely by the capacity of the power, or how much energy the power source stored, which determines how long the power source could power the container. For example, the average car battery outputs 12.6 V, with the power output depending on the current output. However, because resistive heating of a circuit element is proportional to the square of the current, a high current output would cause significant amounts of energy to be converted to heat, which effectively imposes an efficiency limit on the current output. A general rule of thumb is that the maximum efficient current output is equal to the amp-hour rating of the battery divided by ten hours; in other words, the maximum efficient current is the current such that the battery discharges fully in 10 hours (University of Hawaii Ham Club, 1999).

The average car battery is rated for 45 amp-hours, meaning the maximum efficient current output is 4.5 A, as above, so the maximum power output is 4.5A * 12.6V = 57 W, which by definition can be sustained for 10 hours. This is enough power to enable any of the three refrigeration techniques, and 10 hours is a long enough operating time.

Solar cells are a popular option for providing electricity, since there is technically no limit on how much energy the solar cell can supply, as it is essentially powered by the sun. There is, however, a limit on how much power can be outputted. An estimate of power output can be calculated from the average solar irradiance – the power per unit area the sun provides – times the average efficiency of a solar cell. The average solar irradiance is 1000 W/m^2, while the average solar cell efficiency is 15% (Murmson, 2017), leading to a power output of 150 W per square meter of solar cells, for normally incident sunlight. Assuming that the solar cells are mounted on the walls of the container – i.e. not a separate unit placed elsewhere – then for the 0.5 m side length cubic container, the maximum normal area that can be exposed to sunlight is 0.35 m^2 (Weisstein, n.d.), so the maximum power output from a solar cell would be 53 W. The minimum power output, assuming the container is fully illuminated, would be 37.5 W. This power output range is more than enough for vapor-compression refrigeration and potentially enough for absorption refrigeration.

At this point, I realized that there was one important issue I had overlooked with refrigerators: they do not operate continuously, but instead cycle on and off. As such, the power output required of the power source increases many-fold. Fortunately, it appeared that vapor-compression is efficient enough that even a five-fold increase in power input required can be handled by both the simple car battery and solar cells. Comparison to existing models of compact refrigerators that use vapor-compression cooling supported the notion that the power input required would be manageable: Dometic sells a portable compact refrigerator that runs on 36 – 48 W (WAECO USA, n.d.).

However, there are issues with both the battery and solar cell solutions. The battery shares the same issue with the passive cooling approach; eventually, it will need to be recharged, at which point the 40 lb car battery will need to be moved around or a cord pulled over, which defeats the purpose of not needing to be plugged in. Meanwhile, the effectiveness of solar cells as a power source is dependent on the amount of sunlight striking the surface of the container. This precludes the placement of the container in any shaded area, and places the usability of the container at the mercy of the weather. Even with a backup battery, consecutive days of cloudy weather would ensure that the power runs out.

Up to this point, I had sought a design to maintain the portability of the device, but neglected to prioritize designing a reliable and convenient-to-use solution to the actual problem. After all, the need is for a device that maintains refrigerator temperatures for some minimal amount of time when operated outdoors; portability was a feature that would have allowed consumers to use the device as portable cold storage in addition to its original use as a grocery-receiving container. As such, I realized that while I was avoiding a design where the device would need to be plugged into a wall outlet, to increase portability, that design may be the best design. Obtaining power from a wall outlet does not carry the output power and energy capacity concerns that the battery and solar cell designs did, which also means that the device can maintain refrigeration temperatures indefinitely.

As for which refrigeration technique to use, vapor-compression is the clear choice. Even though the design does not have to take into consideration limited input power and energy capacity, there is no reason to not use the most efficient refrigeration technique. Thermoelectric coolers are limited in their ability to cool beyond a certain temperature difference, while the main advantage absorption refrigeration has over vapor-compression is that absorption refrigeration can be used in situations where electricity is limited or unavailable, but that is not likely a situation faced by the intended consumers. The main downside to vapor-compression refrigeration is the amount of noise created by the compressor. However, given that the device will be used outside, noise is not a concern, at least not on the level as when a vapor-compression refrigerator is used indoors.

2.5 Conclusions:

I started by determining whether a passively cooling container, akin to an icebox, would be feasible. Heat transfer analysis showed that a 1 cm layer of cold water can maintain recommended refrigeration temperatures for 8 hours in a 0.5 m cubic container insulated with a 7 cm thick layer of foam insulation. When accounting for convective heat transfer, an 8 cm thick insulation layer is required. However, this passive design had undesirable flaws: the thickness of the insulation limited the storage capacity, the weight of the cooling water limited the portability, and the fact that the cooling water would need to be chilled to reuse the device limited options for placement. All of these factors also reduce convenience for the consumer, which is one of the main selling points of this device.

Meanwhile, an actively cooled container, powered by non-electrical outlet sources, seemed promising, Even when taking into account the fact that vapor-compression refrigerators, operating with the refrigeration method with the highest coefficient of performance, do not cool continuously, but rather cycle on and off, both battery and solar cell solutions were able to generate the amount of power required for at least 8 hours. However, there were still issues with both solutions. With batteries, the weight and need to eventually recharge to reuse presented the same issues as with the passively cooling water. With solar cells, the weather- and placement-dependence of the power source meant that many scenarios where the device would be unusable or unreliable presented themselves.

Thus, the final design of the device is an insulated container that maintains internal temperature using vapor-compression refrigeration, powered by a corded connection to an electrical outlet.

2.6 Further Considerations:

The final design is essentially a compact refrigerator, but it is not as easy as simply taking an existing compact refrigerator and using it outside. There are a few concerns when operating a vapor-compression refrigeration system outdoors. Chiefly among them is that in order for the condensation stage in the vapor-compression cycle to be able remove heat from the refrigerant to the surroundings, the ambient air temperature needs to be lower than the refrigerant temperature; moreover, in order for the refrigerant to condense properly, the ambient air temperature needs to be lower than the saturation temperature. In both cases, if the ambient air temperature is too high, the vapor-compression will cease to work. Installation guides for compact refrigerators that use vapor-compression systems will usually say that the appliance is "intended for household use only" and "not designed for outside installation, including anywhere that is not temperature controlled (garages, porches, vehicles, etc.)" (Danby Products Inc., 2017).

However, this does not mean that it is impossible to use a vapor-compression system outdoors. One possible solution would be to increase the amount by which the refrigerant is compressed in the compression stage; this would increase both the temperature and the pressure, and therefore the saturation temperature, of the refrigerant. The fact that outdoor refrigerators exist shows that it is doable. The Dometic CDF-11 Portable Freezer/Refrigerator user manual states that the "refrigerator is designed to operate in ambient temperatures between 14° - 120°F" (WAECO USA, n.d.), or -10° - 49°C, which covers most non-extreme outdoor temperatures. ARB USA manufactures an "Elements Weatherproof Fridge Freezer" that can be used "in the bed of a pickup" or "the stern of your boat" (ARB USA, n.d.). Both of these offerings are fairly expensive, though, from $450 to $1450, so whether it can be made cheaper will have to be explored.

In order for the device to maintain internal temperature year-round, there also needs to be a heating element to warm the interior when the exterior is below recommended refrigeration temperatures. Without going into specifics, this can be easily taken care of using some form of resistive heating and some mechanism for evenly distributing the heat, in the manner of a hair dryer, perhaps.

Other concerns include corrosion of metal surfaces and pipes, direct exposure to sunlight causing heating of the refrigerator, and dust or pollen accumulating on the condenser coils or fins, which impacts the efficiency of the condenser.

3. Business/Market Analysis

3.1 Introduction:

In this section, I will analyze the value and market potential of using the outdoor refrigerated container as a means of receiving grocery deliveries. I will also explore the smart compact refrigerator market as a potential market for the device.

3.2 Grocery Reception Market Analysis:

The analysis of the grocery reception market I will present in this section will proceed in a linear fashion by exploring three related topics: the supply and availability of grocery delivery services by grocery stores and service providers, the demand and use of these grocery delivery services by consumers, and whether consumers would purchase the proposed grocery-receiving container. Each question is dependent on a positive response to the previous question, because a grocery-receiving container will not be purchased if no groceries are being delivered, and no groceries can be delivered if there is no grocery delivery service.

To address the first topic of the supply and availability of grocery delivery services by grocery stores and service providers, information was gathered on the current state of the grocery delivery market. According to IBISWorld (2018a; 2019), online grocery sales revenue totaled $26bn in the U.S. in 2018, which is about 4% of the $634bn in grocery sales revenue from the same year. While it is unclear whether this comparison is entirely valid – because the grocery sales revenue statistic is for the Supermarkets and Grocery Stores industry, which may not include the grocery sales revenue of Amazon, as it is unlikely to be categorized as a supermarket or grocery store – statistics from other sources echo similar market share values. GlobalData (n.d.) notes that the market share of online grocery sales is 5.5%, a figure backed up by Grocery Shopper IP (2018). Meanwhile, Pamela Danziger, Forbes contributor, quotes similar statistics in an article from Jan. 2018 – “estimates of online grocery’s market share of the total $641b U.S. grocery market vary, from 2% to 4.3%” (2018) – and although she does not explicitly provide a source for this information, Jeff Daniels, CNBC writer, does cite a joint report by the Food Marketing Institute and Nielsen for the 4.3% market share statistic (2017).

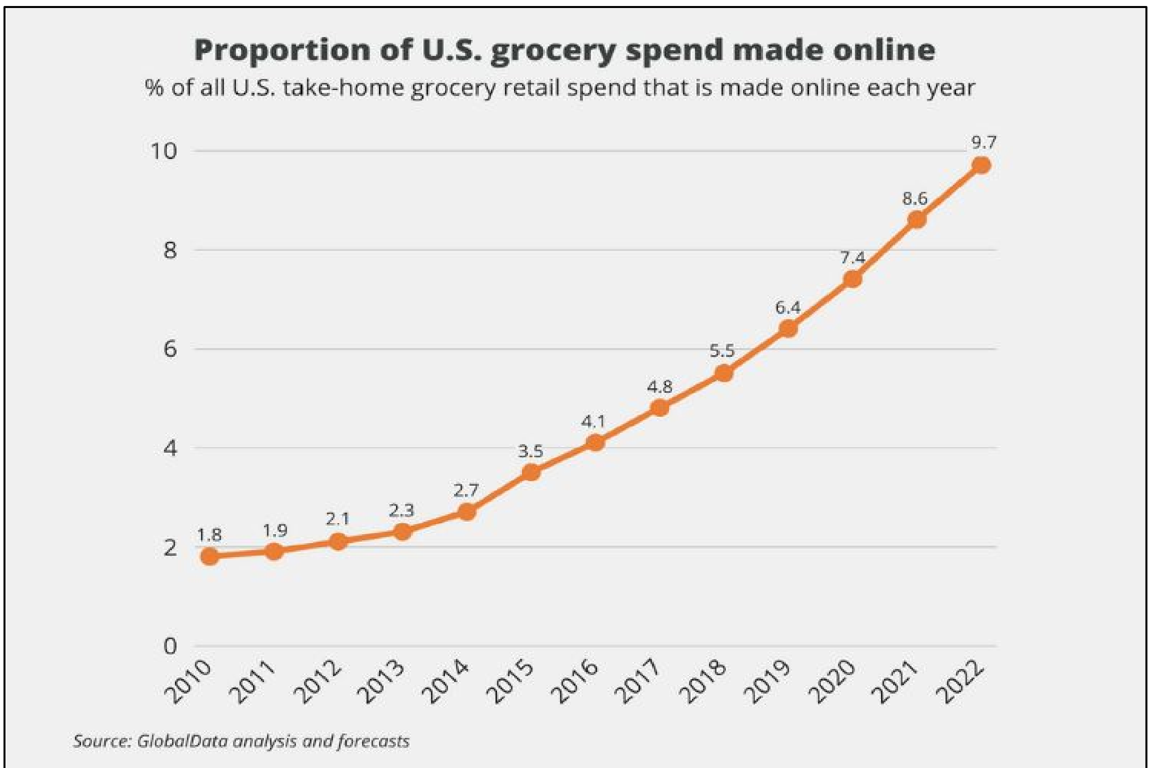


Figure 5: Graph showing the slow but steady growth of online grocery sales as a fraction of the total grocery market. Note that values from 2019 on are predictions. (GlobalData, n.d.)

Despite the online grocery market currently being a relatively small fraction of the total grocery sales market, it has already surpassed expectations in terms of growth, and is expected to significantly increase as well. A 2012 forecast of online grocery sales revenue predicted that the 2018 revenue would be $17.5bn (PitchBook, 2017); as shown in the preceding paragraph, the actual 2018 revenue is about 50% more than the predicted value. As for future growth, the FMI-Nielsen report expects online grocery revenues to grow to $100bn by 2022 (n.d.), while Business Insider Intelligence predicts $92bn in revenue in 2022 (n.d.). These predictions equate to compounded annual growth rates (CAGR) of 40% and 37%, respectively, which are extremely high and optimistic predictions, considering that the average percent growth over the past five years has been only 13.5%, with a peak of 25% for 2015-16 (IBISWorld, 2018a). Brick Meets Click agrees with this more grounded figure, predicting that "online grocery sales will grow 13% as compared to 1.3% for in-store sales," causing the online grocery market share of total grocery sales to grow to "over 8% by the end of 2022" (Bishop, 2018). GlobalData (n.d.) predicts a slightly higher market share of 9.7% in 2022, while Progressive Grocer (2017) predicts that the market share will have reached 10% by as early as 2020. However, because the Progressive Grocer predictions were made in 2016, a particularly high growth year, the annual growth rates were skewed towards the more optimistic side, with an annual growth rate of 40% in 2018 and 2019. Overall, the online grocery market is expected to grow at an annual rate of at least 13%.

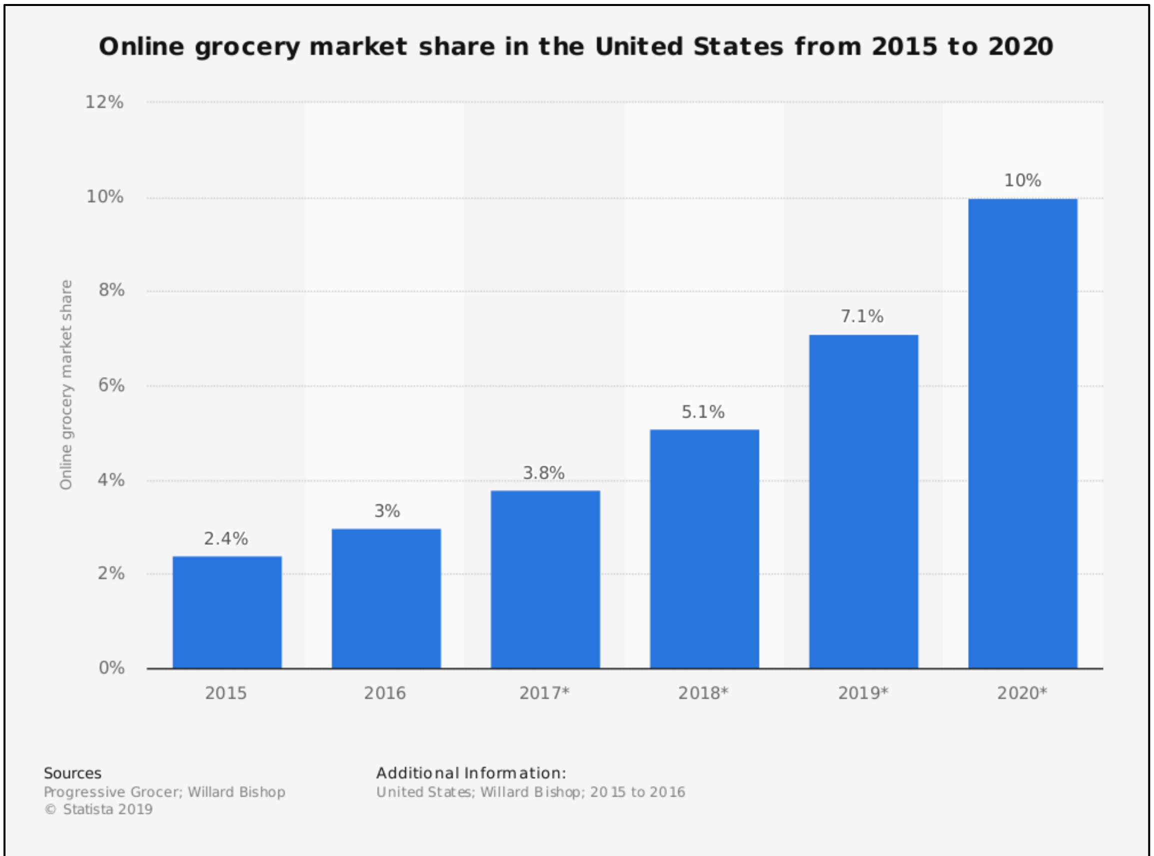


Figure 6: Chart showing the anticipated online grocery market share for 2017-2020, as predicted in 2016. Note the anticipated % growth for 2018-2019 (40%) and 2019-2020 (43%). (Progressive Grocer, 2017)

There is a caveat to the above figures for revenue, however, because the actual grocery delivery market is a subset of the online grocery sales market. All of the above information applies to the online grocery sales market as a whole, which makes no distinction about how and where the groceries are turned over to the consumer. Ordered groceries may be delivered to consumers via a grocery delivery service, but they may also be only collected and packed to be picked up by the consumers themselves at a physical store in a process called curbside pickup or click-and-collect. Meal kits – pre-portioned ingredients that are transported in temperature-controlled packaging from warehouses via common package carriers such as Fedex and UPS, and thus differ from grocery delivery – are also included in online grocery sales. Thus, the revenue numbers above would need to be adjusted to reflect the actual size of the grocery delivery market. Very little information was available about the division of the online grocery sales market into these sub-sections, aside from a sidebar from Brick Meets Click noting that “providers that offer delivery and pickup are expected…to grow their online sales 25% and 30%” (Bishop, 2018), which is twice the annual growth rate for the online grocery sales market as a whole.

One of the major contributing factors for the growth of online grocery sales and grocery delivery is the amount of investment by big players like Amazon, Walmart, and Kroger. In June of 2017, Amazon acquired Whole Foods for $13.7bn, a move that “spooked the industry” (Soper, 2018) because Amazon now has physical stores from which it can send out deliveries and accept returns. In a contemporary analysis of the acquisition, Gartner notes that the acquisition was very likely because “Amazon wants to extend its presence in grocery delivery, a market whose 4.3% online shopping share indicates it is ripe for disruption” (Yockelson & Hetu, 2017). Since Amazon is an online retailing giant, it makes sense to enter a space where there is potential for significant growth in online shopping.

Walmart, which has significantly more physical locations than Amazon-owned Whole Foods, has been aggressively expanding delivery and pickup services. In Jan. 2019, Walmart announced partnerships with four “last-mile delivery providers,” which will expand its grocery delivery service to more geographical locations. Existing partnerships with third-party grocery delivery services such as Postmates, DoorDash, and

Instacart already provide delivery services out of “800 stores, covering about 40% of the population,” a number that Walmart intends to double to 1600 delivery locations by the end of Jan. 2020, while also expanding grocery pickup locations from two thousand to three thousand (Redman, 2019). Meanwhile, Kroger, which is “currently delivering groceries from about 2,000 stores” (Thomas, 2019), is experimenting with autonomous vehicles for grocery delivery. A study by the Capgemini Research Institute (CRI) found that “delivery via autonomous vehicles could potentially increase profit margins by 14%” (Melton, 2019) by reducing the delivery costs, savings which could also be passed onto the consumer to attract more users. Kroger partnered with autonomous vehicle startup Nuro to conduct a three-month pilot program using unmanned vehicles to deliver groceries in Scottsdale, AZ (Bussewitz, 2018; Melton, 2019). The program ended successfully in March 2019, with the two companies planning to start “the next phase of the program – an autonomous-vehicle delivery service at two Kroger stores in Houston” (Wiles, 2019).

With the uptick in grocery delivery and in-store pickup locations by the big players, more and more smaller stores are offering grocery delivery and pickup as well. The CRI study found that “20% of consumers will switch grocers if the grocer does not offer delivery services” (Melton, 2019). Despite the fact that the study surveyed consumers from five different countries, the general sentiment still stands. In a survey of “retail produce and floral executives,” Progressive Grocer found that the percentage of stores that offered delivery or in-store pickup of groceries ordered online increased from 31% in 2017 to 42% in 2018. Meanwhile, the percentage of stores that planned to add those services decreased from 26% to 19% between 2017 and 2018 (Progressive Grocer

(Market Research), 2018a; 2018b). This is not a cause for concern, though, because as stores that plan to add services begin to offer services, the amount of stores that plan to add services will naturally decrease. Most importantly, the total percentage of stores offering or planning to add those services increases from 57% to 61%, representing an increasing desire to provide delivery and in-store pickup of groceries ordered online.

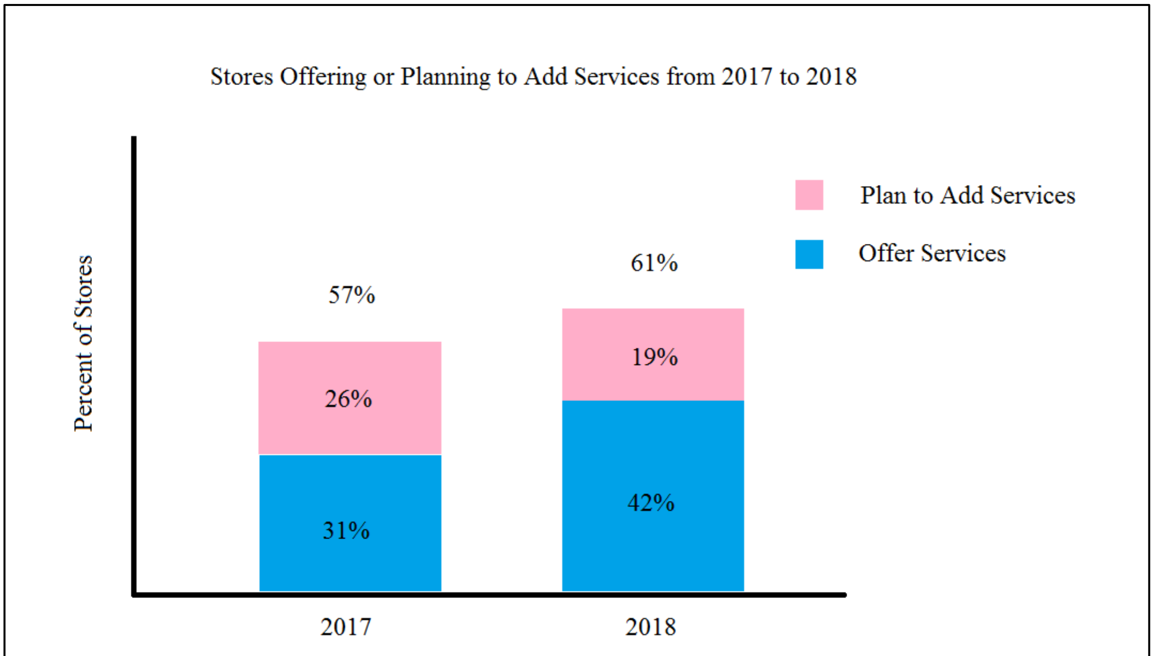


Figure 7: Chart showing the percentage of stores already offering or planning to add home delivery and/or in-store pickup of groceries ordered online. Note that despite a decrease in the percentage of stores planning to add services, the total percentage of stores offering or planning to add services increased. (Progressive Grocer (Market Research), 2018a; 2018b)

The next topic is the demand and use of these grocery delivery services by consumers. After all, investments to create market push by the stores will only go so far; there needs to be a demand for the supply. Depending on the source, anywhere from 25% to 30% of the U.S. population has bought groceries online at least once. The GlobalData (n.d.) report shows that 23.4% of grocery shoppers shopped online for food at least once in 2017, Morning Consult (2018) reports that 33% of all adults have purchased packaged food or drink online as of May 2018, and a survey by Winsight Grocery Business (2018b) shows that 29% of U.S. consumers have used online ordering or delivery as of Nov. 2018.

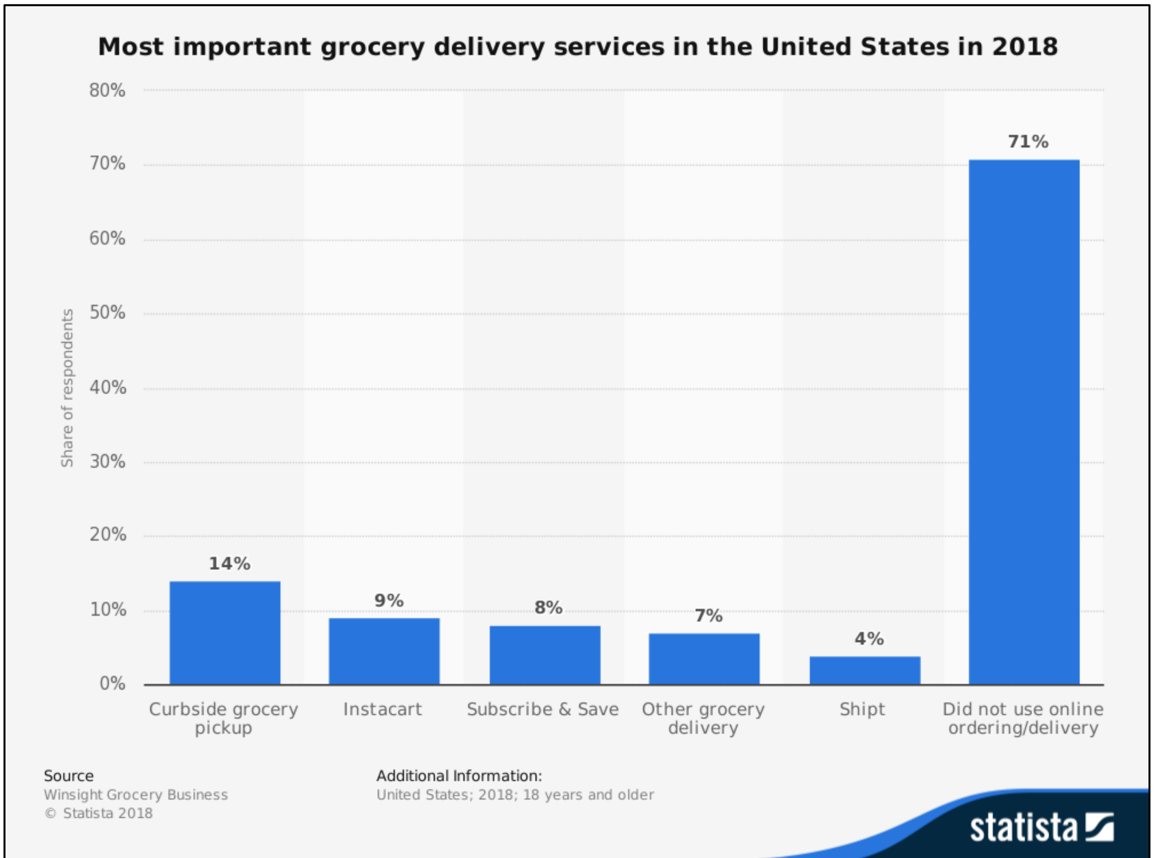


Figure 8: Chart showing the percentage of consumers who have ordered groceries online, as well as which delivery services or in-store pickup were used. Note that of the 29% of consumers who have ordered groceries online, half used curbside grocery pickup at least once. (Winsight Grocery Business, 2018b)

Among those who have tried online grocery shopping, 16% do so on a weekly basis, but 56% make only a few purchases a year. Moreover, 62% of online grocery shoppers purchase “small amount of items as needed” (Morning Consult, 2018). If the assumption is made that purchase size is dependent on online shopping frequency, then the 38% who make significant purchases completely overlaps with the 16% and 23% of weekly and monthly shoppers. The CRI study (2018) actually supports this assumption, reporting that 38% of consumers in the U.S. order groceries from a retailer at least once per week, where, despite whether the survey group includes those who have not ordered groceries online before is not explicitly stated, the logical assumption is that the survey group consisted only of consumers who have ordered groceries online before. Regardless, 38% of consumers who have used online grocery shopping before still means only 13% of all consumers use online grocery shopping to make significant purchases on a regular to semi-regular basis, which may partially account for why the market share of online grocery sales is so low, despite a large number of consumers who have used online grocery shopping.

There are many reasons why the percentage of consumers who have used online grocery shopping is not greater. Of those who have not used online grocery shopping before, 65% cite a general preference for shopping in-person as being the primary reason why. In addition, 51% of all consumers are not willing to pay extra for grocery delivery (Morning Consult, 2018). In a different study that surveyed consumers who didn't expect to buy groceries online over the next year, 76% cited a preference for seeing and choosing products themselves, 54% cited a general preference for shopping in-person, and 42% cited an unwillingness to pay for delivery (Coresight, 2018). Overall, 65% of those who have not used online grocery shopping before do not expect to ever shop for groceries online (Morning Consult, 2018).

Fortunately, there is a silver lining to these low consumer engagement numbers. 35% of those who have not used online grocery shopping before are willing to, but simply have not yet or are waiting for better options. Since roughly 70% of all consumers have not used online grocery shopping before, this means that slightly under a quarter of all consumers has simply not yet used online grocery shopping. This would imply that given enough time and development of new options by online grocery stores, this fraction of consumers will join the 30% of consumers who have used online grocery shopping before to result in a majority of consumers using or having used online grocery shopping.

There is also a fraction of consumers who have not shopped online for groceries before that are willing to pay for delivery. Recall that 51% of all consumers are unwilling to pay for groceries to be delivered, so 49% of all consumers are willing to pay. However, only 33% of all consumers have used online grocery shopping before, so clearly at least 16% of all consumers have not shopped online for groceries before AND are willing to pay. Moreover, only 65% of consumers who have used online grocery shopping before are willing to pay for delivery (Morning Consult, 2018). The final percentage of all consumers who have not shopped online for groceries before AND are willing to pay was calculated to be 28%, or about 41% of consumers who have not shopped online for groceries before are willing to pay for delivery.

Percentage of…	Users	All Consumers				Not Users
Who are…	Willing	Users	Willing & Users	Willing & Not Users	Not Users	Willing
Is…	65%	33%	21%	28%	67%	41%

Table 5: Calculation of the percentage of consumers who have not used online grocery shopping who are willing to pay for delivery. Table is read vertically as "Percentage of (group) who are (characteristic) is (result)." E.g. "Percentage of (all consumers) who are (willing to pay for delivery AND have used online grocery shopping before) is (21%)." The percentages in the greyed cells were retrieved from (Morning Consult, 2018).

Finally, 36% of younger millennials are willing to pay a premium for groceries to be delivered. This percentage is nearly twice as high as the two next older age groups –

older millenials and Gen Xers – where 20% are willing to pay for delivery (Winsight, 2018a). A report by Allied Market Research (n.d.) supports this statistic, noting that "millenials and Generation Z are the most attractive customer segments" because they are "the most tech savvy users, and are ready to pay premium to avail same-day delivery of products." Thus, as times passes and the older generations cease to make purchasing decisions, the younger and more tech savvy generations who are willing to pay for delivery, and the new generations who will have grown up in a world where online grocery shopping is available, will drive the percentage of consumers who shop for groceries online higher.

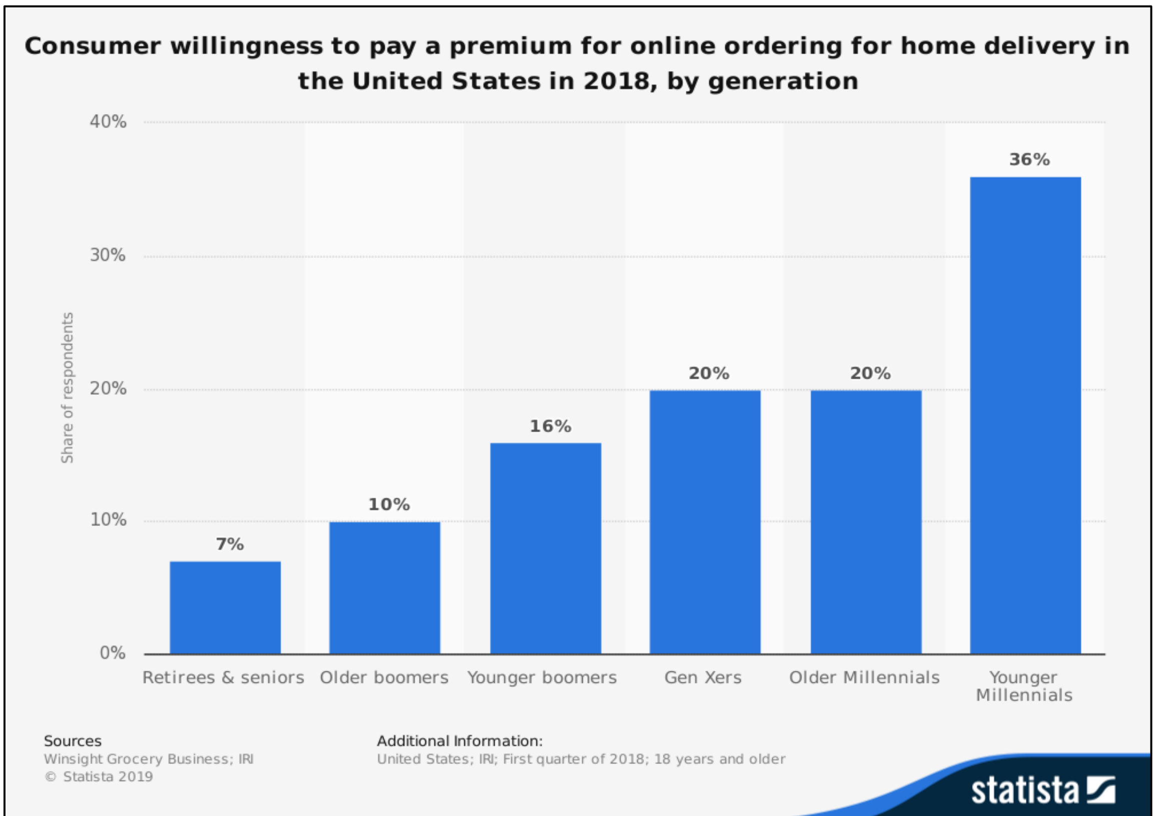


Figure 9: Chart showing the percentage of consumers in various generations who are willing to pay for delivery of ordered groceries. (Winsight Grocery Business, 2018a)

The last topic is whether consumers would purchase the proposed grocery-receiving container. The hypothesis was that consumers, who are required to be present to receive grocery deliveries (Heinen's, n.d.; Shipt, n.d.), would prefer to not be confined to the delivery location for the duration of the delivery time window and would pay for the convenience to not have to be present. In support of this hypothesis, the study by Coresight (2018) found that 13.7% of surveyed consumers who did not expect to buy groceries online over the next year found it "inconvenient to remain home for a delivery." Meanwhile, Morning Consult (2018) reported that 8% of all consumers, including 12% of Generation Z, who have not shopped for groceries online cited convenience as the primary reason why. However, the cost of delivery was of equal (7%) or significantly greater (42%) importance, compared to inconvenience, for the two studies, so until delivery costs become less of a deterrent to grocery delivery, consumers may not care to pay extra money for convenience by purchasing the grocery-receiving container.

Moreover, the grocery items that are ordered and delivered matter as well. Multiple studies show that the most ordered – technically, most likely to be ordered at least once – items are all non-perishables, and may not even be consumables. In one study, staple pantry items, like rice and canned goods, were ordered at least once by 27.5% of respondents, while personal care items were ordered at least once by 15.2% of respondents. Items that required refrigeration ranked towards the end of the list, with beverages, fresh produce, and meats, fish, deli only being ordered at least once by 19.7%, 8.5%, and 5.7% of respondents, respectively (GlobalData, 2018). (See Figure 10 for a complete chart of grocery categories)

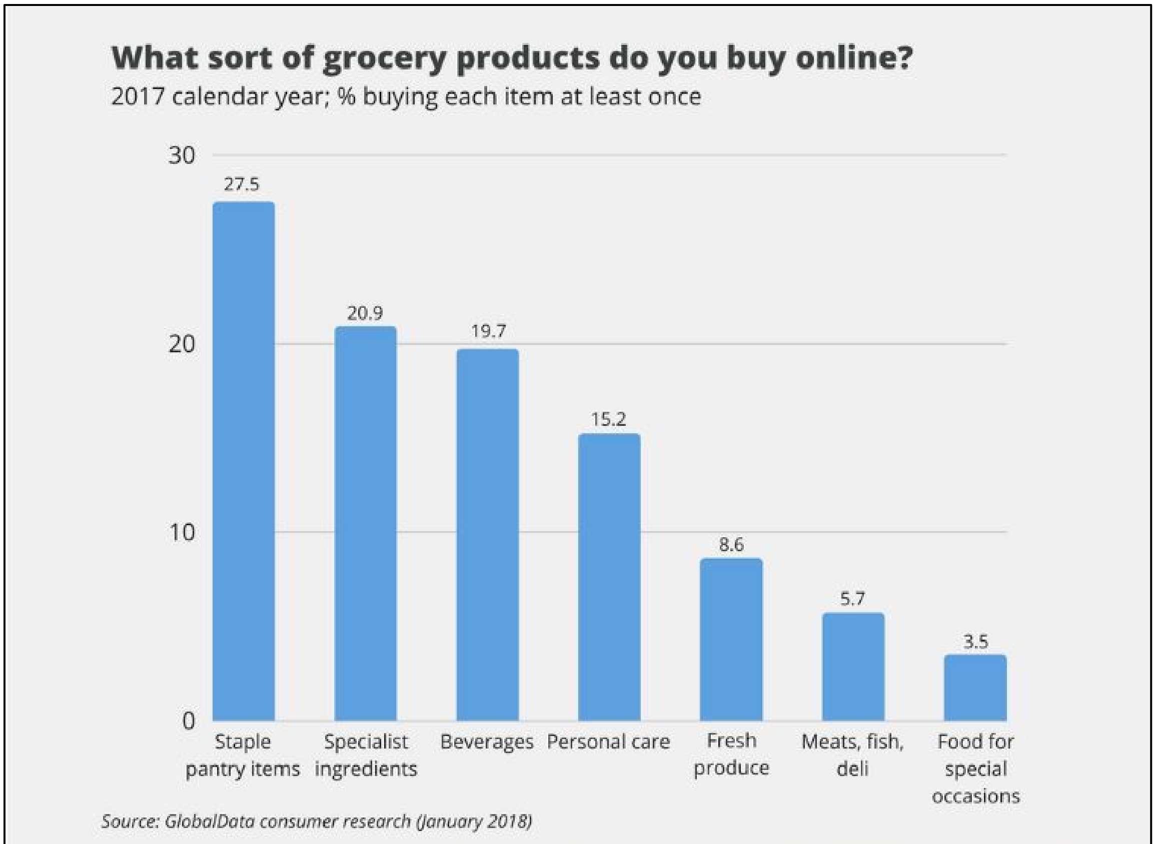
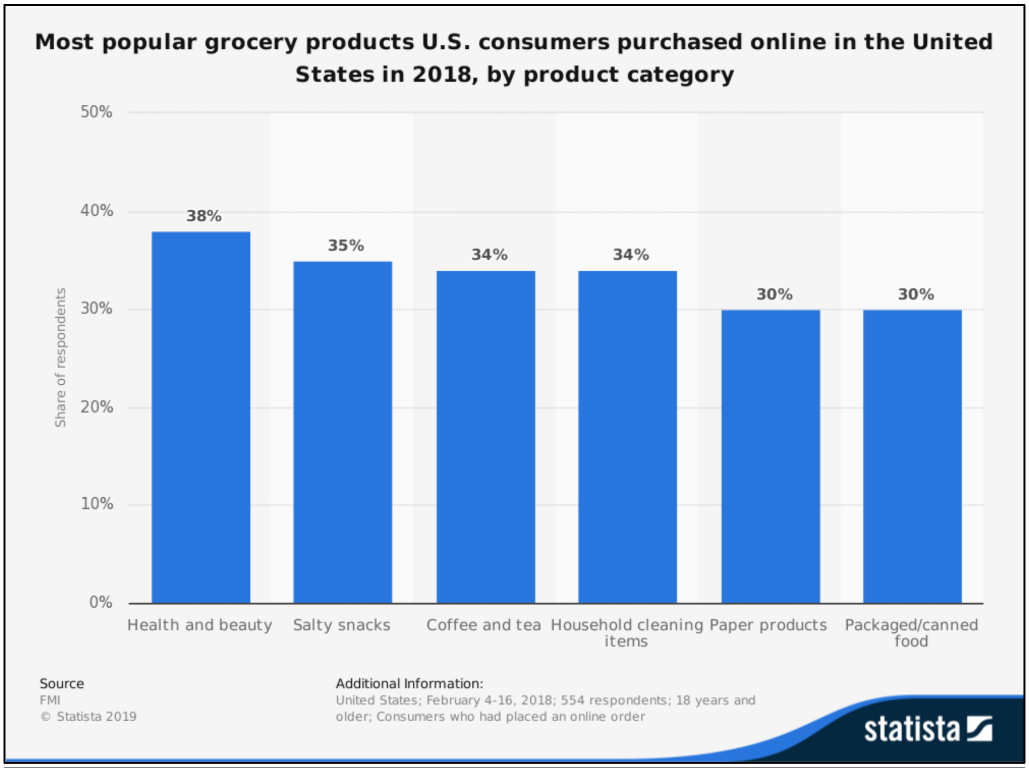


Figure 10: Chart showing the popularity of various categories of groceries bought online. Strictly speaking, this chart does not show how frequently these items were bought, only that more or less consumers bought them at least once. (GlobalData, 2018)

Similar results were found in a study conducted by the Food Marketing Institute, where health and beauty products, salty snacks, and coffee and tea were the three most popular categories, being purchased by 38%, 35%, and 34% of consumers, respectively. Meanwhile, milk and non-dairy substitutes, fresh meats and seafood, and fresh prepared food were only purchased by 20%, 19%, and 10% of consumers. The category of fresh produce is noticeably missing, but the value must be between 20% and 30% of consumers. (FMI, 2018a; 2018b) (See Figure 11 for complete charts of grocery categories)



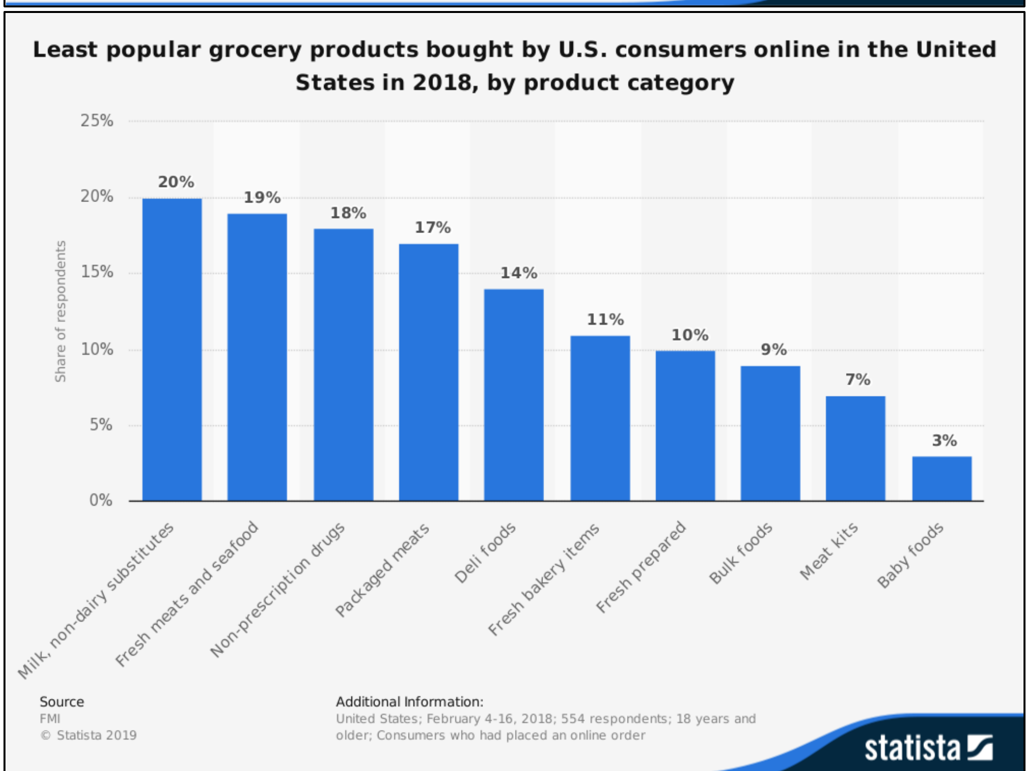


Figure 11: Charts showing the most and least popular categories of groceries bought online. Strictly speaking, this chart does not show how frequently these items were bought, only that more or less consumers bought them at least once. (FMI, 2018a; 2018b)

The results of these studies indicate that most people do not order items that require refrigeration online, which would eliminate the need for a refrigerated grocery-receiving container if delivery is even requested. Furthermore, the studies do not indicate the frequency with which any given consumer buys items that require refrigeration, so while frequent purchases of refrigerated goods would increase the value of the device, infrequent purchases would cause the device to be viewed as an unnecessary investment.

The statement that consumers would not buy a refrigerated grocery-receiving container because they do not currently order items that require refrigeration invites a converse statement: perhaps consumers do not currently order items that require refrigeration because they do not have a refrigerated grocery-receiving container, implying that consumers would be ordering items that require refrigeration now if they had a refrigerated grocery-receiving container now. However, these counter arguments are flawed. The chief function of the device is to allow consumers to not be present to receive delivered groceries, while the ability to receive items that require refrigeration is important, but incidental; the device does not enable delivery of only refrigerated items, but of all items. In other words, the device will only impact sales of refrigerated items insofar as increasing the amount of consumers who can make use of grocery delivery services; for consumers who are currently ordering groceries for delivery, there should be no change in how often they order refrigerated items, because there is no reason they cannot already.

In conclusion, the three questions used to guide the analysis of the grocery reception market – whether grocery delivery services are widespread, whether consumers use these grocery delivery services, and whether consumers would purchase the proposed grocery-receiving container – have been answered. Grocery delivery services are not very widespread yet, but will become more and more so in the next few years as stores both big and small compete to attract and retain consumers. The online grocery sales market, part of which is the grocery delivery market, is still fairly small in comparison to the total grocery sales market, but is expected to grow at an annual growth rate of roughly 13%. Only about 30% of all consumers have ordered groceries online before, with less, around 13%, ordering groceries online on a regular basis, of which an even smaller fraction have the ordered groceries delivered. One of the main reasons consumers do not order groceries online is a general unwillingness to pay delivery fees. Delivery fees are also one of the obstacles for whether consumers will purchase the grocery-receiving container, since consumers may not voluntarily pay for the convenience of not needing to be present for the delivery after being forced to pay for the delivery itself. However, as the grocery delivery market grows, competition may drive delivery fees down, or the practice of groceries being delivered will be so commonplace that the delivery fee becomes an accepted cost. At that point, consumers may be more willing to spend money on secondary convenience like the grocery-receiving container.

Lastly, whether or not grocery items that require refrigeration will become more commonly ordered and delivered remains to be seen. However, even if there is no demand for a refrigerated grocery-receiving container, there may still be a demand for an innovative non-refrigerated grocery-receiving container.

3.3 Smart Compact Refrigerator Market Analysis:

I briefly explored the possibility of marketing the device as simply a smart compact refrigerator by conducting an analysis of the smart compact refrigerator market. The hypothesis was that consumers would find value in having smart features, such as controlled access, interior photos, and mobile notifications, in a compact refrigerator, features that would have been included in the grocery-receiving container design. A search for smart compact refrigerators showed that none currently exist on the market and none are being advertised as being in development, save for a promotional compact refrigerator by Budweiser, which was able to keep track of the number of cans in the refrigerator and inform the consumer of that number via mobile app (Budweiser, n.d.).

This lack of existing smart compact refrigerators does not necessarily mean that consumers do not want them or would find no value in them; refrigerator manufacturers have simply not prioritized designing a smart compact refrigerator. Support for this hypothesis comes in the form of a Hype Cycle produced by Gartner, which tracks the expectation and interest for products over time. The category of “Consumer Smart Appliances”, which includes smart refrigerators of all sizes, has only moved from the Peak of Inflated Expectations into the Trough of Disillusionment in the last two years (Escherich, 2018).

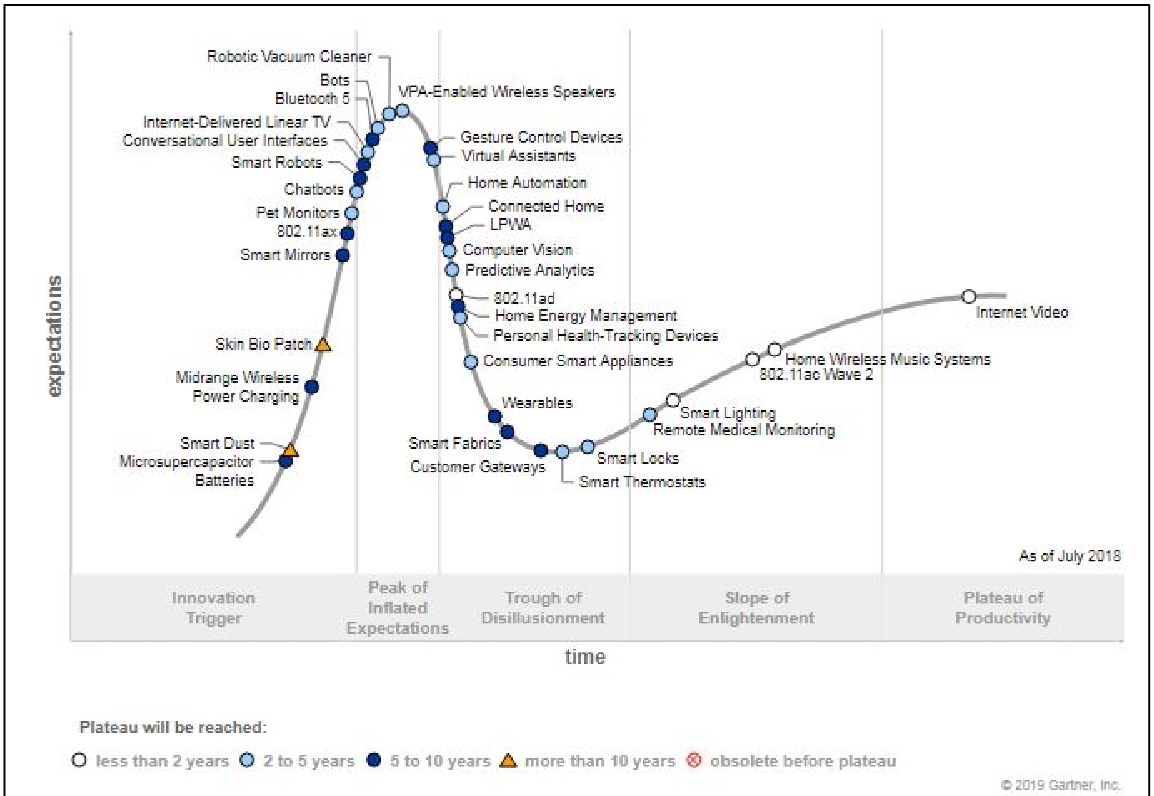


Figure 12: Gartner Hype Cycle for the Connected Home. Notice the position of "Consumer Smart Appliances" on the downward slope of the Trough of Disillusionment. Retrieved from (Escherich, 2018)

The Peak is characterized by high consumer interest due to manufacturers showing off the maximum capabilities of a technology, while the Trough is characterized by consumer dissatisfaction due to failure to deliver on unreasonable expectations by the manufacturers. As such, during the Peak stage, refrigerator manufacturers designed full-size refrigerators with as many smart features as possible, leading to expensive and feature-laden offerings such as the $6000 Samsung Family Hub™ from 2016, which featured a 21.5in touchscreen built into the door, interior cameras, built-in speakers, and Samsung TV mirroring (Crist, 2016; Nebraska Home Appliance, n.d.).

However, as smart refrigerators entered the Trough of Disillusionment, consumer interest in and perceived value of the technology decreased, causing manufacturers to design smart refrigerators with value in mind. As such, Gartner advises against charging a premium for smart features and to view them instead as add-on value (Escherich, 2018). In practice, this means that prices, and potentially the amount of features offered, will decrease, as seen with Samsung's 2017 Family Hub™ refrigerator that offered the same smart features as the 2016 model, but only initially priced at only $3300 (Crist, 2017). In fact, the difference in language between the reviews of the two models, one year apart, shows the change in emphasis in the design. Whereas the 2016 model was "a justifiable splurge if your budget [was] big enough" and had plenty of features that felt "mighty superfluous", the 2017 model was "surprisingly affordable" and "less fancy – and less expensive – than before" (Crist, 2016; 2017). This focus on value is exactly the environment where a barebones smart compact refrigerator, with only simple smart features, can thrive.

Here, I take a look at the current state of the compact refrigerator market, which is a subsector of the refrigerator and freezer market. IBISWorld (2018b) shows that the total revenue for the fridge and freezer manufacturing industry in 2018 is $5bn. The market share that compact refrigerators occupy is not shown, only that the subsectors in decreasing size are bottom freezers, top freezers, side-by-side, standalone freezers, compact, and French-door. However, because the list of subsectors is in order of decreasing size, and so the four subsectors listed ahead of compact must be of equal or greater market share, the compact refrigerator market share can be no greater than 20%.

The compact refrigerator market share and size can also be calculated on the retailer side by dividing the retail sales of compact refrigerators by the retail sales of all refrigerators and freezers. The total retail sales of compact refrigerators from 2010 to

2014 was provided by HomeWorld Business (2015a), while the total product shipment value for the U.S. household refrigerator and freezer manufacturing industry from 2008 to 2014 was provided by the US Census Bureau (2016). Note that products shipped are equivalent to products sold, but product shipment value may not be equivalent to retail value. If the total product shipment value is taken to be equal to the total retail value, then the market share of compact refrigerators can be calculated exactly by dividing the retail sales of compact refrigerators by the retail sales of all refrigerators and freezers. However, if the product shipment value is actually the revenue earned by the manufacturers, then the retail value must be greater than the product shipment value, which would decrease the quotient in the above calculation. At any rate, the average market share of compact refrigerators as a fraction of the refrigerator and freezer market from 2010 to 2014 can be no greater 8.9%.

Year	Retail Sales ($ millions)	Shipment Value ($ millions)	Market Share (%)
2010	299.1	3,481	8.6
2011	302.6	3,461	8.7
2012	309.2	3,497	8.8
2013	321.5	3,364	9.6
2014	326.3	3,615	9.0
		Average Market Share (%)	8.9

Table 6: Calculation of the average market share of the compact refrigerator retail market from 2010 to 2014. Compact refrigerator retail sales data from (HomeWorld Business, 2015a). Refrigerator and freezer product shipment values from (US Census Bureau, 2016).

The market size for compact refrigerator retail market can also be calculated using the above data. A linear growth model predicts that retail revenue in 2018 would be $355.7m, while an exponential growth model predicts a slightly higher amount, $358.9m.

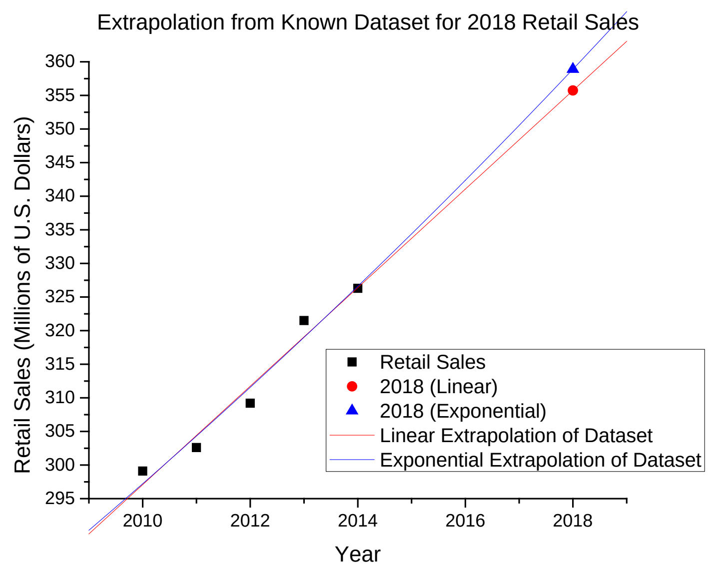


Figure 13: Graph showing estimation of the 2018 compact refrigerator retail sales revenue. Linear and exponential functions were fit onto existing data, and then extrapolated to 2018. Existing data retrieved from (HomeWorld Business, 2015a).

The location where the smart compact refrigerator may be used is important, because a different standard usage changes the value of the smart features. Aside from residential use, compact refrigerators are a staple in college dormitories and offices, where there are different types and numbers of consumers. For example, in a residential setting, the interior camera may be used to check the contents of the compact refrigerator while shopping, whereas in an office setting, the interior camera may be used to remind someone to restock the compact refrigerator. Moreover, due to a higher number of potential users, the rate at which a compact refrigerator's contents deplete may be higher in a non-residential setting.

Compact refrigerators have an average lifespan of 8 years (TIB, 2000), so the total number of compact refrigerators in use in any given year can be calculated by summing the number of units sold in the previous 8 years. The total number of compact refrigerators used in a residential setting is provided by the U.S. Energy Information Administration (EIA). Out of the 117.4 million total homes in the U.S. in 2015, compact refrigerators were used in 0.9 million homes as the primary refrigerator and in 8.1 million homes as the secondary refrigerator, for a total of 9 million compact refrigerators used in a residential setting (U.S. EIA, 2018). Thus, the total number of compact refrigerators in use in 2015 is needed; however, only sales data for 2010-2014 was found (HomeWorld Business, 2015b).

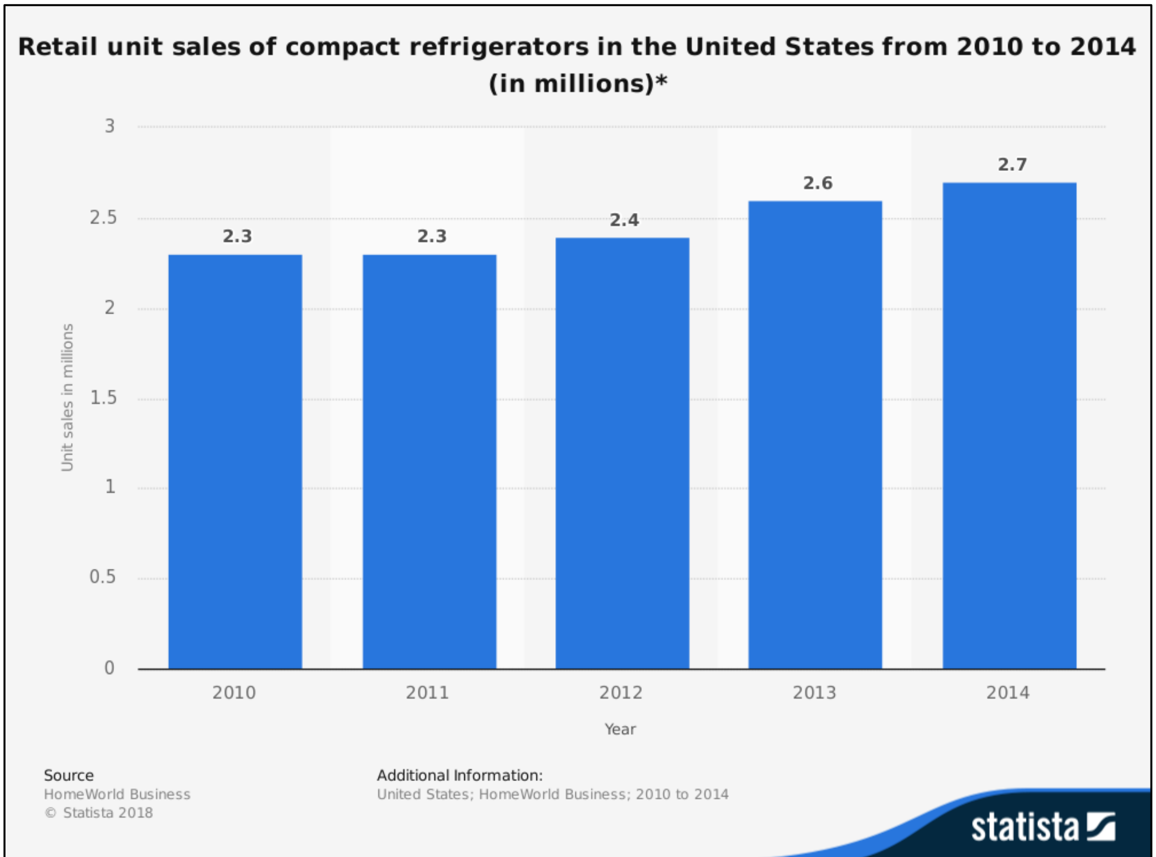


Figure 14: Chart showing the number of compact refrigerator sold in the US from 2010 to 2014. Note that the number sold increases more or less consistently by 0.1 million per year. Retrieved from (HomeWorld Business, 2015b).

Making the assumption that the growth was linear, the number of units sold in 2010 was taken to be the average number of units sold between 2006 and 2014, which when multiplied by 8 results in a total number of compact refrigerators in use in 2015 of 18.4 million units. Thus, only about half of all compact refrigerators are used in a residential setting.

The goal of this analysis was to determine whether it would be feasible to market the device simply as a smart compact refrigerator. First, I discovered there are currently no smart compact refrigerators on the market or in production, which represents an opportunity for entry, as long as there is not a clear lack of interest or demand. Based on the position of smart appliances on the Gartner Hype Cycle, I argued that the reason for the non-existence of smart compact refrigerators was that the companies with the ability to design and manufacture smart refrigerators had been focused on making high-end, full-size smart refrigerators, and are only now starting to produce more affordable models. With the current focus on increasing value by decreasing prices, introducing an inexpensive, smart compact refrigerator with simple features at this time would be a natural continuation of the trend.

Then, I researched the market size of compact refrigerators, which is a subsector of all refrigerators and freezers, for both manufacturing and retail. On the manufacturing side, I was able to deduce that the market share of compact refrigerators could be no more than 20%, leading to a maximum market size of $1bn for compact refrigerator manufacturing in 2018. On the retail side, I calculated the compact refrigerator market size to be between $356m and $359m, depending on the method of extrapolation. I was also able to determine that the market share could be no greater than 9%.

Finally, I showed that half of all compact refrigerators are used in a non-residential setting, which is important because a different setting changes the value the device provides. A smart compact refrigerator used in a residential setting may provide a different amount of value and fulfill a different need than one used in an office or dormitory setting.

3.4 Obstacles to Entry:

The existence of a significant number of competitors, in both the grocery reception and smart compact refrigerator markets, is a major obstacle to entry. Because the device is essentially a modified compact refrigerator, the immediate competitors in both markets would be refrigerator manufacturers, which can vary from international conglomerates like LG or Samsung to primarily compact refrigerator manufacturers like Danby. Regardless of the size of the competitor, though, they all possess existing knowledge about and expertise in manufacturing refrigeration systems; knowledge and expertise I would need to take time to develop. In this regard, Amazon may be a competitor too, in the grocery reception market, simply because they are invested in the online grocery sales market and have the resources to develop expertise in refrigerator manufacturing quicker than I would be able to.

Solid intellectual property, ideally in the form of a patent, is a startup's best defense against significant competition. In order for a device to be patentable, it must be useful, novel, and non-obvious (Thoughts to Paper, n.d.). Useful is defined as the device working and serving a purpose. Novel simply means the device does not currently exist.

Non-obvious is the difficult criteria to prove, and means that someone with expertise in the relevant field would not have thought of the device already.

A smart compact refrigerator, such as one for the smart compact refrigerator market, easily passes the useful criterion. Since no other smart compact refrigerator with the same specific features as the device currently exists, it may be tempting to claim novelty as well, but an in-depth patent search would be required to fully justify the claim. However, the most important problem is that the device would likely fail the non-obviousness test, because full-size smart refrigerators already exist. Conceptually, the device is simply a scaled-down smart refrigerator. Although, if the smart features are incorporated in a different way, the specific design of the device may pass the non-obviousness criterion.

The device for the grocery reception market is a smart compact refrigerator, with modifications to enable outdoors use. The device is also clearly useful. Novelty, as always, requires an in-depth patent search, but the device does not currently exist on the market. The main issue is still the non-obviousness criterion, because, broadly speaking, the device is a combination of existing technology. Full-size smart refrigerators already exist, ARB USA (n.d.) sells a lockable, outdoor-capable compact refrigerator, and Dometic manufactures a portable, vapor-compression compact refrigerator (WAECO USA, n.d.). Even the potential feature that the device would be able to heat the interior when the exterior temperature was below desired temperatures already exists; Koolatron produces a thermoelectric cooler that "heats to approximately 135°F/57°C inside" (Koolatron, 2014). As before though, the specific design of the device and how exactly the various existing technologies are combined may still be enough to pass the non-obviousness criterion.

3.5 Conclusions:

At the current state of the online grocery shopping market, it would be difficult to make the case for marketing the device as a grocery-receiving container. However, the prospects will improve over time as big players like Amazon, Walmart, and Kroger continue to invest money into online grocery shopping, increasing the market size, while also normalizing the act of buying groceries online. As online grocery shopping becomes commonplace and delivery fees become an accepted part of the process, consumers will be more willing to pay for the added convenience of not needing to be present for the delivery. The final question that remains to be seen is whether deliveries of refrigerated products will become more popular, although even without the need for refrigeration, consumers can still take advantage of a container that prevents theft of delivered groceries.

Meanwhile, although smart compact refrigerators do not currently exist, now would be a good time to consider entry into that market. Because smart appliance technology is currently in the Trough of Disillusionment on the Gartner Hype Cycle, value is key, so an inexpensive compact refrigerator with only basic smart features may prove to be competitive with full-size refrigerators that have more features but are more expensive. The question then becomes whether it is possible to incorporate the necessary smart features at a low cost, so that the retail price is not significantly higher than the already inexpensive compact refrigerators on the market.

Lastly, the combination of the existence of significant competition and potential lack of patentable intellectual property for both markets is a serious obstacle, although if a patent can be acquired through clever design of the devices, then the existence of competition becomes somewhat less threatening.

4. Conclusion

Scientific analysis showed the most technologically feasible, while inexpensive and convenient, design of the device to be an insulated container, powered by an electrical outlet, which uses vapor-compression refrigeration to maintain interior temperatures of 0°C to 4°C when the outside air temperature is above intended values. The vapor-compression system of the device would need to be designed to be able to operate in outdoor conditions, and heating would need to be provided to the interior when the outside air temperature is below intended values, although the exact mechanisms by which these two adjustments would function were not discussed.

Market analysis showed that while marketing the device as a grocery-receiving container is premature, marketing the device as a barebones smart compact refrigerator is a good idea. In fact, because the smart compact refrigerator may not need to have outdoor functionality, so temperature considerations do not need to be accounted for, the design process will be easier. All that remains is to see whether a compact refrigerator with smart features can be manufactured and retailed at a comparable price to current compact refrigerators. However, the existence of significant competition and potential lack of patentable intellectual property for the device should not be overlooked, as it may preclude entry into either market.

The plan will be to determine whether there is patentable intellectual property for either model of the device, either as is or with refinement of the design, which would inform which model to further develop and which market to enter. In the case that both models have patentable intellectual property, than I would start by developing and marketing the indoors-only model of the device as a smart compact refrigerator, because I believe it is a good time to enter that market, and because the relatively uncomplicated and easier indoors-only design can be brought to market faster. The indoors-only model will increase brand recognition, while raising capital to design, test, and manufacture the outdoors-capable models in time for the online grocery shopping market and grocery delivery to reach critical mass.

Appendix

The First Law of Thermodynamics states that the change in internal energy ΔU of a closed system is equal to the amount of heat Q transferred to the system plus the amount of mechanical work W done *on* the system by the surroundings. That is,

$$\Delta U = Q + W \tag{A1a}$$

where Q is negative if heat is transferred away from the system and W is negative if mechanical work is done *by* the system on its surroundings (Cengel, Cimbala, & Turner, 2012; Kittel & Kroemer, 1980). Note that a closed system refers to the condition that no matter is transferred to or from the system, because that mass flow would carry energy as well. The First Law is also commonly written with differential quantities as

$$dU = dQ + dW \tag{A1b}$$

Mechanical work done *on* the system by the surroundings is defined as

$$\Delta W = -P\Delta V \tag{A2}$$

Since $\Delta V < 0$ for mechanical work done *on* the system, the negative sign ensures that W will be positive, so that the contribution to the internal energy of the system is positive, per eq. (A1a).

Internal energy is defined as the sum total of the energies of the molecules that make up the system, as opposed to "external energy" such as kinetic or potential energy, which the system possesses as a whole. Internal energy includes sensible and latent energy, as well as chemical and nuclear energy. In general terms, internal energy is the energy needed to create the system as it is observed (Cengel, Cimbala, & Turner, 2012). This paper focused on sensible and latent energy – energy due to the kinetic energies of the molecules and energy due to the phase of the system, respectively – because no chemical or nuclear reactions occurred, which would require consideration of those energies.

A related quantity is that of enthalpy, symbolized by *H*, which is defined as the sum of the internal energy *U* of a system and the product of the pressure *P* and volume *V* of the system.

$$H = U + PV \tag{A3}$$

where the *PV* term represents the work required to be done by the system to displace the surroundings to make space for itself, and is considered to be unusable because it cannot be extracted (Kittel & Kroemer, 1980). Enthalpy can be defined using the First Law by noticing that the total work *W* done *on* the system is actually a sum of the effective work *W'* done *on* the system minus the inextricable work *PV* done *by* the system to create space for itself.

$$W = W' - PV \tag{A4}$$

Substituting into eq. (A1b), and rearranging,

$$dU = dQ + d(W' - PV) = dQ + dW' - d(PV)$$

$$dQ + dW' = dU + d(PV) = d(U + PV) \equiv dH \tag{A5}$$

Enthalpy takes the place of internal energy for processes at constant pressure. In processes where no effective work is done, the amount of heat transferred to the system *dQ* is directly equal to an increase in enthalpy *dH*, per eq. (A5) (Kittel & Kroemer, 1980). An expression can be derived for the differential effective work by substituting eq. (A2) into eq. (1a) to get

$$dU = dQ - P\Delta V$$

then adding *d*(*PV*) to both sides and simplifying

$$dU + d(PV) = dQ - PdV + d(PV)$$

$$d(U + PV) = dQ - PdV + VdP + PdV$$

$$dH = dQ + VdP \tag{A6}$$

where a simple comparison of eqs. (A5) and (A6) shows that $dW' = VdP$, similar to eq. (A2).

An adiabatic process is defined as a process where no heat is transferred; that is, $Q = 0$. This occurs when the closed system and its surroundings are at the same temperature and thus there is no temperature gradient to cause heat transfer, or, more practically useful, when the closed system is well insulated so that only a negligible amount of heat is transferred (Cengel, Cimbala, & Turner, 2012). For adiabatic processes, the First Law shows that the amount of work done *on* the closed system directly leads to an increase in internal energy.

$$\Delta U = W \tag{A7}$$

An isentropic process is defined as a process in which the entropy of the system is unchanged. An in-depth discussion of entropy is somewhat irrelevant to the current topic, but suffice to say that the entropy of a given system can change by any of three ways: mass transfer, heat transfer, or irreversibilities, such as frictional energy loss. Thus, an adiabatic process for a closed system is automatically an isentropic process, if friction is ignored, which, while unrealistic, is useful for modeling real processes. Of particular interest are isentropic processes on an ideal gas system, because the properties of the system after the process can be calculated.

The model of the ideal gas is a very useful approximation for determining behavior of most gases in most real-world conditions. The core relation of the ideal gas model is, naturally, the ideal gas law, which relates the pressure P, volume V, and temperature T of the ideal gas.

$$PV = nRT \tag{A8a}$$

where n is the number of moles of gas in the system and R is the ideal gas constant, sometimes called the universal gas constant, and is equal to R = 8.314 J/mol•K (Cengel, Cimbala, & Turner, 2012). For a closed system, the amount of gas remains constant, so the ideal gas law can also be written as

$$\frac{PV}{T} = nR = constant \tag{A8b}$$

However, the value of n is typically not known, so the more useful form of eq. (A8b) is

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \tag{A8c}$$

which allows for the calculation of the final value of one of the three quantities after a change in the system, given the final values of the other two quantities and the initial values of all three quantities.

The ideal gas constant is actually defined using Boltzmann's constant k_b.

$$R = N_A k_b \tag{A9a}$$

where N_A is Avogadro's number (Kittel & Kroemer, 1980). A slightly more useful equation can be obtained by multiplying both sides by the number of moles n.

$$nN_A k_b = Nk_b = nR \tag{A9b}$$

where N is the total number of molecules in the system. Note that the constant quantity nR from eq. (A8b) is recovered.

The ideal gas model also provides an expression for the internal energy U of a system,

$$U = \frac{f}{2} nRT \tag{A10}$$

where f is the number of degrees of freedom the ideal gas has (Kittel & Kroemer, 1980).

For an ideal gas undergoing an isentropic process, the final pressure, volume, and temperature can be calculated from the initial values if just one of the final values is known (Cengel, Cimbala, & Turner, 2012; Kittel & Kroemer, 1980).

$$P_1 {V_1}^{\gamma} = P_2 {V_2}^{\gamma} \tag{A11a}$$

$$T_1 {V_1}^{\gamma - 1} = T_2 {V_2}^{\gamma - 1} \tag{A11b}$$

$$T_1 {P_1}^{\frac{1-\gamma}{\gamma}} = T_2 {P_2}^{\frac{1-\gamma}{\gamma}} \tag{A11c}$$

where γ is the heat capacity ratio (see below). Note that the above equations are completely equivalent due to the ideal gas law, eq. (A8c).

There are limitations to the accuracy of the ideal gas model. Errors arise when the gas is complex or has polar regions, because the ideal gas model assumes point particles that do not interact with each other outside of collisions. The temperature and pressure of the gas is important as well, because the ideal gas model deviates from reality severely near the critical point and near phase change boundaries (Cengel, Cimbala, & Turner, 2012).

The Joule-Thomson expansion is one process that illustrates the inaccuracy of the ideal gas model. Joule-Thomson expansion is the isenthalpic process by which a gas is forced through a small, insulated opening from a high pressure area to a low pressure area, which causes a change in the temperature of the gas. Whether the temperature increases or decreases depends on the sign of the Joule-Thomson coefficient μ_{JT}, which is defined as the partial derivative of temperature with respect to pressure, at constant enthalpy.

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_H \tag{A12a}$$

Or, in terms of easily measured properties of the gas,

$$\mu_{JT} = \frac{V}{C_P}(\alpha T - 1) \tag{A12b}$$

where V is the initial volume, C_P is the heat capacity at constant pressure, α is the volumetric coefficient of thermal expansion, and T is the initial temperature of the gas. Note that the sign of μ_{JT} is determined by the sign of (αT - 1), so whether the gas heats up or cools down upon passing from a high pressure area to a low pressure area is dependent on how responsive the volume of the gas is to a change in temperature (Gans, 1993).

Ideal gases, however, experience no temperature change due to Joule-Thomson expansion, because $\mu_{JT} = 0$. This is due to the fact that $\alpha = 1/T$ for an ideal gas, which can easily be shown using the definition of α (Kittel & Kroemer, 1980).

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P \tag{A13}$$

The ideal gas law, eq. (A8a), can be rearranged to give V as a function of T and P.

$$V = \frac{nRT}{P}$$

which when substituted into eq. (A13) yields

$$\alpha = \frac{1}{V}\left(\frac{nR}{P}\right) = \frac{1}{V}\left(\frac{V}{T}\right) = \frac{1}{T} \tag{A14}$$

In addition, the fact that the Joule-Thomson expansion is isenthalpic leads directly to the result that ideal gases do not experience temperature due to the expansion. Recall that enthalpy is defined as

$$H = U + PV \tag{A3}$$

Substituting the expression for the internal energy of an ideal gas, eq. (A10), and the ideal gas law, eq. (A8a), into the above equation shows that the enthalpy of an ideal gas depends only on *T*.

$$H = \frac{3}{2}nRT + nRT \tag{A15}$$

Since the enthalpy remains unchanged through the Joule-Thomson expansion, the temperature of the ideal gas cannot change either (Cengel, Cimbala, & Turner, 2012).

Heat transfer to or from an object will cause the object to increase or decrease in temperature, or even induce a phase change, if enough heat energy is transferred. Let the ratio between the amount of heat transferred and the corresponding change in the temperature of the object be given by the heat capacity *C*, defined as

$$C = \frac{dQ}{dT} \tag{A16}$$

More specifically, using the differential form of the First Law of Thermodynamics, eq. (A1b), and keeping the volume *V* constant so that the mechanical work *dW* goes to zero per eq. (A2),

$$dU = dQ$$

$$C_V = \left(\frac{\partial U}{\partial T}\right)_V \tag{A17a}$$

where C_V is the heat capacity at constant volume. A similar process can be applied to enthalpy, eq. (A6), to show that, at constant pressure

$$dH = dQ$$

$$C_P = \left(\frac{\partial H}{\partial T}\right)_P \tag{A17b}$$

where C_P is the heat capacity at constant pressure (Cengel, Cimbala, & Turner, 2012).

Note that C_P will always be greater than C_V because C_P includes mechanical work done *by* the system on the surroundings in order to create room to expand into to maintain constant pressure. The result of this inequality is that the heat capacity ratio k, defined as the ratio of the heat capacity at constant pressure to the heat capacity at constant volume, must be positive (Cengel, Cimbala, & Turner, 2012).

If enough heat is transferred, an object will experience a phase change, whether between the solid and liquid states or liquid and gaseous states, or something more exotic. The energy required to cause a phase change is given in terms of unit mass, and is called the latent heat of fusion for phase changes between the solid and liquid states, and latent heat of vaporization for phase changes between the liquid and gaseous states (Cengel, Cimbala, & Turner, 2012; Kittel & Kroemer, 1980). The latent heats are determined experimentally and can be found in the literature. One important fact is that the latent heats of fusion and vaporization are significantly greater than the specific heat capacities for a small temperature change for the corresponding substances, regardless of phase; in fact, for many substances the latent heat of fusion or vaporization will be greater than the specific heat capacity for a large temperature change.

The phase change from liquid to gas is called vaporization. Vaporization encompasses two phenomena: boiling and evaporation. Boiling is a bulk phenomenon where the entire liquid is at a temperature where it is saturated with heat, such that any additional heat input will cause some amount of liquid to vaporize. Random collisions under the surface of the liquid will also transfer enough kinetic energy to molecules to vaporize and “bubble out” of the liquid in a process called cavitation. The temperature at which the liquid becomes saturated is known as the saturation temperature, colloquially known as the boiling point, and varies with changes in pressure. The other form of vaporization, evaporation, is a surface phenomenon, and can occur at temperatures below the boiling point. Molecules at the surface of the liquid gain enough energy through random collisions to vaporize immediately, but molecules below the surface that gain enough energy quickly lose that energy again to collisions.

For a pure substance, the saturation temperature is the temperature at which the liquid becomes saturated, for a given atmospheric pressure. Similarly, the pressure at which a pure substance becomes saturated is known as the saturation pressure, and is given relative to the temperature (Cengel, Cimbala, & Turner, 2012).Related to the saturation pressure is the vapor pressure, which is the pressure exerted by the gaseous phase of a pure substance at phase equilibrium with its liquid phase for a given temperature. Phase equilibrium refers to a state where the amount of mass in each phase reaches a consistent level; in other words, when the amount of molecules entering a phase equals the amount of molecules leaving that phase. Although vapor and saturation pressure measure different phases, they are actually equivalent measures.

Vapor pressure and saturation pressure should not be confused with partial pressure, which is the pressure exerted by a gas in a mixture with other gases, as opposed to a pure substance (Cengel, Cimbala, & Turner, 2012). The partial pressure can be approximated by taking the mole fraction of the gas of interest and multiplying it by the total pressure.

$$P_p = \chi_{gas} P_{total} \tag{A18}$$

where χ_{gas} is the number of moles of the gas of interest divided by the total number of moles of gas. In order for a system with both gaseous and liquid phases present to reach phase equilibrium, the partial pressure must equal the saturation pressure of the liquid; in the limit that there is only one gas in the mixture at phase equilibrium with a liquid phase, the partial pressure is the total pressure, which in turn must be the saturation pressure. For example, a bucket of water in a dry room will evaporate until enough water vapor has been created to allow the partial pressure to reach vapor pressure, or the water will evaporate completely before the system can reach phase equilibrium.

The Peltier effect is a phenomenon where a voltage applied across a conducting or semiconducting material causes heat to be transferred from one side of the material to the other side. Consider a semiconducting material with a voltage applied across it. The voltage will cause charge carriers – electrons and/or holes – to be transported from one side of the material to the other. This movement of charge carriers transports some amount of energy as well.

$$E_e = (E_C - \mu) + \frac{3}{2} k_B T \tag{A19a}$$

$$E_h = (\mu - E_V) + \frac{3}{2} k_B T \tag{A19b}$$

where E_e is the average energy carried by an electron and E_h is the average energy carried by a hole. μ is the Fermi energy, since different conducting materials in contact will have the same Fermi energy, while E_C and E_V are the conduction and valence band energies, respectively. $\frac{3}{2} k_B T$ is simply the average kinetic energy for an ideal electron gas in three dimensions (Kittel, 2005).

The average energies carried by the charge carriers leads to simple expressions for the Peltier coefficient Π, which is defined as the energy carried per unit charge.

$$\Pi_e = -E_e/e \ = -\left(E_C - \mu + \frac{3}{2}k_B T\right)/e \tag{A20a}$$

$$\Pi_h = \quad E_h/e \ = \quad \left(\mu - E_V + \frac{3}{2}k_B T\right)/e \tag{A20b}$$

where e is the electron charge. Note that Π_e is strictly negative because otherwise, electrons, which are negatively charged, would carry negative thermal and kinetic energy, which is not allowed (Kittel, 2005).

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