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Conceptual study of a portable cooling system based on renewable energy for use on fruits and vegetables

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Dedicated to my family

Preface

This master thesis has been completed at the Norwegian University of Science and Technology and at the Indian Institute of Technology Kharagpur in the spring of 2019. The thesis consists of a literature review on cold chains and cooling systems, and documentation of refrigeration, horticultural products, and cold chains in India. The thesis further consists of a comprehensive design of a portable and renewable energy based cooling system for use on fruits and vegetables in India.

The work has been done in cooperation with SINTEF Ocean as part of the Re-FOOD project, which is an international partnership between Norway and India. Erling Vingelsgård, Tom Andre Bredesen and myself traveled to IIT Kharagpur from 21.01.2019 to 05.04.2019 as part of the work, where we investigated the use of refrigeration in India.

I would like to extend my gratitude to my supervisor Prof. Trygve Magne Eikevik for his help and for giving me the possibility of working on this master thesis. Furthermore i wish to thank Dr. Ignat Tolstorebrov for much help as my co-supervisor in all aspect of the thesis work. I would also like to thank Prof. Armin Hafner and Norsk Kjøleteknisk Forening for their trust in me as a recipient of the Gustav Lorentzen grant. Lastly i also wish to thank my other co-supervisors Dr. Kristina N. Widell, Prof. Anandaroop Bhattacharya, Prof. Prasanta Kumar Das, and Prof. Maddali Ramgopal for all their assistance in writing this master thesis.

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Abstract

The worlds population is steadily rising and more people are making their way out of poverty each day, as a result the demand for enough nutrient rich food is ever increasing. India is a country where the both the population and the state of development is in rapid growth, vast parts of its population is however still poor and undernourished. As India is one of the largest producer of fruits and vegetables in the world, this sector has the possibility of being a thriving industry both domestically and internationally. There are however immense postharvest losses before the product can even reach the consumer, which is largely attributed to the improper use of cold chains in the country. One of the most beneficial implementations available for value addition and efficiency increase of such cold chains is the use of designated cooling systems for removal of field heat, and such a system is the focus of the work done in this thesis.

A literature review is done on the topic of cold chains and cooling systems. Documentation of the state of refrigeration in India is done, horticultural products of special relevance is investigated, insight is presented into the typical cold chains for domestic and export applications of these products, and quantified information from the stay in India is presented through survey responses given by Indian natives. The state of cold chains, refrigeration and cooling in India is found to be vastly lacking in both capacity and efficiency, however it is also found to be in a state of growth where it shows great potential for further development. This foundation is used to establish a potential beneficial cooling system for the scenario, which is a renewable and portable cooling system for use on apples, grapes and mangoes in India.

A physical design of the cooling system is presented, and a further logistical implementation of this system in India is constructed. Related theory is used to make a comprehensive simulation model in the software program EES for the complete cooling system. The model simulates airflow and corresponding factors of importance through the geometry, refrigeration loads and the corresponding refrigeration system, transient considerations related to the cooled products, and the renewable energy supply to the system. Results from the model is used to reach an optimized system configuration, which is implemented for cooling of apples, grapes and mangoes in the respective climatic regions of Dehradun, Mumbai and Kolkata.

The optimized design, assumptions and conditions gives a cooling system with a 4 kW compressor that uses R600a as a refrigerant, and a 1 kW fan that provides airflow through the geometry. The energy supply consist of a a foldable solar PV-panel of 47.3 m^2, and a battery with a size of 7.5 kWh. The system will at design conditions have a 10 hour daily operational time in the respective climatic regions. For these conditions, the system will cool a total of 2880 kg of apples from 36.4 °C to 3 °C, 2560 kg of grapes from 38 °C to 3 °C, and 3648 kg of mangoes from 39.7 °C to 12 °C during one day. The cooling will be done in three batches for apples and mangoes, and in four batches for grapes. For apples, grapes and mangoes the respective cooling time is 173, 110 and 175 minutes, and the respective COP of the refrigeration system at these dimensioning conditions is 3.81, 3.857 and 4.042. The complete cooling system is investigated in relation to the Indian scenario, and it is concluded that the system has several potential benefits here.

Abstrakt

Verdens befolkning er i stadig økning hvor flere og flere mennesker tar seg ut av fattigdom hver eneste dag, som et resultat følger det at behovet for nok næringsrik mat øker. India er et land der både innbyggertallet og levestandarden opplever rask vekst, allikevel er store deler av landers befolkning svært fattige og underernærte. Ettersom India er en av de største produsentene av frukt og grønnsaker i verden, er dette en sektor med muligheter for en sterk industri gjeldende både nasjonalt og internasjonalt. På tross av dette er det massive tap av disse produktene før de i det hele tatt når frem til forbrukeren, noe som i stor grad skyldes dårlig utnyttelse av kuldekjeder i landet. En av de mest påvikningskraftige implementasjonene tilgjengelig for å øke verdi og effektivitet i slike kuldekjeder er designerte nedkjølingssystemer som fjerner overskuddsvarme fra høstede produkter, og et slikt system er fokusområdet for arbeidet i denne oppgaven.

Et litteraturstudie er gjort innen fagfeltet rundt kuldekjeder og nedkjølingssystemer. Dokumentasjon av standarden for kjøling i India er utført, hortikulturelle produkter av spesifikk relevanse er undersøkt, innsikt i typiske kuldekjeder for innlands og eksportformål er presentert, og kvantifiserbar informasjon fra oppholdet i India er presentert via svar gitt i en forbrukerunderskelse. Den nåværende standarden rundt kuldekjeder, kjøling og spesifikk nedkjøling i India blir dokumentert til å ha store mangler både i kapasitet og effektivitet, men de samme områdene er også dokumentert til å være i tydelig vekst med store potensialer for videre utvikling. Denne bakgrunnen brukes til å etablere et potensielt fordelaktig nedkjølingssystem i dette scenariet, et system som baserer seg på fornybar energy og som er transportabelt, til bruk for nedkjøling av epler, druer og mango i India.

Et fysisk design av dette nedkjølingssystemet presenteres, og en videre logistisk implementasjon av systemet blir konstruert. Relevant teori brukes til å lage en omfattende simuleringsmodel med programvaren EES for det komplette nedkjølingssystemet. Modellen simulerer luftstrømning og korresponderende viktige faktorer i forhold til geometrien, kjølelaster og det påfølgende kjølesystemet, transiente hensyn i forhold til produktene som nedkjøles, samt det fornybare energiforsyningssystemet. Resultatene fra denne modellen brukes til å bestemme et optimalisert system, et system som implementeres for nedkjøling av epler, druer og mango i de respektive klimatiske forholdene nær Dehradun, Mumbai og Kolkata.

Det optimaliserte designet, antagelsene gjort og betingelsene som er gjeldende gir et nedkjølingssystem med en 4 kW kompressor som bruker R600a som kjølemedium, og en 1 kW vifte som sørger for luftgjennomstrømning i geometrien. Energiforsyningssystemet består av et sammenleggbart solbasert PV-panel på 47.3 m^2, og et batteri med en størrelse på 7.5 kWh. Systemet will under designforholdene ha en 10 timers daglig operasjonstid under de respektive klimatiske forholdene. For disse betingelsene vil systemet nedkjøle 2880 kg epler fra 36.4 °C til 3 °C, 2560 kg druer fra 38 °C til 3 °C, og 3648 kg mango fra 39.7 °C til 12 °C i løpet av en dag. Nedkjølingen vil bli gjort i tre partier for epler og mango, og i fire partier for druer. For epler, druer og mango vil den respektive nedkjølingstiden være 173, 110 og 175 minutter, og den respektive COPen til kjølesystemet ved disse dimensjonerende forholdene er 3.81, 3.857 og 4.042. Det komplette nedkjølingssystemet undersøkes i forhold til det Indiske scenariet, og det konkluderes med at systemet har flerer potensielle fordeler her.

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Nomenclature

Latin letters

$\dot{E}$	Energy flow rate	W
$\dot{m}$	Mass flow rate	kg/s
$\dot{Q}$	Heat flow rate	W
$\dot{V}$	Volumetric flow rate	m^3/s
$\dot{W}$	Work rate	W
$\dot{W}_{resp}$	Heat of respiration generated by fruits and vegetables	W/kg
A	Area	m^2
B_s	Battery size in terms of energy	kWh
Bi	Biot number	$-$
c_p	Specific heat capacity at constant pressure	$kJ/(kgK)$
D_d	Depth of discharge correction factor	$-$
D_f	Doorway flow factor	$-$
D_s	Sphere diameter	m
D_t	Doorway open-time factor	$-$
E_f	Effectiveness of open-doorway protection	$-$
F_m	Density factor	$-$
Fo	Fourier number	$-$
H	Height	m
h	Specific enthalpy	kJ/kg
h_c	Convective heat transfer coefficient	$W/(m^2K)$
h_{lf}	Latent heat of fusion	kJ/kg
k	Thermal conductivity	$W/(mK)$
L	Characteristic dimension	m
L_x	Length of item x	m
m	Mass	kg
N_o	Number of door openings	$-$

n_x	Amount/number of item x	–
P	Pressure	Pa
p_a	Vapor pressure of air surrounding a commodity	Pa
p_s	Vapor pressure at a commodity surface	Pa
Q	Heat	J
S_f	Refrigeration load safety factor	–
S_i	Solar irradiance	W/m^2
T	Temperature	K
u_s	Superficial velocity	m/s
X	Vapour fraction	–
x	Distance	m
Greek letters		
α	Thermal diffusivity	m^2/s
δ_w	Wall section thickness	m
Δ	Difference between two state points	–
ϵ	Porosity, the void fraction of a space	–
η	Efficiency	–
μ	Roots of parametric equation	–
μ_{visc}	Dynamic viscosity	kg/ms
Ψ	Volume ratio	–
ψ	Inefficiency factor of a battery	–
ρ	Density	kg/m^3
τ	Time interval	s
τ_d	Time period for infiltration considerations	h
τ_o	Time the door stands open	min
τ_p	Time from initial door opening to closing	s
θ	Dimensionless temperature	–
ζ	Absolute humidity of air	$kgH_20/kg_{d.a}$
Subscripts		
air	Air	
amb	Ambient	
avg	Average	
box	Box holding product	
$bulk$	Bulk of commodity	
$center$	Product center	
$cooler$	Cooling system	
day	Day	

$eastwest$	East and west	
end	End	
$evap$	Evaporator	
fan	Fan	
hx	Heat exchanger	
i	State point i	
ice	Ice	
ind	Inside the cooling system	
$infilt$	Infiltration	
$inter$	Internal	
is	Isentropic	
j	State point j	
n	State point n	
$outd$	Outside the cooling system	
$panel$	PV panel	
$prod$	Product	
$real$	Real	
$resp$	Respiration	
sec	Section	
sl	Sensible and latent	
$superf$	Superficial	
sys	System	
tot	Total	
$trans$	Transmission	
w	Wall	
Coefficients and constants		
f_{resp}	Respiration coefficient	$-$
g	Gravitational constant	$9.81m/s^2$
g_{resp}	Respiration coefficient	$-$
k_t	Transpiration coefficient	$ng/(kgsPa)$
U	Overall heat transfer coefficient	$W/(m^2K)$
Abbreviations		
CA	Controlled atmosphere	
CFC	Chlorofluorocarbon	
CFD	Computational Fluid Dynamics	
COP	Coefficient Of Performance	
EES	Engineering Equation Solver	

GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
IoT	Internet of Things
ODP	Ozone Depletion Potential
Ppm	Parts per million
PV	Photovoltaic
R1270	Propylene
R290	Propane
R600a	Isobutane
R717	Ammonia
R744	Carbon dioxide
Re	Reynolds number
RFID	Radio-Frequency Identification
RH	Relative Humidity
TTI	Time-Temperature Integrator
UT	Union Territory
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1 Background

Hunger is still one of the most prominent challenges facing the global community, even though enough food is produced each year to feed more than the entire world population(FAO, 2018). There is a global loss of 1.3 billion tonnes of food each year, and reduction of these losses are key in sustaining the livelihood of millions of starving people. India is one of the largest producers of food globally, but also one of the larges sources of postharvest waste. With a population that is expected to rise both in numbers and in individual wealth in the coming years, the importance on maximizing the value and output from food production is key. As the cold chain capacity in India only covers a fraction of the food produced, and with documentation of poor logistical solutions, numerous intermediary stakeholders, and little use of advanced technology in food production, the wastage of food before it reaches the consumer has been documented to be 30 to 40% for fruits and vegetables (Hegazy, 2016), while some report even higher numbers. There is a definitive need for cold chain implementation and efficiency increase in India, a need which is especially relevant for the largely poor and rural living population. The use of refrigeration systems can be highly energy intensive, and working fluids used in such systems can have high environmental impacts. So much so that the proper management of these fluids are considered to be the single largest contributing factor to reduction of greenhouse gases overall (Hawken, 2017). It is therefore imperative that the coming development of cold chains in India and similar countries is done in a sustainable and environmentally friendly fashion.

The need for portable and renewable cooling

A portable and renewable off-grid cooling system could prove as a viable solution for many of the issues present in the Indian scenario. A large part of the food production in India is done in the rural and poor areas, where there is little or no electrical supply and stability, and very few accessible options for a cold chain. The inclusion of a portable cooling system allows rural farmers to gain access to a cold chain they would not otherwise reach, and the use of a off-grid energy solution allows such a system to have viable uses even in areas with no electrical grid. The use of designated cooling systems is furthermore among the most value adding and efficient contributions to a cold chain through quality enhancement and increased shelf life of fooditems, something which is especially relevant for horticultural products harvested in high temperature conditions (Kanlayanarat et al., 2009).

1.2 Problem description

There is a definitive need for cold chain implementation and efficiency increase in India, a need which is highly relevant for the largely poor rural population. One possible way of reducing losses and increasing product value of fruits and vegetables in India is to quickly cool the product after harvest. In this project, a portable cooling system based on renewable energy will be designed. The system will be sized so that is movable on the back of a truck, and emphasis will be made on environmentally friendly design with natural refrigerant and solar power as energy input. The system will be designed as an off-grid solution that provides cooling possibilities in areas of fruit and vegetable production with little or no connection to the electrical grid. The tasks to be considered are:

1. Literature review on:
   (a) The cold chain, with emphasis on the Indian scenario.
   (b) Solar based cooling systems.
2. Investigation into relevant Indian fruits and vegetables with regards to typical cold chains and product properties.
3. Design a portable cooling system based on renewable energy using a natural refrigerant.
4. Make a simulation tool to determine energy use, performance and behavior of the designed system.
5. Investigate potential feasibility of the designed system in the Indian scenario.
6. Preparation of a scientific paper from the main results of the Master Thesis.
7. Make proposals for further work.

The work will be conducted in cooperation with SINTEF Ocean and IIT Kharagpur as part of the Re-FOOD research project. As part of the work, an international stay at IIT Kharagpur will be conducted from 21.01.2019 to 05.04.2019. The objective of this student work is to participate in projects for improving and developing the cold chain in India. More specifically, the goal of the thesis is to investigate the Indian cold chain, and develop a conceptual design of a cooling system applicable to the investigated scenario. The scientific paper is given in word format to the supervisor of this master thesis, Prof. Trygve M. Eikevik.

1.3 Structure of the thesis

Each chapter will be initiated by briefly summarizing the contents presented in the given chapter.

Chapter 1 is an introduction to the problem being addressed in the thesis. The background illustrating the importance of such work is briefly explained, the problem description and tasks to be considered are given, and an overview of the thesis structure is presented.

Chapter 2 is an investigation into literature relevant to the work of the master thesis. The topic of cold chains is studied for the recent trends, workings, methods, tools and current status of the subject. Specific considerations for warm climates are further studied, with emphasis on Indian cold chains. Furthermore, some insight into relevant cooling systems is studied.

Chapter 3 is a documentation of relevant aspects for use of the later designed cooling system in India. The chapter includes a summary of relevant information for refrigeration in India, presentation of results from a survey conducted in India, investigation into a selection of horticultural products that may need cooling, illustration of Indian cold chains, and suggestions for how a cooling system can be designed in relation to the Indian considerations.

Chapter 4 presents the chosen design and the method used for dimensioning a cooling system in the Indian scenario. The physical layout of the system and how it will operate is presented, the theory used to explain the physical behaviour of the system is shown, and the corresponding computer simulated implementation of this theory is explained. Also included is a logistical solution for use of the designed system in India, and the operating conditions for the system.

Chapter 5 presents relevant results from the simulation of the cooling system, and discussions are done related to the validity, behaviour and choices made. Furthermore, the complete system and its operation is discussed in relation to the knowledge gained in the previous chapters.

Chapter 6 states the conclusions made from this master thesis work.

Chapter 7 states suggestions for further work related to this master thesis work.

The bibliography lists the sources of information used for the work on this master thesis.

The appendix gives additional information related to the thesis work, that is not included in the main body of the text. This includes additional theory and methods relevant to the work, the complete simulation code that has been made, and a risk assessment form for travel to India.

Chapter 2

Literature review

2.1 The cold chain

Background and trend

The cold chain is the linkage of processes and the equipment used when a perishable product and its activities is controlled and monitored throughout its supply chain, this is done to avoid product degradation and is mainly achieved by use of refrigeration as temperature control (Aung and Chang, 2014; Montanari, 2008; Ndraha et al., 2018). The typical cold chain of perishable food is illustrated in Figure 2.1. In general, a cold chain is firstly initiated at the point of cooling, i.e when the product

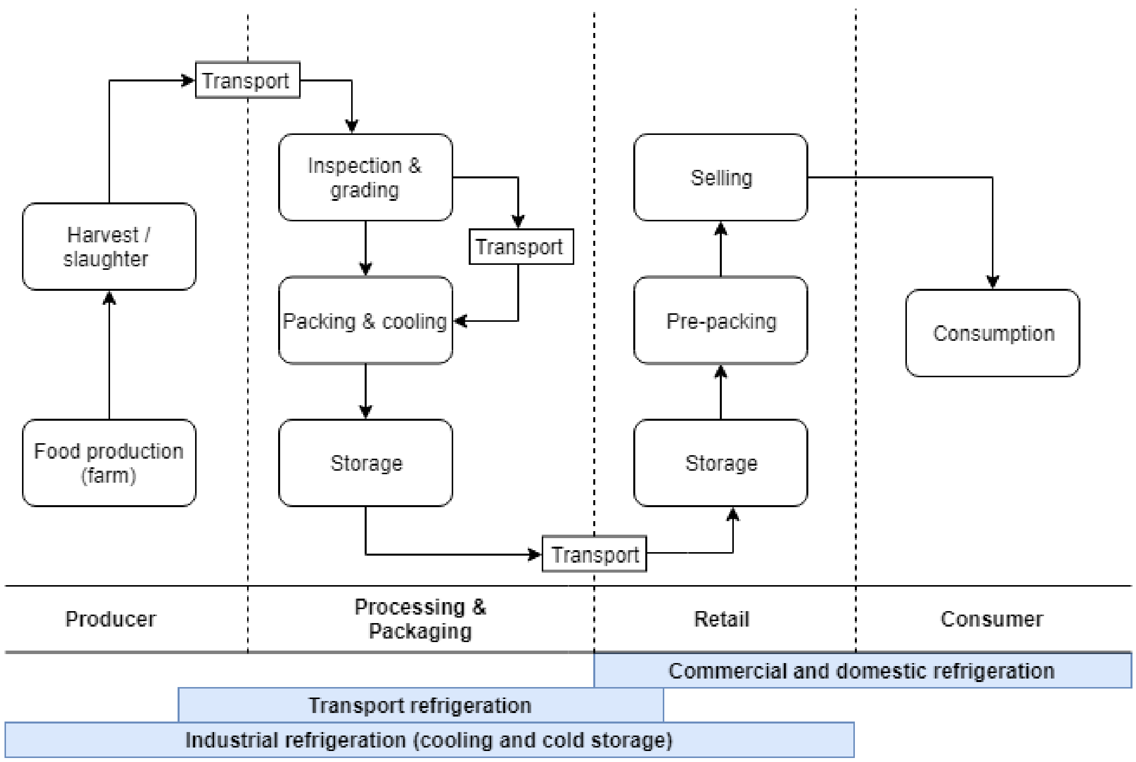


Figure 2.1: Illustration of the cold chain (Guilpart and Clark, 2018)

temperature is reduced down to proper storage temperature. This temperature is preferably kept constant throughout the rest of the movement and handling that the product will experience before it reaches the consumer. When this is achieved with minimal temperature variation and maximum logistical efficiency, the cold chain is considered to be optimal.

The need for a cold chain comes from the perishable nature of certain items and products, and the desirability of preventing these items from decreasing in value, integrity and quality. Products that benefit from the use of a cold chain are generally biological material that degrade when exposed to the natural environment. This include vaccines, blood, fruits and vegetables, meats, fish and dairy products among others (Joshi et al., 2011).

Over the course of the last 20 years the academic publications on the topic of food cold chains show a trend towards increased focus and interest (Shashi et al., 2018; Ndraha et al., 2018). The trending increase in interest for the subject of food cold chains follows the increasing acknowledgement that there are large losses in edible food-products as a result of improper cold chain management and analysis (Badia-Melis et al., 2018). The literature review on the topic of food cold chains by Shashi et al. (2018) present a graph showing the trend, stating that their literature review is the first study based on peer-review articles that covers close to all aspects of the food cold chain. The presented graph illustrates the number of papers published each year from 2001 to 2016, indicating the trending increase in topic interest for food cold chains, see Figure 2.2. A similar trend and graph can be found in the review by Ndraha et al. (2018), who draws the same conclusion of more studies published, and increasing interest in cold chains.

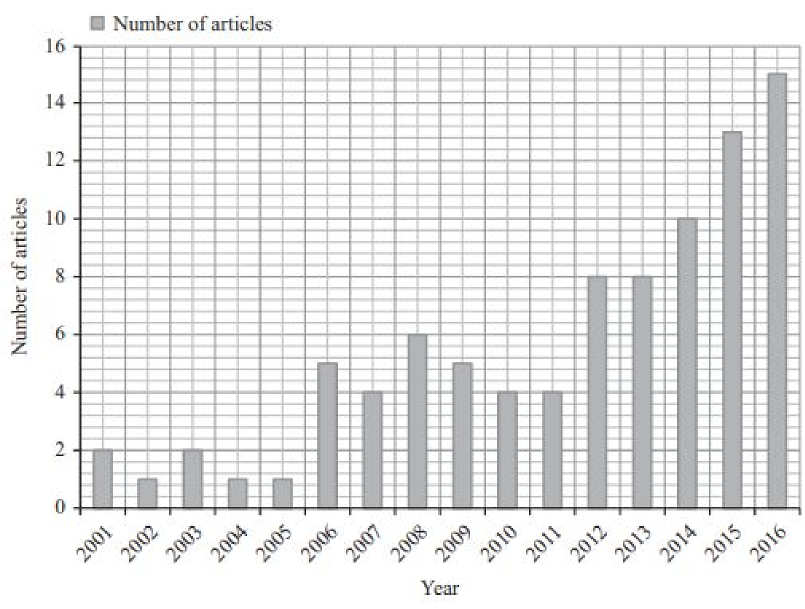


Figure 2.2: Trend in relevant food cold chain publications for the literature review by Shashi et al. (2018).

Investigations into the fresh produce(fruits, vegetables and flowers) cold chain literature in the years 1989-2009 show similar increase in topic interest, but to some extent an absence of academic journal publications (Shukla and Jharkharia, 2013). Their findings indicate that in this time period many stakeholders have their primary focus on costumer satisfaction and maximizing revenue rather than waste reduction.

Primary cooling, secondary cold storage

The cold chain generally starts with primary cooling, which for a fooditem is the temperature reduction of a commodity as shortly after harvest or slaughter as possible. This is for horticulture generally referred to as pre-cooling, however the term pre-cooling will just be referred to as cooling throughout the scope of this thesis. The primary cooling reduces the commodity temperature from ambient harvest or slaughter temperature down to proper storage temperature. This should be done as quickly as possible after harvest or slaughter, so that the commodity is experiencing decaying conditions for a minimal amount of time. The process of cooling a commodity is generally very energy intensive, and is often the most energy intensive part of the cold chain. For this reason, the primary cooling is often times done separately from the storage of the commodity, where a designated system that has been specifically designed for reducing the commodity temperature is used. After the commodity has been cooled down to a desired temperature, it is placed in a secondary cold storage. The cold storage should be designed to have optimal temperature, atmosphere and humidity conditions for keeping the quality and integrity of the commodity in good and safe conditions, for as long as is required until the commodity will be sent to a retailer or it is consumed.

Temperature abuse, methods and logistics

The main impacting factor on food quality and shelf life in a food cold chain is the cold chain temperature and how this is managed, making it important to understand why and where there are unwanted temperature variations in the cold chain - The temperature abuse of the cold chain (Ndraha et al., 2018). This comes from the vital correlation between the rate at which most fresh food perish and the temperature of the commodity (Eriksson et al., 2016). Although of high importance in optimizing cold chains, the vast majority of temperature abuse is reported in developed countries, while there are limited research in the scale of temperature abuse in developing countries (Mercier et al., 2017; Ndraha et al., 2018). The reason for this is most likely that developing countries have a larger focus on actually implementing working cold chains in the first place, rather than measuring and reporting temperature data to optimization links of a potential one (Mercier et al., 2017). Based on the high amounts of temperature abuse occurring in developed countries, it can be assumed that the same is even more prevalent in developing countries (Ndraha et al., 2018).

As the temperature of products is vital in maintaining sustainable food cold chains, there is high importance on the logistics and traceability methods used in a food cold chain to maintain and supply correct temperature (Ndraha et al., 2018). Logistical methods are a field of study in it self, where the attempt to optimize and most efficiently plan the distribution and organization of a complex operation is done. In terms of cold chain logistics, the goal will be to achieve the most efficient path from producer to consumer, where the temperature is kept at desired levels with as little temperature variations as possible(Ndraha et al., 2018). Since a typical cold chain is made up of several separate stakeholders, the logistical considerations will be a complex combination of the needs and desires of all the different stakeholders. For this reason, considerations regarding the logistics of a complete cold chain is often overlooked and sub-optimal, resulting in food losses and temperature variations due to the lack of cooperation between stakeholders, a scenario especially prevalent in developing countries(Ndraha et al., 2018; Gokarn and Kuthambalayan, 2017).

The initial methods for improvement of the cold chain logistics is to increase cooperation between the different stakeholders for better transparency of operation at each level, this is especially relevant for cold chains where the stakeholders work independently of each other(Gokarn and Kuthambalayan, 2017). Further considerations are to optimize a functioning logistical chain for best quality of commodities and highest stakeholder revenue, where several technological tools and managerial methods can be used to increase cold chain efficiency through proper tracking and management of commodity flows (Montanari, 2008).

Several logistical methods have been suggested in published papers for optimizing the logistics of cold chains. Hsu et al. (2013) models solutions for optimal delivery cycles of foods at different temperature ranges, where the model provides a possible methodology of determining effective delivery cycles of different fooditems. A relating study by (Hsu and Chen, 2014) follows up by suggesting solutions for optimal delivery size and scheduling for similar considerations. Another study by Hsiao et al. (2018) suggests a solution algorithm for improving the logistical distribution of delivery vehicles for the final stages of the cold chain, while the study by Hsiao et al. (2017) formulates a model problem for food cold chain distribution, and produces from this a potential distribution plan that meets the consumer needs and requirements.

Traceability of the cold chain is a method of further optimizing links and logistics of food distributions from farm to table(Engelseth, 2009). The model solutions for optimizing logistics of the cold chain mentioned in the previous paragraph, show methods that are starting to utilize technological tools such as simulation to improve the cold chain. Traceability methods in the cold chain takes this connection between logistical considerations and technological tools further, where monitoring and data collection of the links and commodities in the cold chain is used to highlight issues and potential improvements in the cold chain(Oskarsdottir and Oddsson, 2019). Traceability of the cold chain is achieved through use of technological tools such as monitoring devices and sensors(Engelseth, 2009), and is the tracking and collection of information or data about the commodities and links in the cold chain. With the help of these tools, information can be acquired and analyzed to find bottlenecks in terms of food loss, reduction in quality, and possible cold chain inefficiencies(Oskarsdottir and Oddsson, 2019). Further use of other technological tools can be of high value in making a cold chain as effective and safe as possible, and require attention(Ndraha et al., 2018).

Technological tools

Many technological tools are used in cold chains to improve traceability, safety, efficiency and reducing losses. The most important tools are described in Table 2.1.

Tool	Description	Helpfulness	Challenges	Reference
Best before date printing	Tags printed on food with predicted expiration date	Determine perishability and quality, required by some legislation	Mismatch between predicted and real shelf life leading to wastage	Gransson et al. (2018), Marklinder and Eriksson (2015)
RFID(Radio frequency identification) tags	Tags giving traceability data when interacted with	Tracking of temperature, humidity etc. upon interaction	Signal delays, low data capacity, small reading range	Kumari et al. (2015), Jedermann and Lang (2007)
WSN(Wireless sensor network)	Electronic sensors monitoring traceability data continuously	Continuous tracking of temperature, humidity, position etc.	Signal delays, lack of robustness	Wang et al. (2015)
TTI(Time-temperature integrator)	Systems predicting product history based on i.e chemical or bacterial change	Real time estimation of perishability and quality, widely used	Can underestimate shelf life giving unnecessary wastage	Arias-Mendez et al. (2014), Koutsoumanis and Gougouli (2015)
Data analysis	Capture and analysis of datapoints across a cold chain	Locate potential cold chain issues, i.e temperature abuse and logistical inefficiencies.	Requires resources and equipment for data capture and analysis.	Chaudhuri et al. (2018), Singh et al. (2018)
IoT(Internet of things)	The communication and connection between objects through the internet	Interconnect separate stakeholders, improved transparency and cold chain control	Requirement for equipment and systems for operation	Yan et al. (2016), Verdouw et al. (2016)
Packaging & insulation	Materials used during storing, transport and retail of commodities	Protection of commodity, easier storage and transport	Restriction of cooling airflow, waste from material	Coles et al. (2003)

Table 2.1: Important technological tools used in cold chain management.

The current cold chain

As illuminated up until this point of the literature review, the research forefront in cold chain technology and practice has evolved through the last 20 years. Prior focus primarily involved costumer satisfaction with waste reduction and energy consumption having secondary priority (Shukla and Jharkharia, 2013). However the current day focus on cold chains shows increased focus on logistical optimization and better traceability, and with the use of new technologies such as RFIDs, WSNs, TTIs, the IoT, and big data analytics, better temperature control and measurement is achieved (Badia-Melis et al., 2018).

The large amounts of food waste and the less than satisfactory cold chain implementation in developing countries are recognized by many authors in the field of cold chain research (Gligor et al., 2018). As emphasized up until this point, the correlation between level of technological advancement and efficiency of a cold chain is logical. However the conditions a cold chain must be operated in is also of importance, such as warm and cold climates which impacts the considerations that must be done along the cold chain. Therefore it is of relevance to investigate the specific challenges and solutions that has been studied in such regions.

2.2 Warm climate cold chain

The differentiating factor in warm climate cold chains is quite obviously the warm ambient temperature, where warm climate is for the scope of this thesis considered as that of the most typical areas of high ambient temperature. These are areas such as the southern parts of Asia, Africa and central South America, or local areas of similar climatic conditions.

As previously stated, the main impacting factor on food quality and shelf life in a food cold chain is the temperature(Ndraha et al., 2018). Ambient temperatures in warm climates can be as high as 40-55 °C in the warm months, meaning the degradation of food and ultimately the rate of spoilage is greatly increased if refrigeration of the commodity is not done. As a general rule, the rate of degradation is doubled for each increase of 10 °C, meaning the rate of degradation for high ambient climates can be as much as four to six times as large as comparative colder climates at 20 °C in the same season(Kitinoja, 2013). Swiftly achieving and maintaining a temperature that decreases rate of degradation and ensures food quality and safety is crucial in such environments, and is of high concern for an optimal cold chain and reduction of food losses(Aung and Chang, 2014).

Other considerations include that of refrigeration systems and their design in high ambient conditions. Since the rejection temperature at the condenser must be high with high ambient conditions, the choice of working fluid require considerations so that effective refrigeration can be achieved(Bruelisauer et al., 2013), where $\mathrm{CO_2}$ is the one that requires greatest modification of a system. Lorentzen (1994) describes the working fluid CO_2 as one of high potential due to its beneficial properties and low environmental impact, however its use in high ambient conditions are challenging. For high ambient conditions these systems must be modified to give a good enough overall performance, such as the system solution investigated by Gupta and Dasgupta (2017).

Further possibilities that have been investigated for high ambient temperature refrigeration is the use of evaporative cooling(Basediya et al., 2013; Dadhich et al., 2008). These types of systems are cheap and work well in high temperature and low humidity climates, but are very dependant on such conditions, and perform poorly under humid or milder conditions(Duan et al., 2012). Under appropriate conditions, this technique can be particularly beneficial for the cooling of fruits and vegetables, as the favorable environment for storage of fruits and vegetables is the low temperate and high humidity produced such systems (Jain, 2007). Furthermore, there is most often a correlation between a warm climate and high solar irradiance, which gives potential for use of solar power as the energy input of refrigeration units in these areas. Such systems are becoming more actual, and the potentials for solar powered refrigeration systems show great promise both economically and performance wise in areas of decent solar irradiance(Lazzarin, 2017).

India

India is a typical country with a warm climate, where the above considerations are prevalent in its cold chain. However, India is also a developing country, and as previously seen there is a clear correlation between how developed a country is, and how good its cold chains are(Gligor et al., 2018). The combination of these factors are the causes for large postharvest wastage of food in India, where 10 to 25 % of products like meat and fish are lost, and as much as 30 to 40 % of fruits and vegetables are lost(Hegazy, 2016). These losses are amplified in importance as India is one of the worlds largest producers of food due to its appropriate climate, especially in terms of tropical fruits and vegetables(NCCD, 2015).

India is a country of plentiful natural resources with a high degree of soil fertility, where as much as half of its total land area is farmable for agriculture(Halder et al., 2011). India is overall the second largest producer of fruits and vegetables in the world, but it is also one of the largest sources of food waste globally. The supply chain, and therefore also a potential cold chain, for fruits and vegetables are often time more complex than other chains due to high perishability in the Indian climate and large fluctuations in supply and demand.

Several published studies have been done relating to Indian cold chains and food waste, and the main problem areas are for the most part clearly identified and known(Gokarn and Kuthambalayan, 2017). The Indian cold chain is often times segmented and comprised of many different stakeholders throughout, with the addition of sub-optimal use of technological tools, poor logistics in these systems and high perishability due to the ambient conditions, the resulting losses occur(Viswanadham, 2006). This is especially relevant for Indian fruits and vegetables, where waste can largely be attributed to the many independent links in the cold chain not working symbiotically, lack of cold chain infrastructure, poor harvesting methods, and inefficient logistics in the food cold chain (M. and K., 2016). These problem areas constitute the bottlenecks for proper implementation of cold chains in India, and they are all interconnected in cause and result of each other (Figure 2.3).

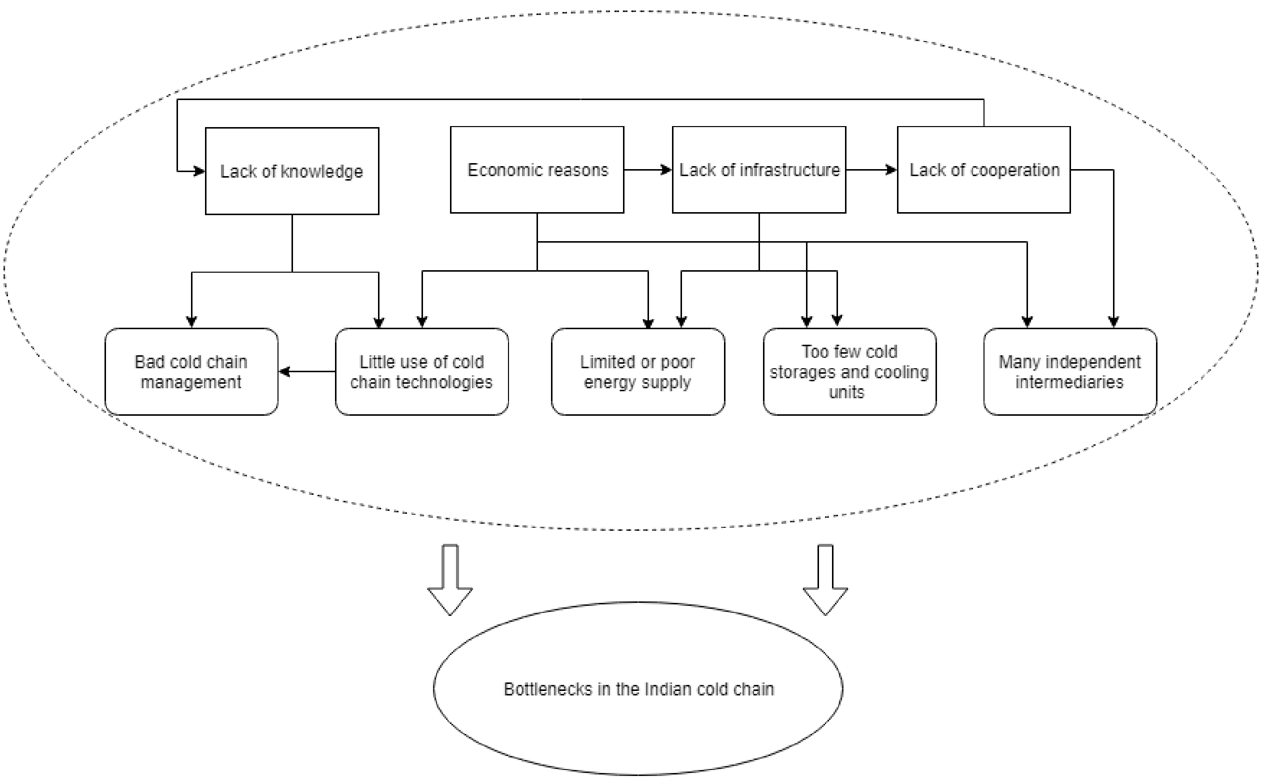


Figure 2.3: Illustration of the major causes for bottlenecks in the Indian cold chain, and their interconnectivity (Negi and Anand, 2015).

As the causes of food waste is for the most part identified and studied for the Indian cold chain, the real challenge is the economical and sufficient implementation of cold chains appropriate to the Indian scenario, in a sustainable and efficient way(Hegazy, 2016). While India is increasing in both population and as more citizens are working their way out of poverty, there will also be a great increase in the amount of refrigeration needs of both homes and food. Due to the gap in technology, the available standards of refrigeration systems are often inefficient and outdated, many of which are based on environmentally harmful working fluids. The energy that will be used to power all these new refrigeration systems, and the use and management of the needed working fluids are vital for the future of the environment. The importance is stressed by one of the most comprehensive projects withing environmental solutions, the drawdown project by Hawken (2017), which place the proper management of refrigerants as the single most important solution available for the reduction of greenhouse gasses. The potential impacts of not stressing and facilitating for good solutions in the future of these groups can therefore prove to give dramatic effects on the environment(SEforAll, 2018).

2.3 Relevant cooling systems

In perspective of the cooling system for design in this thesis, a short insight into the methods and technologies of potential in high ambient temperature cooling systems and associated renewable energy sources is relevant.

The process of cooling fooditems swiftly after harvest or slaughter has been demonstrated by many sources of research to be a clear catalyst in reducing decay, slowing respiration, reducing moisture loss, and in general causing a longer shelf life (Aswaney, 2007). Horticulture will after harvest generally have a higher temperature than the preferred storage temperature, and the reduction of the product temperature through cooling is one of the largest energy requirements in a cold chain, which is particularly prevalent for products in high ambient conditions. Having a designated system to remove the large amount of field heat in a harvested horticultural product will therefore be imperative in increasing shelf life and quality of a product, and will also allow refrigeration systems further down in the cold chain to be of smaller capacity since the necessary heat of the product is already removed (Rahman, 2007). However, for the process of cooling to be viable it is vital that the cold chain is uninterrupted and stable, as the breaks in the chain will cause the refrigeration gained to again be lost to the ambient.

Rahman (2007) summarizes several available methods of cooling, where the most prominent ones for cooling of horticulture is simple room cooling, forced air cooling, evaporative cooling and hydrocooling. Room cooling and forced air cooling are the approaches most generally viable since this approach uses air as the heat transferring fluid, which is compatible with all horticultural products as long as the relative humidity is appropriate. Forced air cooling is simply a modification of room cooling where one or several fans cause a pressure difference which circulate air around a refrigeration system and the products, at a faster rate than the natural convection used in standard room cooling. For comparison, the use of forced air cooling can reduce the cooling time to as little as 10-25% of the cooling time in comparative room with no pressure difference. Hydrocooling is an even faster method of cooling, as the heat transfer rate through water due to its large heat capacity is much higher than for air. Hydrocooling does however pose practical problems for several horticultural products as it requires the product to be fully compatible with being submerged in water, and a hydrocooling water bed will also become a accumulator for contamination and soil which must be considered. Evaporative cooling is an inexpensive method well suited for products of relative high storage temperatures, where the physical process of evaporation of water is utilized to draw out heat from a product when dry air is moved over a wetted product.These types of systems are cheap and work well in high temperature and low humidity climates, but are very dependant on such conditions, and perform poorly under humid or milder conditions (Duan et al., 2012).

As the need for cooling or cold storage increases with temperature, and since the temperature is most often related to the solar irradiation of a region, the potential of using renewable solar power for cooling applications in the agricultural sector of warm climates is a highly relevant solution (Kim and Ferreira, 2008; Mekhilef et al., 2013). The use of renewable solar power for cooling and refrigerated storage applications have promising outlooks, as shown in the investigation of potential technologies such as solar electric and solar thermal refrigeration by (Kim and Ferreira, 2008). For the Indian scenario, solar power is abundant in many regions, while at the same time many rural regions where food is produced has low quality or no electrical grid connection (Sen and Bhattacharyya, 2014). India is the country with the largest rural poor population in the world, many of which do not have access to proper electrical supply and lack connections to proper cold chains. As many of these are also involved in farming activities but lack the value addition of a cold chain, the potential for a system operating off-grid and using solar refrigeration for cooling has the potential to increase revenue and probability of livelihood (SEforAll, 2018). As solar powered technologies grow in production numbers and technological advancement, such solutions provide both reliable, economically feasible, and renewable off-grid solutions (Lazzarin, 2017; Mekhilef et al., 2013). Furthermore, the potential for solar energy in agriculture show promise, and off-grid renewable solutions for rural India has the potential of being both affordable and reliable (Sen and Bhattacharyya, 2014; Mekhilef et al., 2013).

Chapter 3

The Indian scenario

Common practices in Indian cold chains and typical products of such cold chains will be investigated and documented in this section. The state of refrigeration in India is documented from literature, relevant horticultural products for potential cooling in India is investigated, and the corresponding domestic and export cold chains for such products is studied. Apples, grapes and mangoes are chosen to be the most relevant horticultural products for cooling in India, and it is these products that the cooling system will be designed for. Knowledge gained from the the field study at IIT Kharagpur is presented in the form of quantitative responses from the local people, in relation to the presented literature. The information presented is then used to form the basis on which a cooling system for the chosen horticulture in the Indian scenario will be designed.

3.1 Refrigeration in India

Current situation

The use of refrigeration in the rural parts of India is mainly attributed to the long term storage of a few selected commodities such as potatoes, or for some cases of very perishable items such as dairy products and frozen goods (NCCD, 2015). India is a vast country with large differences in ways of life and economic standard, and there are several developed exceptions to the overall impression of Indian cold chains and refrigeration usage. However the largest part of the population and economy is built around a culture of eating fresh locally grown and produced food, where little or no refrigeration is used.

As previously illustrated, there are many bottlenecks present in the proper utilization of cold chains in India. This goes hand in hand with the current low standard and lacking availability of refrigeration equipment and infrastructure in the country. The general use of refrigeration in India is for the most past still at a stage of infancy and lack of development, especially for perishable footitems. In addition, the quality and state of technology for much of the refrigeration equipment used in India is of poor quality and inefficient operation, where much of the equipment is made of low standard materials and is implemented poorly on site. The sector did not see significant rise in application before the early 2000's, as illustrated by the capacity of Indian cold storages reported by NCCD (2015) in Figure 3.1.

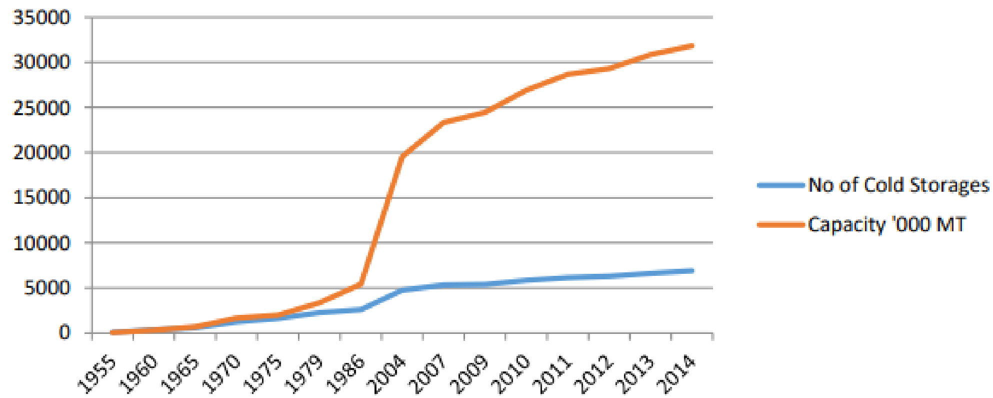


Figure 3.1: Evolution of the number of cold storages and corresponding capacity in 1000 tonnes of product for cold storages in India as reported by NCCD (2015).

Although the trend is in clear development, there is still a large gap between the current state of refrigeration and what is required to reduce losses of food and provide consumers with year round variation and quality. The capacity of cold chain infrastructure is an indicator of the mismatch between food production and handling capabilities, and this capacity is just a fraction of the necessary amount in India as seen inTable 3.1.

Cold chain infrastructure	Installed capacity	Required capacity	All India gap [%]
Pack houses [number of]	249	70 080	99.6
Cold storage [tonnes]	31 823 700	35 100 662	9.3
Refrigerated vehicles [number of]	9000	61 826	85.4
Ripening chambers [number of]	812	9 131	91.1

Table 3.1: Required and installed capacity of cold chain infrastructure for India in 2015 (NCCD, 2015).

NCCD (2015) finds an extensive lack of infrastructure other than cold storages, while the required capacity of cold storages is just lacking by about 10%. The report further estimates the lack of cold storage for fruits and vegetables nation wide to be around 8 million tonnes, while the required frozen cold storage is just 78 000 tonnes. This number of 10% is questionable, as this is the required cold storage capacity for all fooditems in India, and just by looking at the Indian production of fruits and vegetables one can see that there is some discrepancy (Table 3.2). Furthermore, the current and projected future requirements of cold storages in India is mainly used for potatoes, where over 75% of the total storage capacity is used for only this commodity. When all other fooditems such as dairy, meats and fish are also considered, there is reason to assume that the required capacity stated by NCCD (2015) is for the current state of cold chains in India, and not in terms of a fully developed industry. Other more recent sources put the amount of required cold storage capacity at more than 61 million tonnes, and that this capacity requirement also will increase greatly in the future (Roy, 2019).

Cooling of horticulture

The rapid removal of field heat directly after harvest is vital in high temperature conditions such as India, where just one hour of exposure to hot field conditions at around 35 °C will incur a loss in shelf life of one full day, even if the product is later kept at optimal storage conditions (Kanlayanarat et al., 2009). The same report made by FAO further states the importance of horticulture being rapidly cooled after harvest as one of the most efficient quality enhancements available, and that it is among the most value adding practices that can be used in the horticulture chain. However, specific cooling of fooditems is a concept rarely utilized in India, as exemplified by the cold chain infrastructure requirements in Table 3.1 where there is not even a mention of needed cooling. The general approach in India is to use cold storages for pull-down of the commodity temperature from ambient down to proper storage conditions, and cooling of fooditems is very rarely considered. This in turn may lead to overdimensioning of cold storages in capacity, and the commodity that is to be refrigerated will remain at elevated temperatures for an extended duration, which again reduces quality and shelf life. The same applies to the horticultural segment of Indian food production, where the need for cooling is not yet felt by the consumer and people are largely accustomed to buying seasonal produce from their local vendors. It is to a large extent the farmer and consumer that ends up absorbing the losses of both the lack of cooling and the lack of refrigeration in general, as these processes are something they have little control over in India (Aswaney, 2007).

There are some exceptions in India where cooling of horticultural products is not only occasionally used, but is the common standard for much of the harvested products. This is especially the case for exported grapes, where a large amount of the harvest is cooled immediately after harvest and a well developed cold chain is present (Aswaney, 2007). The reason for the use of cooling in the specific case of grape export is due to a line of trade that was initiated in the 1990s, where several businesses in the grape production areas started looking into exports to distant regions like Europe. The large travels distance takes about three week by boat, and the demand of the costumer requires the grapes to be maintained at high consumer quality. The only way of achieving this was found to be rapid cooling directly after harvest, and having a continued unbroken cold chain throughout. India is because of this now a large supplier of grapes to European countries like The Netherlands, Germany and The United Kingdom. Furthermore, the same article by Aswaney (2007) list several fruits and vegetables that have similar potential while requiring swift cooling after harvest, among them being apples and mangoes. With India's central geographical location in relation to the rest of the world, and its large production of horticulture, it has the possibility of being a vast global exporter to almost all parts of the world. For this to be achieved, it will however undoubtedly require efficient and large scale cooling promptly after harvest, and a well developed cold chain to accompany it.

Transport refrigeration

Very few commodities are regularly refrigerated during transport in India, as stated in Table 3.1, only around 15 % of the required capacity of refrigerated transport is currently available. Other sources of Indian cold chain industries estimate that there are 104 million tonnes of perishable products being transported domestically each year, and that only 4 million on these are kept at temperatures other than the ambient (Singh, 2019). Meats and fish are often times transported live between farm and consumer and slaughtered at or close to the point of sale. The situation is similar for fruits and vegetables, which are generally loaded in sacks and transported in the back of open trucks with no refrigeration. Figure 3.2 shows a truck outside Kolkata transporting potatoes to a storage. There are exceptions such as ice cream and other frozen products that can not be transported in the high ambient conditions without refrigeration, but these products are comparatively quite rare in most parts of India.

Figure 3.2: Typical truck transport of vegetables in India.

The refrigerated transport sector is largely unorganized and consists of many separated and individual stakeholders, like the case is for the rest of the Indian cold chain. As much as 75 % of the truck owners in India control five vehicles or less, giving rise to very poor logistics and difficulty of operation for stakeholders in the other parts of the cold chain. This again greatly hinders the ease at which proper cold chains and interactions between stakeholders can be achieved, and is a vital reason for the disconnect between the different parts of a potential cold chain in India. Furthermore, the road network is in many areas of poor quality, especially in rural areas where food is produced. This in turn can cause damage on transported food due to rough treatment, delay or hinder efficient transportation, and reduce the availability of produced fooditems to the market (Singh, 2019). There are however hopeful prospect in the sector as especially the refrigerated transport sector is on a path of growth, in adherence to the promising growth of the Indian cold chain industry in general (NCCD, 2015).

Refrigerants

CFCs (Chlorofluorocarbons), HCFCs(Hydrochlorofluorocarbons) and HFCs (Hydrofluorocarbons) have been commonly used as refrigerants and are still prominent in India, but such refrigerants are being phased out due to the legislations of the Montreal (1987) and Kyoto (1997) protocol. India is however classified in the A5 country group 2, which is the group that has the longest time span for phase out of HCFCs. The most commonly used refrigerants to date in India are listen in section A.2, and are for most application the respective HFC and HCFC refrigerants R134a and R-22, which have a very high environmental impact. The natural refrigerant class of hydrocarbons are considered for some small scale industry and domestic applications, but for the most part the suggested refrigerants that are to replace the currently used ones are still for other but less impacting HFCs. Furthermore, the option of using natural refrigerants are stated to be mostly considered for niche areas and applications. The justification for continued use of HCFC and HFCs are largely practical and economical, as the equipment and technologies required for use of more environmentally friendly refrigerants are not known as available or economically viable enough (ISHRAE, 2015a). Despite the current situation of refrigerant use in India, the position of the Indian society of refrigeration (ISHRAE, 2015a) on the future use of refrigerants is that the environmental parameters are more critical than traditional thermodynamic considerations. The phase out of damaging refrigerants will also be a reality in the near future, and the transition to more use of natural refrigerants and refrigerants that have little or no effect on global warming or the ozone layer is inevitable. Further information about refrigerants are given in subsection 5.4.1.

Energy sources

The use of cold chains and cold chain technologies are energy intensive, and will incur an extra cost for the potential stakeholders. For a year round warm climate such as for most parts of India, the energy usage of temperature reducing systems will be especially high. The primal energy medium for powering refrigeration systems is electrical power, and in India this electrical power is largely generated from coal with a sizable mix of renewables as well (Figure 3.3).

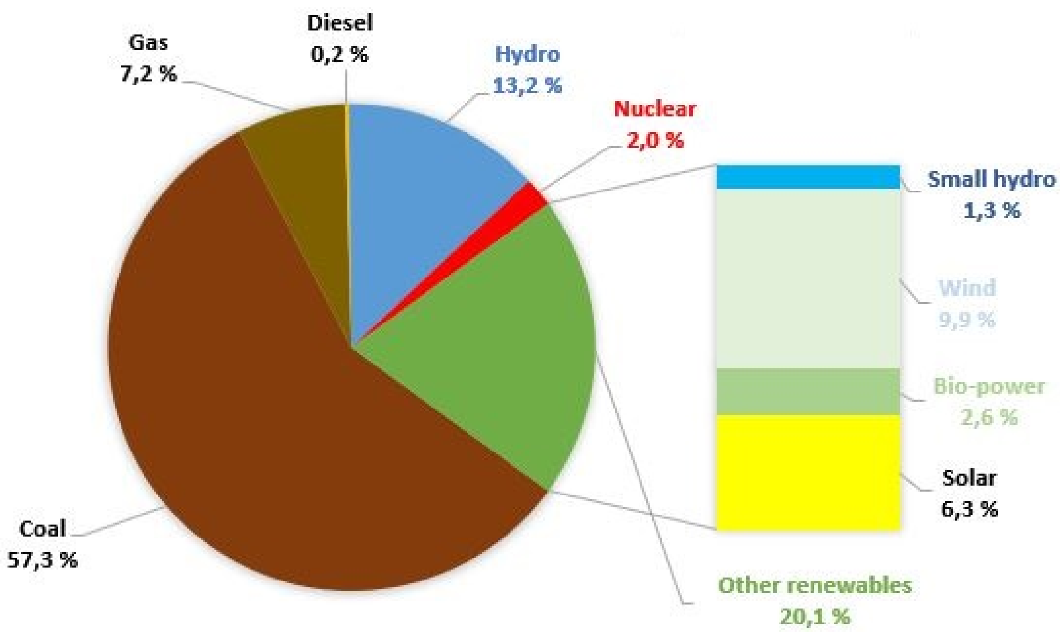


Figure 3.3: Indian electrical power generation sources, as reported by CEA (2018).

The large portion of coal in the mix gives an electrical supply which is environmentally unfriendly. However, a much more important factor is the stability and availability of this electrical supply. People living in modern urbanized areas and people with higher economical mobility generally have full access to sufficient power, but for a very large portion of people in India that do not match this description, the situation is quite the contrary. Large parts of Indian population, especially the rural and poor parts, have little to no connection to sufficient electrical grids, and those that are connected can experience frequent loss off power (Palit and Bandyopadhyay, 2017). This lack of power or power stability when it is accessible is a detrimental factor for the operation of refrigeration systems and cold chains in India, as keeping a stable low temperature in such a warm climate with unstable energy supply is near impossible. Furthermore, the price of electricity is very high compared to the available funds many Indians have, and the use of electrical power is limited to only the most vital uses. For these reasons, the use of renewable off-grid energy generation is not only an environmentally beneficial solution, but it may also be the most practically and economically viable solution is many Indian applications (SEforAll, 2018). The use of solar powered energy generation of refrigeration systems in warm and highly solar irradiated areas is one such application, where the diurnal cycle of available and required energy is generally in coherence.

3.2 Relevant fruits and vegetables

India is a country of plentiful natural resources with a high degree of soil fertility, where as much as half of its total land area is farmable for agriculture (Halder et al., 2011). The vast amount of farmable land and diverse climate in India enables it to be one of the most prominent producers of food in the world, where it is the second largest producer of fruits and vegetables after China. Statistics of total produced fruits and vegetables by region, complemented by statistics for some selected horticulture of high influence in India is presented in Table 3.2.

	All types				
Region (state/UT)	Fruits [tonnes]	Vegetables [tonnes]	Tomato [tonnes]	Potato [tonnes]	Mango [tonnes]
Andhra Pradesh	10 088 820	5 442 770	2 236 560	-	2 803 660
Bihar	4 230 630	14 400 120	1 001 010	6 345 520	1 464 930
Gujarat	8 477 170	13 401 390	1 319 110	3 549 380	1 241 590
Karnataka	7 023 690	7 804 570	2 046 140	455 450	1 725 670
Madhya Pradesh	5 783 060	15 568 260	2 285 900	3 161 000	371 480
Maharashtra	9 749 800	9 452 070	976 580	251 460	463 170
Odisha	2 386 940	8 755 510	1 290 990	278 750	778 720
Tamil Nadu	6 635 100	6 976 150	645 700	-	975 110
Uttar Pradesh	10 296 140	26 251 000	819 370	13 851 760	4 512 710
West Bengal	3 516 710	22 825 450	1 204 430	8 427 000	693 390
Remaining regions	21 994 980	38 186 670	4 906 180	7 096 730	3 612 090
Total	90 183 040	169 063 930	18 731 970	43 417 050	18 642 520

Table 3.2: Amount of fruits and vegetables in tonnes, produced by India in 2015, listed by a selection of influential regions (Agricoop, 2017, 2018)

A selection of important fruits and vegetables produced in India will be investigated further, where the information is based on the literature by Rahman (2007),ASHRAE (2018) and NCCD (2015) unless otherwise stated and referenced. Some complementing information about important food characteristics is included in section A.1, namely water activity, respiration, transpiration, ethylene production and sensitivity, and processing impacts.

General product information

Apples in India are largely produced in the northern regions of Jammu & Khasmir, Himachal Pradesh and Uttarakhand, which combined amounts to over 98% of the national production. India is the fifth largest producer of apples in the world, with a world share of about 3%. It is harvested seasonally from June to November, with peak season for most of the production from August to October. It has a low respiration rate (Table A.2), a high production of ethylene (Table A.3), and a high ethylene sensitivity (Table A.4). Apples stand out in terms of their average shelf life, which is substantially longer than any other type of fruit. They should optimally be kept at a temperature of between 0 and 1 °C, with 90-95% RH, with minor variations depending of the specific type of apple considered. Apples can under optimal conditions, which include a controlled atmosphere (CA), have a shelf life ranging from 3 months to a year depending on the type. They should be cooled shortly after harvest, as the amount of deterioration caused by keeping it at field temperature for one day equals one week in a proper storage. Freezing injury is a prevalent concern for cooling and cold storage of apples due to the product temperature being close to its freezing point(-1.1 °C), which can cause cell destruction, structural damage and moisture loss.

Grapes in India are largely produced in Maharashtra and Karnataka, which combined amounts to over 94% of the national production. India is the 9th largest producer of grapes in the world, with a world share of about 4%. They are seasonally harvested from November to May, with peak season from March to May. It has a low respiration rate, a moderate production of ethylene, and a low ethylene sensitivity. Grapes are harvested at a mature stage of growth, which means they must be cooled quickly after harvest to avoid overripening and decay of the products. Once the grapes have been cooled down to less than 4°C, they should optimally be kept in a cold storage at around -1°C and 90 to 95% RH. Grapes and especially their stems are highly susceptible to water loss both during cooling and storage due to their relative large surface to volume ratio, and it is important to keep a high humidity both during cooling and storage.

Mangoes in India are largely produced in Andhra Pradesh, Uttar Pradesh and Karnataka, which combined amounts to over 55% of the national production. India is also the largest producer of mango in the world, with a world share of 40%. It is mainly harvested seasonally from January to July , where most states have peak season between April and June. It has a very high respiration rate, a moderate production of ethylene, and a high ethylene sensitivity. Mangoes are tropical fruits, and are preferably stored and transported at about 12-13°C and 90-95% RH. After transport it is optimally ripened at 21-24 °C, but temperatures as low as 15-18°C can be sufficient. Below 10 °C mangoes can suffer chilling injury, and ripening at above 27°C can give a very strong flavour and spotted skin.

Onions in India are largely produced in Maharashtra, Madhya Pradesh and Karnataka, which combined amounts to over 55% of the national production. India is the second largest producer of onions in the world with a world share of about 20%, beaten once again by China which has a world share of about 26%. Onion harvesting in India varies by season, and the peak, lean and non-production seasons also vary by state. Peak season for most states is between February and June, such as for Maharashtra which has production only from March to May with peak production in April. A different example is Karnataka which has production from April to November with two separate peak season, from April to June and September to October respectively. Onions have low respiration rates, very low ethylene production, and low ethylene sensitivity. After harvest onions should optimally be cured until dry at 20 to 30 °C and 65-70% RH, this can be done in the field or in separate locations, and is done to avoid decay in later storage. The onion can then be sold and consumed shorty after for fresh consumption, or stored for a longer time to offset the seasonal nature of when it is harvested. A temperature of 0°C and a relative humidity of 65-70% is optimal for keeping the onion dormant, and it can under these conditions be stored for between 1 to 8 months depending on the type of onion.

Potatoes in India are largely produced in Uttar Pradesh, West Bengal and Bihar, which combined amounts to over 65% of the national production. India is the second largest producer of potatoes in the world with a world share of about 12%, beaten again by China which has a world share of about 26%. Potato harvesting in India is mostly seasonal, where the major producing states harvest from December until April, with peak seasons mainly from March to April. Potatoes have low respiration rates, a very low ethylene production, and moderate ethylene sensitivity. Potatoes are harvested either early crop during congested periods, but most often as late crop harvest when possible. Early crop potatoes are more easily perishable, and are generally stored immediately at 4°C before curing for 4 to 5 days at 21°C(to ripen and heal bruises and cuts) and then used. However if used for frying they should be stored at 21°C, to avoid sugar accumulation and dark colour in the fried potato. Late crop potatoes on the other hand benefit from being cured at 10 to 16°C directly after harvest, and can then be kept at 3 to 4°C for 5 to 8 months if needed. Potatoes in general can be kept relatively dormant at 10°C for between 2 and 4 months, and late crop potatoes that are to be used withing 4 months should be kept at this temperature instead. Greening of the potatoes is avoided by storing it in the dark, and a RH of between 90-95% is most beneficial for quality and minimal shrinkage.

Tomatoes in India are largely produces in Andhra Pradesh, Karnataka and Madhya Pradesh, which combined amounts to 50% of the national production. India is the second largest producer of Tomatoes in the world with a world share of about 10%, beaten by China which has a world share of about 32%. Tomato harvesting in India varies between the states and the months, but the largest part of the production is year round. Andhra Pradesh produces consistently all year, while Gujarat produces all year with peak production from December to March, and Karnataka produces only between May and September with peak production from May to July. Tomatoes have moderate respiration rates, a moderate ethylene production when mature and green, a high ethylene production when ripe and red, and a high ethylene sensitivity. Tomatoes are harvested when mature and green, and is preferably kept between 10 to 15°C and 90-95% RH. Temperatures below 13°C reduces ripening the most but in general little ripening delay can be practically achieved, furthermore this low temperature can increase later decay and hinder proper ripening to a bright red colour. The tomato is best ripened slowly between 14 to 16°C, but the most common practise is in temperatures between 20 and 22°C for best efficiency, ripening conditions above 21°C does however often increase decay.

The typical harvest seasons for the majority of production of each of the selected products in India is illustrated in Table 3.3. Where majority of production means that more than 50% of the harvest by weight is harvested as shown by the table. The harvest season for the remaining amount of commodity may vary slightly for states of minor production.

Product	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Des
Apples						Lean season	Lean season	Peak season	Peak season	Lean season		
Grapes	Lean season	Lean season	Peak season	Peak season	Peak season						Lean season	Lean season
Mangoes	Lean season	Lean season	Lean season	Peak season	Peak season	Peak season	Lean season					
Onions			Lean season	Peak season	Lean season	Lean season						
Potatoes	Lean season	Lean season	Peak season	Peak season								Lean season
Tomatoes	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest	Year round harvest

Peak season   Lean season   Year round harvest

Table 3.3: Indian harvesting season for the majority production of each type of the selected fruits and vegetables(NCCD, 2015).

An illustration of the major production states for apples, grapes and mangoes in India is given in Figure 3.4. There are as previously described also several other states with notable production of all these three fruits, and with production of a large amount of other commodities. It is however only the most relevant products and corresponding areas of production in relation to the scope of this thesis work is included here.

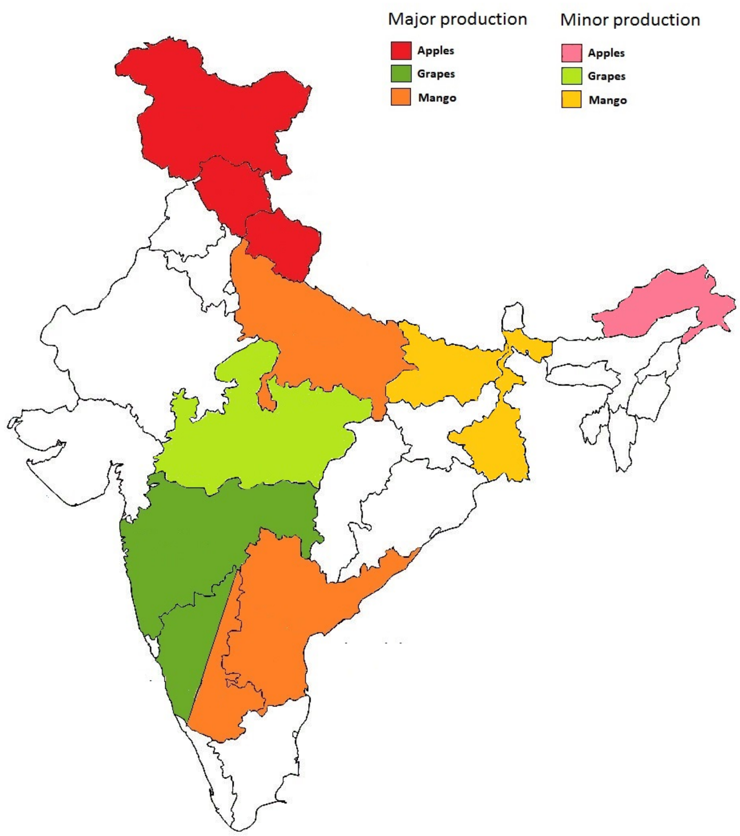


Figure 3.4: Illustration of the major production states of apples, grapes and mangoes in India, with the inclusion of some relevant states with minor production.

The potential shelf life of the selected products when refrigerated under proper conditions, as previously discussed, is tabulated in Table 3.4. The benefits of cold storage on shelf life is also illustrated, and the importance of CA conditions is included.

		Shelf life in weeks		
Commodity	Optimal temperature [°C]	Refrigerated	Unrefrigerated	CA benefit
Apple	0 to 1	12-52	2-4	High
Grapes	-1 to 0	4-6	1	Moderate
Mango	10 to 13	3-6	1-2	High
Onion	0	4-32	4-6	Low
Potato	4 to 21	12-32	3-5	Low
Tomato	10 to 15	3-7	1-2	Moderate

Table 3.4: Storage conditions and benefits for the selected Indian fruits and vegetables.

3.3 Relevant cold chains

How important a cold chain is in India is a matter of perspective. Potato is for example a product of high importance in terms of sustaining nutrition for the general population in India. This is reflected in the large amount of potato storages that are used compared to other fooditems, as seen in Figure 3.5.

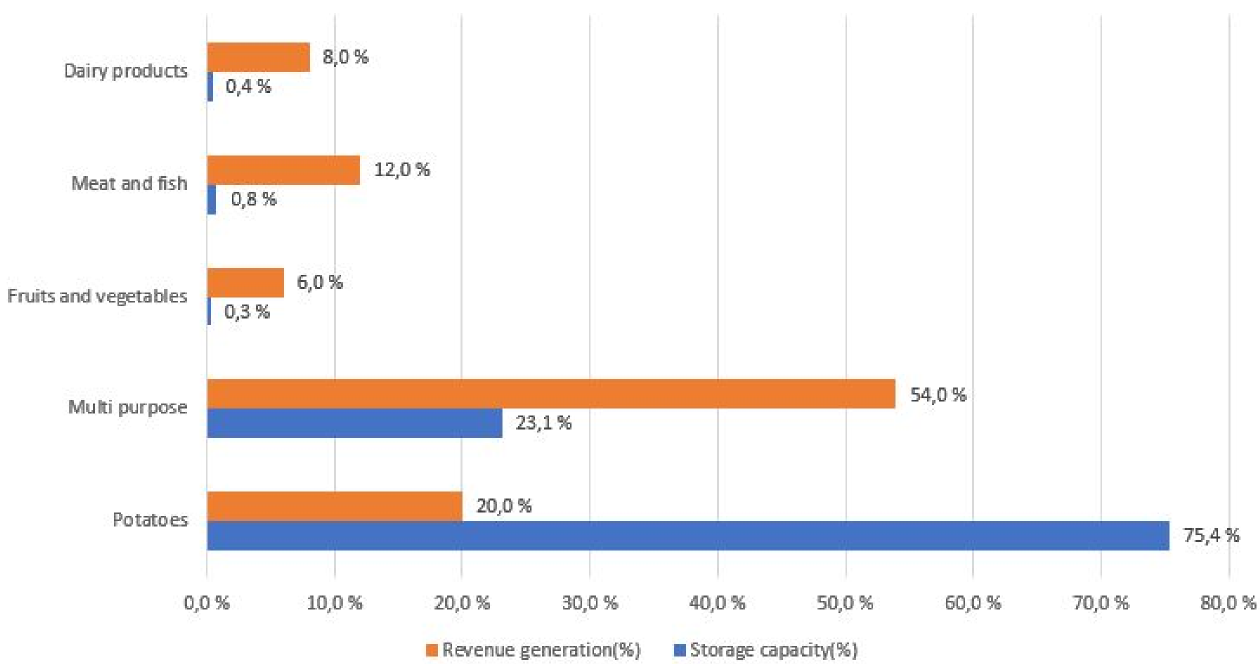


Figure 3.5: Comparison between cold storage capacity used, and revenue generated from the same storages in India for the year 2013 (RX-India, 2013).

In terms of economical value of the different categories of fooditems, there is a clear advantage in terms of the other types of food than potatoes. The storage capacity is however mainly used for potatoes so that a staple food source is maintained throughout the year, as potato is a basal nutritional product that can be stored for a long time. This is crucial when sustaining the large Indian population with food is the goal, however the economic feasibility of refrigerating low value products is not optimal.

When economic feasibility of refrigeration is considered, the importance of a cold chain shifts towards acquiring the highest possible value for a product, and to have sufficient demand and corresponding supply. The four top categories in Figure 3.5 illustrate this to a more noticeable degree. Relatively small amounts of the different foods are refrigerated, however the share of revenue generation from these small amounts are significant.

Products of continued consideration

For the scope of the rest of this master thesis work, the products that will mainly be considered are apples, grapes and mangoes. This is due to their relative high value, and relative high degree of perishability causing short shelf life if left in ambient conditions. These products are therefore considered most relevant for introduction of a cold chain, when possible real viability of such a cold chain is important.

3.3.1 Domestic

The optimal cold chain for domestic production and consumption of a commodity will more or less be equivalent to the general cold chain illustrated in Figure 2.1.

The real cold chain domestically in India is however very different, where the three types of horticulture for domestic consumption is most often produced and consumed in a similar manner locally. The cold chain is most often very inefficient, with numerous stakeholders, little or no refrigeration at all and with detrimental amounts of losses. For the case of domestically produced and consumed mangoes, post harvest losses has been estimated to be as much as 35%, and only 7% is losses at the consumer level(Sab et al., 2017). Due to a lack of willingness from farmers to be involved in the complications of the supply chain, a lot of the Indian domestic fruit sales are done through contract markets. The farmer and a middleman or commission agent makes an arrangement on quantity, quality and price before the commodity is ready for harvest, and the farmer is free of responsibilities other than the production and delivery. The contract market offers security of income and reduced risk, however the result for the farmer is also a lower profit on produced commodities(Gopalakrishnan, 2013). The typical domestic cold chain of fruits in India is in reality a supply chain with no refrigeration, as illustrated in Figure 3.6.

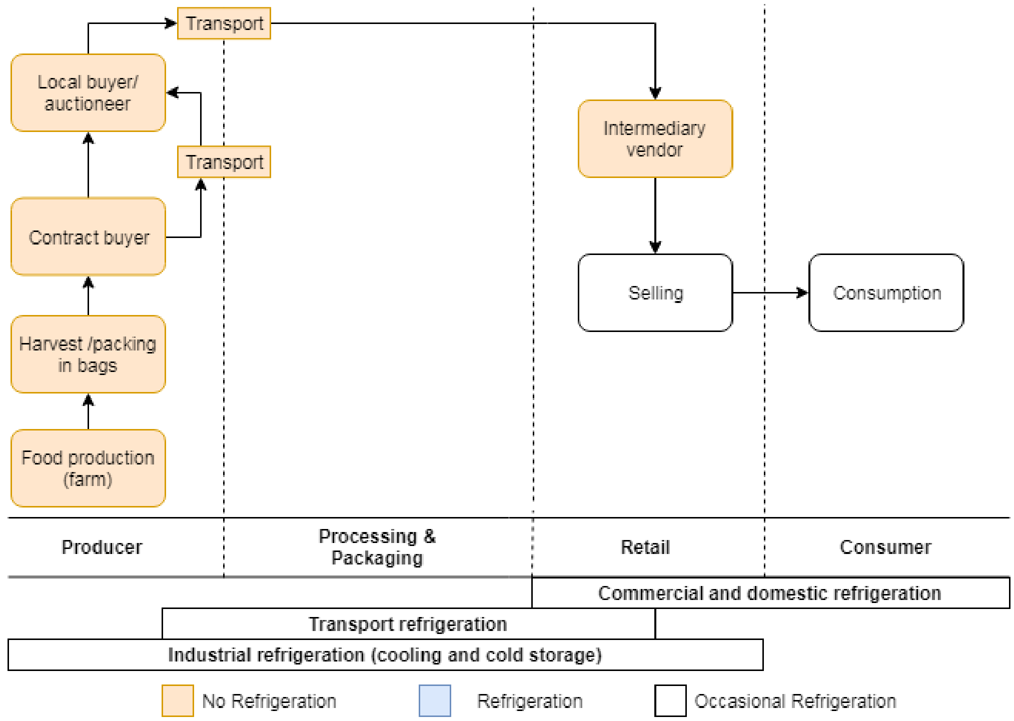


Figure 3.6: Typical supply chain of fruits domestically in India.

The domestic consumption is to a large extend determined by the areas of production for the three different fruits. The profile for consumption above and below national average of the three selected fruits is shown in Figure 3.7

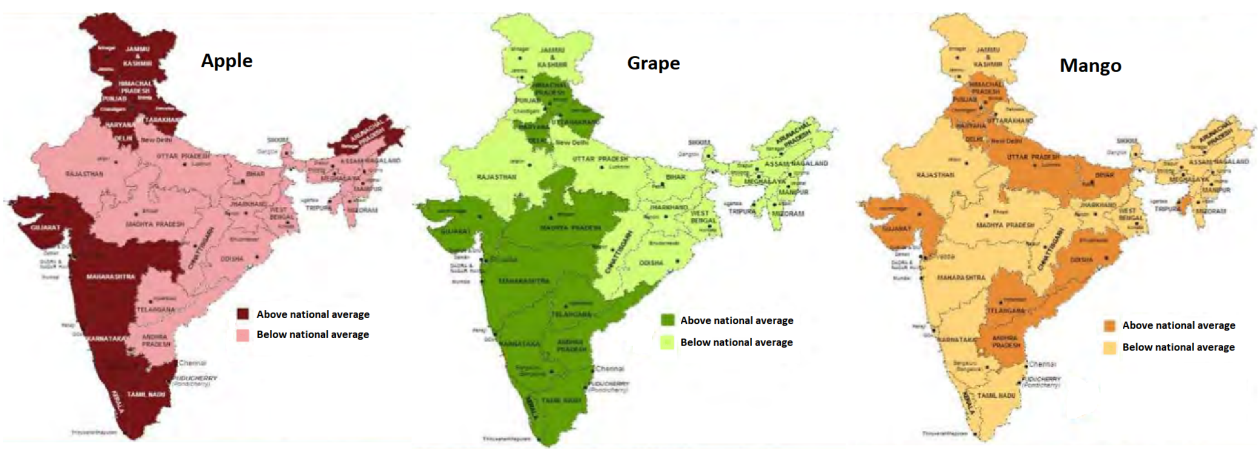


Figure 3.7: Per capita monthly consumption profile of apples, grapes and mangoes in Indian states (NCCD, 2015).

Much of the culture and infrastructure in the domestic market of fruits and vegetables is focused around the use of fresh food at all times, where there is no refrigeration at any point from production to consumption, i.e no cold chain. This might be a good solution for the foods that are bought and eaten shortly after it has been produced, it is however the direct opposite of a good solution for all the food that is not bought immediately, and for foods that must go through long time periods of transport or storage. This lack of cold chains, combined with many intermediary stakeholders and poor logistics in general, are largely the reason for the vast losses of food domestically.

This lack of refrigeration also causes a very seasonal supply and demand of the seasonally harvested fruits and vegetables, since the domestic supply in the market is more or less determined by the season of production(Table 3.3). The prices naturally follow the supply and demand in an opposite manner, making the prices drop significantly in the harvest season and then again rise significantly after the harvest season is over. This relationship is shown in Figure 3.8, Figure 3.9 and Figure 3.10 for apples, grapes and mangoes respectively. The implementation of swift cooling and proper cold storages in India has the potential for stakeholders to utilize these price fluctuations, and thus get a greatly increased price of sale at a later time.

Since apples have such a long potential storage life(Table 3.4), the domestic price and quantity fluctuations illustrated in Figure 3.8 can be fully utilized. With prompt cooling after harvest and subsequent cold storage, the supply and demand mismatch can be used for profit to a larger extent. A large amount of apples are available during and briefly after their harvesting season (Table 3.3), and storing apples from December to June can give an approximate increase in value from 90 to 150 INR/kg in retail price. This value increase is substantial, and can give validity to the use of implementing a cold chain.

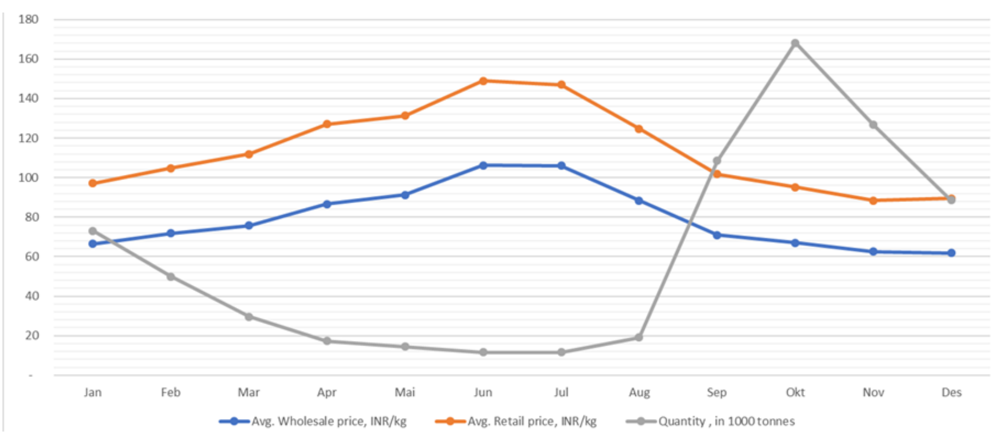


Figure 3.8: Average wholesale prices, retail prices and quantity of apples arrived in major Indian cities per month for the years 2015 to 2018 (NHB, 2019a).

The realizable value increase for grapes is less, as their potential storage life is just 6 weeks, and the supply drops quite quickly. Some value increase can be accessible as seen from Figure 3.9, where there will be an increase in retail price of 20 INR/kg for the potential viable storage of grapes from the middle of March to the start of May. This value increase is however less substantial, and grapes can not be stored long enough to reach the point of a substantial increase in price.

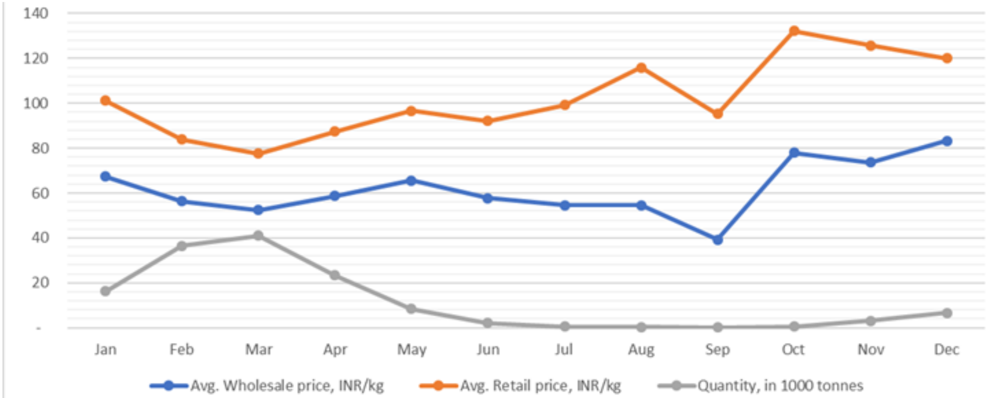


Figure 3.9: Average wholesale prices, retail prices and quantity of grapes arrived in major Indian cities per month for the years 2015 to 2018 (NHB, 2019a).

Alphonso mango does again have indications of some substantial increase in price seen in Figure 3.10. Their potential storage life is also 6 weeks, and from the middle of June to the beginning of August the retail price can increase from about 110 INR/kg to 160 INR/kg. This increase is in total percentage less than for apples, but the increase in price is in a much short time span of just 6 weeks.

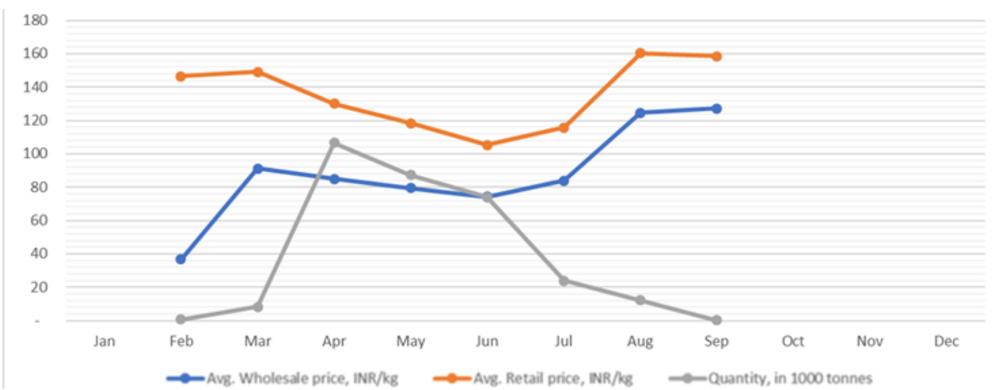


Figure 3.10: Average wholesale prices, retail prices and quantity of Alphonso mango arrived in major Indian cities per month for the years 2015 to 2018 (NHB, 2019a).

3.3.2 Exports

The Indian export market is large in potential, yet largely unutilized. Most of the produced horticulture is used domestically, and a lot of the export is to geographically close areas like Nepal and Bangladesh. Some export is done to more distant countries, but there is large potentials here as most of the commodities produced are not cooled, making exportation difficult. Most exports of fresh fruits are done without cooling, except for grapes as previously identified. The cold chain of exported apples, grapes and mangoes will ideally be quite similar. The National Horticulture Board suggests simple guidelines for what is needed in a cold chain for export of fruits, this cold chain is shown in Figure 3.11.

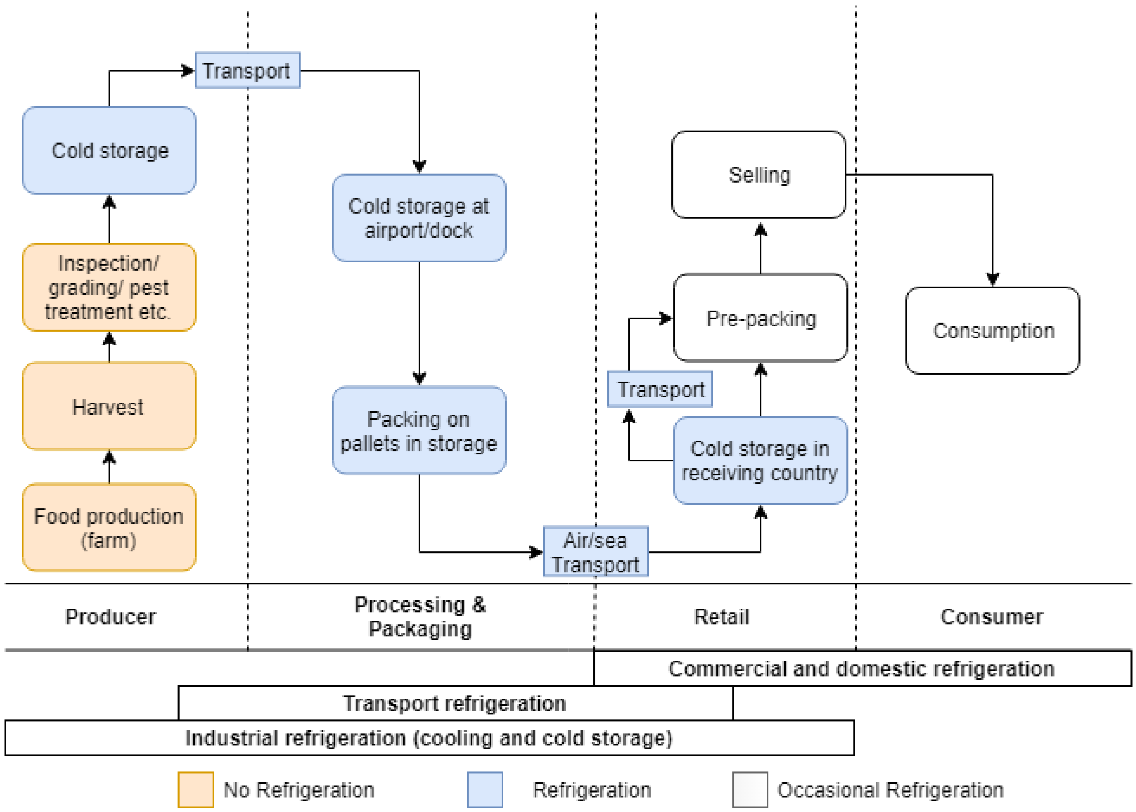


Figure 3.11: The recommended cold chain for exported fruits from India according to the National Horticulture Board (NHB, 2019b).

It is however quite unlikely that there will be a cold storage available at the producer level, as the amounts of cold storages in India is so small for fruits and vegetables, and such a situation is unrealistic. There is also no mention of cooling, which is due to the situation previously described, where pull-down of temperature is done inefficiently in the storage.

The real case is often different. For most commodities other than grapes there is rarely any cooling used, causing the cold chain to be initiated late in the flow of produce, and requiring the use of cold storages as means of reducing temperature. Figure 3.12 illustrates how a non optimal cold chain for Indian exports may look like, which is often the case.

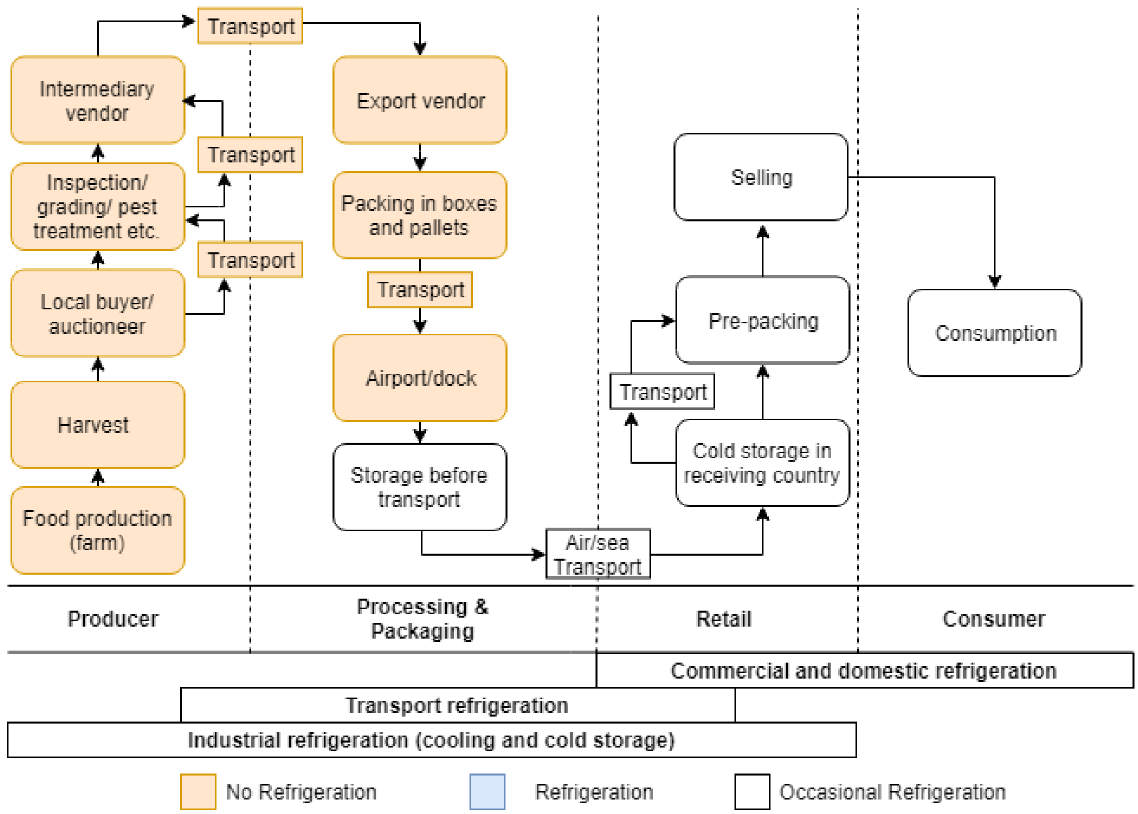


Figure 3.12: Illustration of the typical real case for export of Indian fruits.

As can be seen from figure Figure 3.12, there is often times a large number of intermediaries trading produce between each other, and transporting the produce between different places. The large number of intermediaries and improper supply chains have been found to increase cost with as much as 60%, without adding extra value(Joshi et al., 2009). Furthermore, the cold chain is many times initiated very late in the flow of commodity, after the produce has been kept at elevated temperatures for a prolonged amount of time. For export to geographically close countries the produce is generally moved from production to consumption with no refrigeration at all.

The Indian export market has a large potential for profit if a proper cold chain is implemented, so that the shelf life of the products is long enough to be transported. Grape export to the Netherlands is one of the most prominent cases of fruit export in India, where grapes require a cold chain for it to be able to be transported the long distance. Table 3.5 shows Indian export data of fruits to a selection of important countries. Although these prices can be dependant on many factors such as quality, type of crop, amount of stakeholders and so forth, they still indicate that the revenue received from grapes in the Netherlands is not extraordinarily high. This may further indicated that the functioning cold chain of exported grapes from India is to a large extent the result of some stakeholders initiative and entrepreneurial spirit. Therefore it is possible to think that this might also be applicable to the other types of fruit, and that the potential for export is viable as long as there is an international demand. Furthermore, it can be seen that the value of the exported commodities is substantially higher for export to the western countries listed. This is naturally in part caused by the added cost of such a long exporting distance, but the case of grapes having a well developed and prosperous cold chain industry is again an indicator that these extra costs still result in substantial profits.

Export to	Mango		Grapes		All other fruits	
	Export $[tonnes]$	Value $[\$/kg]$	Export $[tonnes]$	Value $[\$/kg]$	Export $[tonnes]$	Value $[\$/kg]$
U. Arab Emi.	23 542.5	1.22	13 574.9	1.26	72 831.0	0.95
Saudi Arabia	2 670.5	1.28	9 483.0	1.16	18 092.5	0.97
Qatar	2 321.9	1.32	1 211.7	1.18	1 211.7	0.89
Oman	2 230.5	1.1	2 799.4	1.29	22 889.0	0.73
Nepal	7 878.1	0.3	7 763.6	0.29	98 939.2	0.25
U. Kingdom	3 728.5	2.0	18 594.2	1.85	1 270.9	3.45
Canada	526.2	1.41	576.2	1.94	297.7	1.31
Malaysia	222.0	1.17	830.6	1.83	3 431.9	0.98
Germany	135.5	1.40	16 449.5	1.70	1 001.2	1.68
Netherlands	21.5	2.33	58 457.0	1.72	4 612.8	2.59
Tot. all export	49 180.5	~ 1.5	188 221.1	~ 1.55	320 900.9	~ 1.4

Table 3.5: Amount of Indian fruits exported and corresponding value of sale per kg to a selection of important countries in 2018 (APEDA, 2019).

The average revenue listed for each category of fruit is given with a $\sim$ to illustrate that this is an approximate value. Countries with high revenue per kg but very small amounts of export will give an artificially high value for the average, so the number is slightly altered to be more realistic.

3.4 Field investigation

During the work of this thesis a stay at IIT Kharagpur in India was conducted from 21.01.2019 to 05.04.2019, where the stay was supported under the international SINTEF project Re-FOOD. Work on the master thesis topic in India was conducted in cooperation with the local academic resources of the mechanical department, working within refrigeration technologies. Further knowledge was gained and documented through empirical studies of refrigeration and food management at the IIT Kharagpur campus, and also at other locations in India including the city of Kharagpur, Kolkata, Goa, Darjeeling and The Sundarbans.

3.4.1 Survey

A survey was conducted in an effort to quantify opinions, knowledge, and awareness of the local people in Kharagpur related to their food habits and refrigeration. The survey form was made available online in English, and the same form was also translated by local faculty to Bengali and Hindi which is the two most used languages in the region. The online survey was distributed to students and academic faculty at the IIT, while the translated versions were printed and delivered to local food vendors inside the campus and restaurant owners. There were a total of 65 respondents. Several of the vendors were uncomfortable writing answers on the forms due to lack of reading and writing abilities, and the large part of these answers were collected by asking the questions directly with the use of one of the local doctorate students doing the translation. The survey contained

23 questions in total, where the initial questions were used to group the respondents in terms of educational level, occupation, gender and age. The further questions were used to document the habits and awareness of the respondents on the use of refrigeration. Out of the 23 questions, nine were selected to give answers of importance to this thesis work and is therefore presented. The numbering of the questions is related to their presentation in this section, and not on the actual question number in the survey.

Question one to the left in Figure 3.13 gives a 51 to 49% advantage to the answer yes, indicating that the previously described culture of eating all food locally produced and fresh is a prevalent practice. It is especially notable that none of the chicken and fruit and vegetable vendors refrigerate the food they sell. All but one of the fish vendors asked did use refrigeration, it was however found through interaction with the vendors that this refrigeration was in all cases limited to one single block of ice wrapped in banana leaves, and that only a portion of the larger fishes sold was kept in this packaging over night. The reason was that much of the fish was caught and sold in a matter of a few days, and that the vendors significantly reduced their prices to mitigate losses once the quality started to deteriorate. Question two in the same figure indicates a clear consciousness around the food quality for both consumers and suppliers. It also gives a minor indication of the seasonal supply and demand of produce for the fruit and vegetable vendors as the respondents consider season and price important, which is closely interlinked as previously documented.

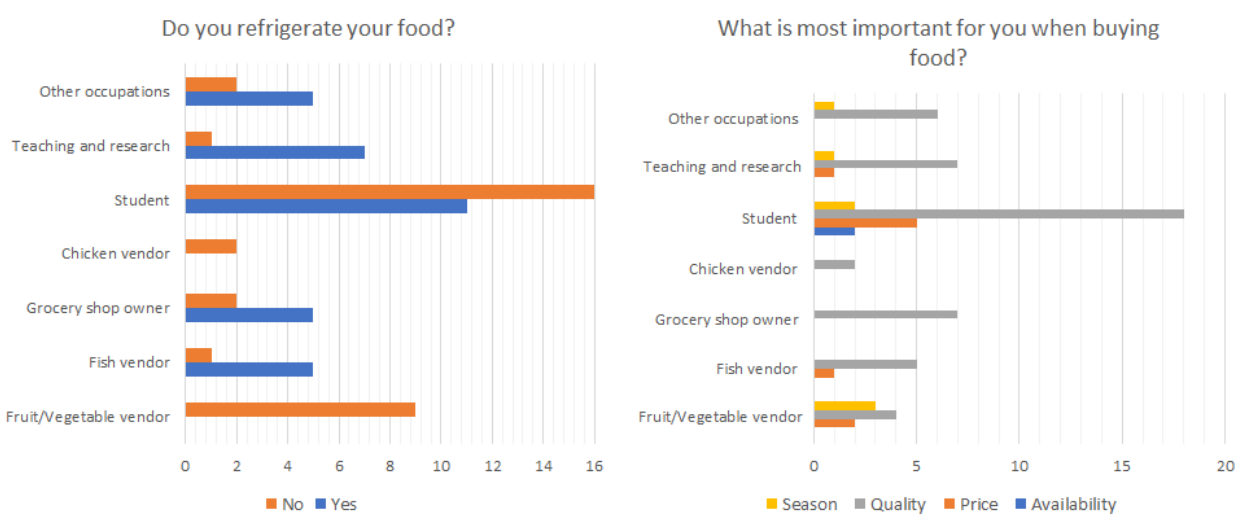


Figure 3.13: Survey questions one and two.

In question three (Figure 3.14) it is reported that close to 60% of the respondents throw away less than 10% of the fruits and vegetables they acquire for sale or consumption, a trend that illustrates the practice of avoiding losses at the consumer end. The responses of the fruit and vegetable vendors if further notable, which show that 2/3 throw away more than 10% of their stock, and that more than 1/3 throw away over 20% of their stock. The sample size is way to small to make conclusions based on such results, but it does indicate inefficient practices in the specific case of the vendors in Kharagpur. Such inefficiencies has also been previously documented to be present for many of the fruit and vegetable chains in India, and with many stakeholders between the producer and consumer such losses at each stage are detrimental for the Indian fruit and vegetable supply.

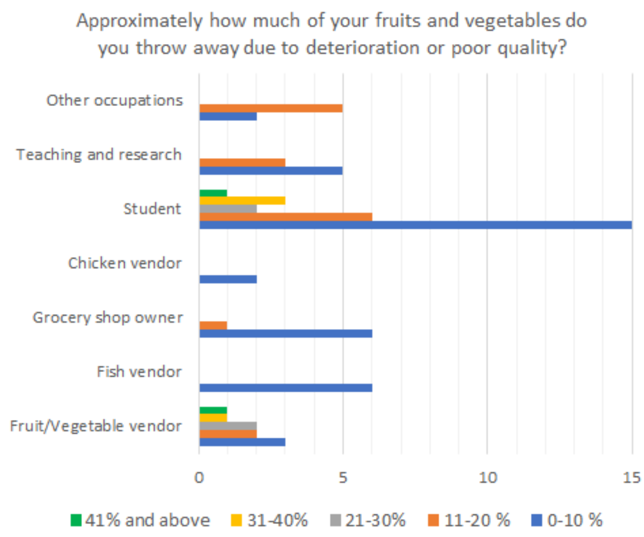


Figure 3.14: Survey questions three.

Questions four and five in Figure 3.15 does to some extent show a mismatch between the way of thought and the way of practice. The responses on question four to the left in the figure shows a clear trend indicating that the knowledge of how important refrigeration is for preservation of food is known, with a few exceptions. The responses on question five to the right in the figure does however illustrates some discrepancy, where a larger portion of the respondents indicate that it is not particularly important that their food has been refrigerated. Again, this must be seen in relation to the cultural way of thinking about food in India, where many still prefer the food to be fresh and unrefrigerated. It is once more notable to see the responses of the fruit and vegetable vendors, where they in general give very high importance to the use of refrigeration on question four, but give very little importance on their own merchandise being refrigerated. The same is also present to some degree for the grocery shop owners.

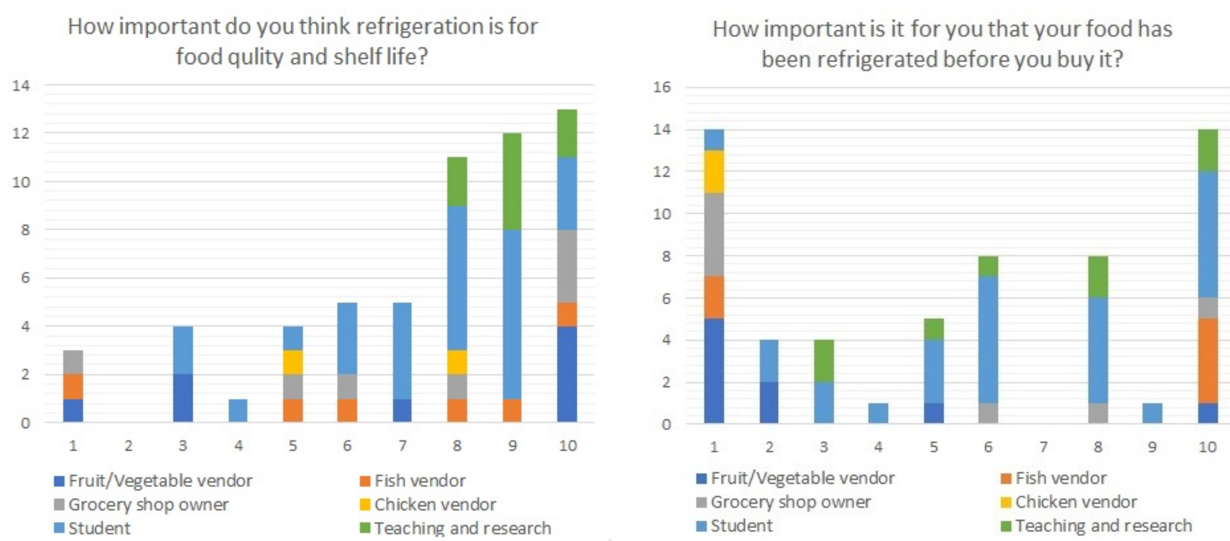


Figure 3.15: Survey questions four and five.

Questions six and seven in Figure 3.16 are connected questions, where 75% of the respondents on question six say that there should be more refrigeration in Indian homes. The majority of respondents in question seven also recognize economical factors as the main reason for the shortage. The respondents were then given the option of providing justification for their choice on question seven, here 44 responses were given. A selection of these are quoted directly:

“Economy is the main reason, but poor electrical grid is also a very large reason and problem.”

“It’s a personal choice, many people don’t buy fridge because they don’t see a need for it. Also it is too expensive for many people.”

“Money is most important, but also many people want the food to be fresh, which it is not after it has been refrigerated.”

“Refrigerators are still beyond the reach of the poor people in India. Lack of proper housing with electricity is another important reason.”

“There are two sides of the coin, refrigeration minimizes food wastage and enhances life but should be used for products like milk, fruits etc. and not cooked food as leftovers are not the best form of food speaking in terms of quality and also takes away culture of fresh-cooked home made meals.”

“In India most of the people are farmers or rural living, and their economic condition is poor. Moreover, there are many undeveloped places in India where electricity is not available.”

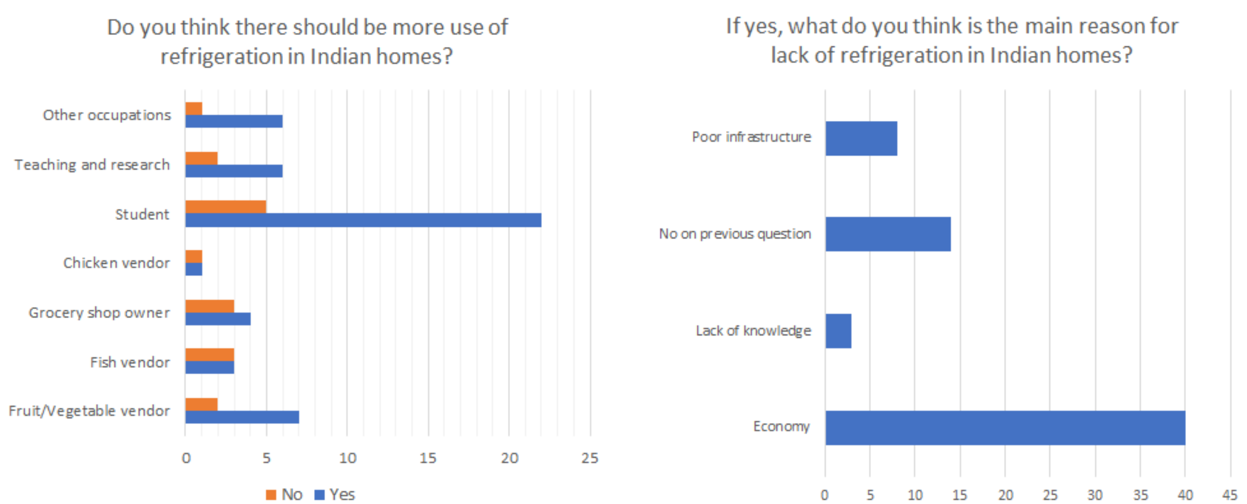


Figure 3.16: Survey questions six and seven.

Questions eight and nine in Figure 3.17 are connected questions, where 66% of the respondents on question eight say that there should be more refrigeration between where food is produced and their home in India. A noticeable difference is in the change in responses for the suppliers of food, where the majority of vendors and show owners wanted more refrigeration in homes, but the majority does not want more refrigeration along the supply chain. Upon further inquiry, the general feedback from this group of vendors that said no on question eight was that the current situation was sufficient. The responses on question nine was more diverse, but with a majority of 34% of respondents attributing lack of refrigeration to poor infrastructure, and 22% attributing it to economical reasons. The respondents were also here given the option of providing justification for their choice on question nine, where 45 responses were given. A selection of these are quoted directly:

"There is lack of proper cold chain facilities and availability of electricity."

"The demand for cooling is met in the market. Demand and supply is equal."

"Food should be grown close to where it is consumed. The present model of urbanization is a nightmare for sustainability."

"In my locality from where I belong, no cold storage facility is available near by to store the vegetables. This is due to lack of awareness as well as poor economic condition of the farmers. Also, there is minimum support from government organizations in increasing the awareness and developing the infrastructure."

"Since the producers and the sellers only care of profits, they don't take care of what should be done in between."

"The cost of using refrigerator adds to the price of vegetables and fruits which might turn away people from purchasing it."

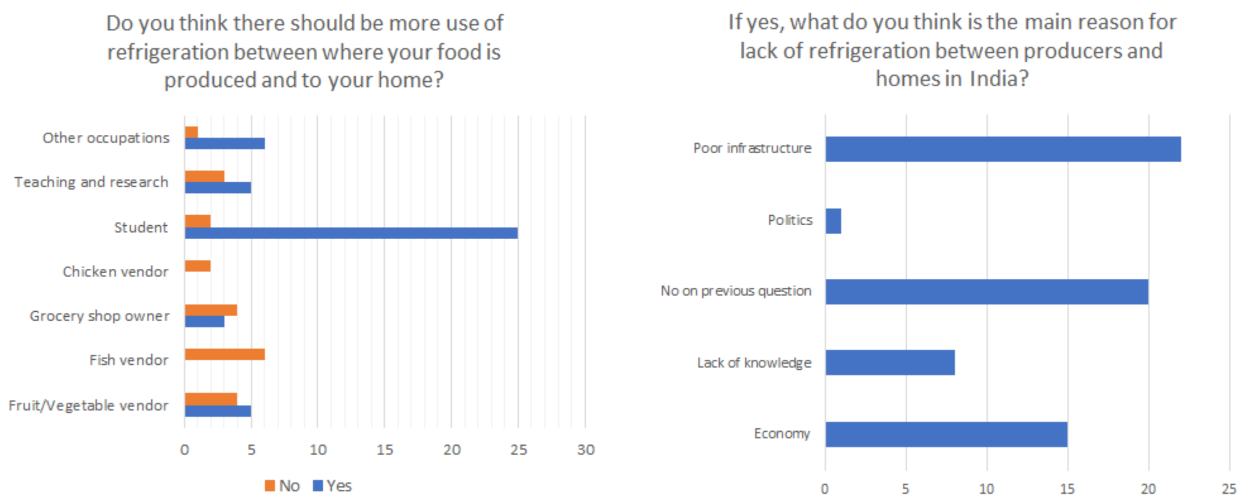


Figure 3.17: Survey questions eight and nine.

For all the survey questions it is important to note the small sample size, and that the geographical location is restricted to only Kharagpur. The responses are therefore not enough to make definitive conclusions. They do however include enough people to show trends in the empirical data, which again can be used with the existing literature to support the given trends and the claims presented. They further give a quantifiable insight into the thoughts and opinions of people living in the Indian scenario, which is otherwise only documented from literature.

3.5 A cooling system in the Indian scenario

The design of a cooling system in the Indian scenario must attempt to accommodate for the situations and the needed considerations presented in the previous chapters. The lack of cooling systems overall is the initial problem area that must be mended, which is done by the general implementation of a designated cooling system. This will in turn allow for cold storages to have lower refrigeration capacities, product degrading processes will decrease, the shelf life will increase, product quality will retain for a longer time, losses in product will decrease, and economically beneficial trades over longer distances such exports will be more feasible. The cooling system will be designed for cooling of apples, grapes and mangoes, as these are products of high value both domestically and internationally, where only grapes experience cooling at present.

The large number of intermediary stakeholder is an inefficiency in both the supply and cold chain that reduces realized value of product for the producers, and increase the cost of the consumer. Making sure a cooling system is designed so that both the upstream and downstream parts of the cold chain contain few and interconnected players is therefore beneficial. One way of doing this is to have a cooling system that initiates cooling of the product at the area of harvest, and thus have few or no other players involved before the cooling starts. The cooling system will therefore be designed as transportable, since the production of apples, grapes, mangoes, and also most other horticultural products in India is seasonal and in different areas. As previously documented, the economical benefits of multi purpose refrigeration systems is high, and with a transportable system the production seasons of apple, grape and mango in India fit together to allow for year round cooling of these products separately.

As these products are produced mostly in rural areas, where it has been documented that the supply of energy is unstable or not present at all, an off-grid energy solution will be implemented. Solar powered refrigeration systems, and especially PV-panel driven ones, have been documented to be viable solutions for high temperature and highly solar irradiating areas like in India, and will be the off-grid renewable energy solution of choice. Furthermore, it is important that the cooling system is cheap to build and simple in operation to accommodate for the economical barrier it might be to build such a system, and to make the process of building and operating such a system feasible for workers. The system should further ensure swift cooling through efficient geometry and operation, and be constructed to be as energy efficient as possible. It is important to maintain environmentally friendly construction and operation, not only though the use of renewable energy but also through the use of a refrigerant that does not cause substantial harm to the environment. These considerations form the foundation for a conceptual design of a portable cooling system based on renewable energy for use on fruits and vegetables.

Chapter 4

Conceptual design and method

This chapter describes the physical design of the entire cooling system, with the encasing geometry, energy system, produce boxes, refrigeration system, and other physical implementations needed. The operating conditions for dimensioning of the system is given, and the method used for simulating the entire system is explained. Finally, a logistical solution for use of the cooling system in India is presented. The physical design and the operating conditions will set the boundaries for operation of the system, and simulation of this system will be used to determine how the system can work as well as possible within these boundaries.

4.1 System design

The system is designed based on the consideration presented in section 3.5 to be an asset in tackling the many issues present in the Indian cold chain, and to utilize the large potential in the Indian horticulture market both domestically and internationally. The design is a cooling system for fruits and vegetables which is portable, based on renewable energy, and with a refrigeration system that uses a natural refrigerant. As previously discussed, the system will mainly be designed for apples, mangoes and grapes. The system will provide an off-grid solution for cooling fruits and vegetables especially in rural areas but also potentially more centralized areas. Because it is designed for use in India where challenges in farming and cold chains are highly prevalent, emphasis is made on designing a low cost system that is simple in operation and construction. The system is also designed with a focus to maximize cooling airflow through the products in an even distribution, so that the products are cooled as uniformly and as swiftly as possible. The system is illustrated in Figure 4.1 and Figure 4.2, in two and three dimensions respectively. The refrigeration system is only drawn for the view from the door in Figure 4.1, to ease viewing. The black arrows indicate airflow inside the system, and the black spheres surrounded by circles indicate airflow out of the paper. The metal walls of the container is excluded from the illustrations for ease of viewing. The dimensional sizes of the cooling system are given in Table 4.9. Explanation of the design and illustrations will follow.

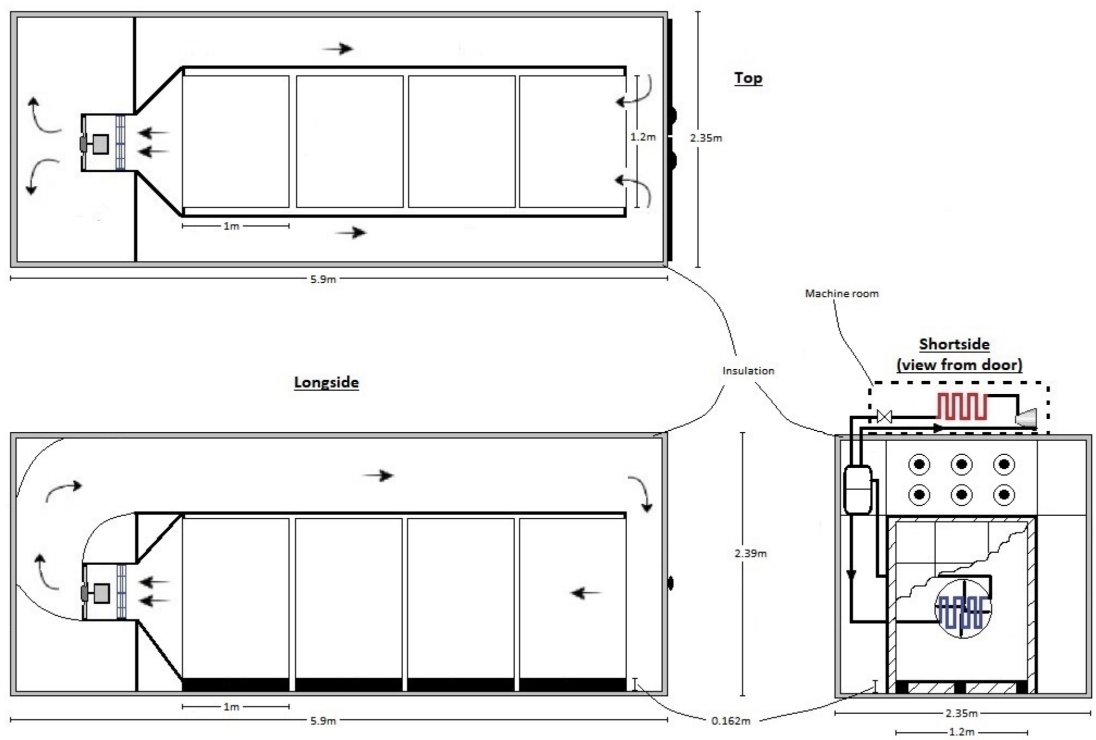


Figure 4.1: Simple sketch of the cooling system in two dimensions, seen from top and sides with four stacked pallets inside.

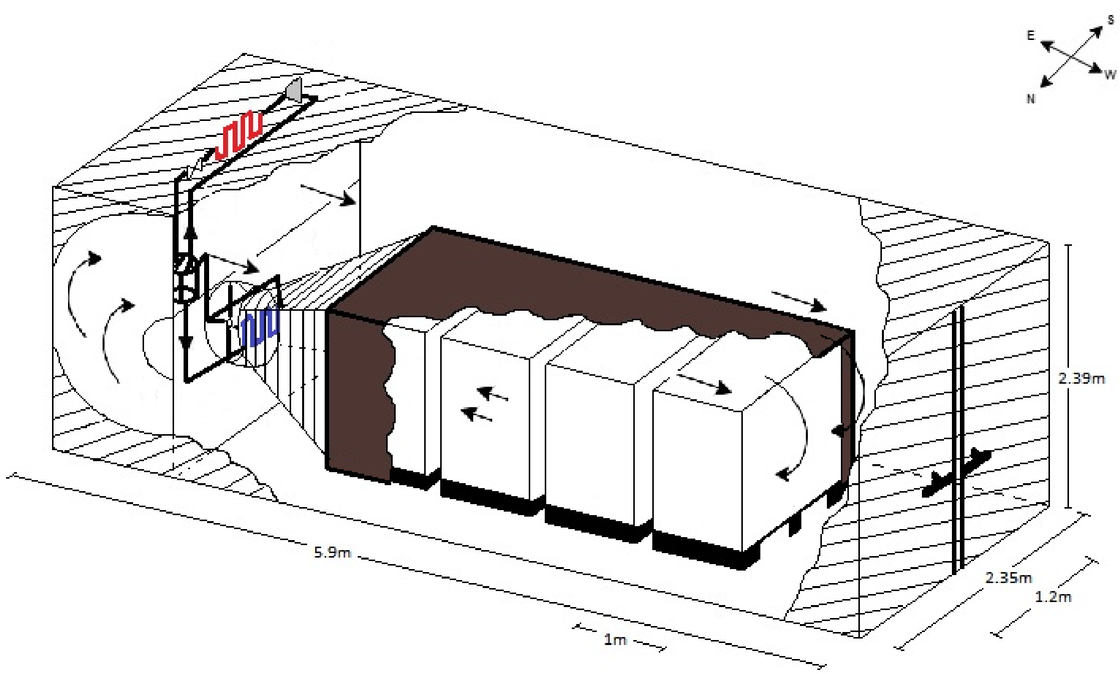


Figure 4.2: Simple sketch of the cooling system in three dimensions, with four stacked pallets inside.

4.1.1 Geometry

Outer geometry

The outer casing of the system will be based on use of a shipping container, this way the system is portable but still large enough to cool down a significant amount of products. Shipping containers are generally standardized on a global scale, and most trucks and other modes of transport are designed for transporting these containers. Such containers are also widely available for purchase at a relatively low price, and can be bought second hand at an even lower cost. The design is based on a 20ft ISO container (Uniteam, 2019), where all internal surfaces are insulated with 150mm of expanded polystyrene having a thermal conductivity of $k_{ins} = 0.037[W/mK]$, according to ISHRAE (2015b) recommendations. A plastic vapor barrier and a piece of sheet metal is also added to the internal surfaces to prevent condensation leaching into the insulation and to protect from physical damage respectively. The refrigeration system pipes will go in and out of the container at the roof. There will be a small machine room at the roof containing the compressor and condenser, for easy access in case of maintenance.

Solar system

The solar system will be on top of the cooling system container, as illustrated in Figure 4.3. The refrigeration load will be relatively large to produce a significant amount of cooled product, meaning that the solar panel area in most cases will have to be larger than the available roof space of the container. This can be achieved by having panels mounted with hinges on each side of the solar panel parallel to the roof, and thus have foldable panels that go down the side of the walls. This increases the possible solar panel area by more than three, and will also give protection from solar irradiation hitting the walls during operation. Furthermore, the side walls can have an adjustable support structure, like a telescopic rod, so that they can follow the sun movement through the day. The mounting structure for the solar panel is placed 30 cm above the container roof, giving a potential solar panel area of 47.3 m^2 with solar panels on the sides, as opposed to 14.8 m^2 if only the flat roof is mounted with panels. The panel will have an assumed efficiency of 15%, which is a standard readily available.

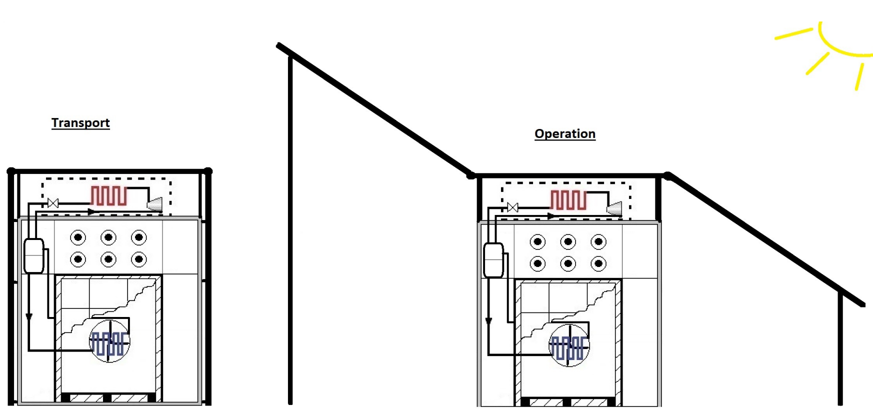


Figure 4.3: Illustration of the exterior solar panel mounted on the cooling system during transport and during cooling operation, in 2D.

The battery will be placed on the flat roof adjacent the machine room of the refrigeration system, below the solar panel. This way the battery is protected from direct solar radiation, and it is also close to the compressor, fan and solar panel in terms of connecting electrical wires.

Inner geometry

The refrigeration system and product that is to be cooled is placed inside the insulated walls of the container. The refrigeration system is placed in the back of the container, and holes through the sidewalls are drilled for the pipes. The refrigeration system will be a modular solution that can be easily installed into the back of any insulated container. It consist of a supporting structure containing a circular air duct where the evaporator and a fan that provides a pressure difference is placed. There should be a hatch cut out under the evaporator coils to allow for water to drip off in case of frost formation and corresponding defrost on the coils. The pressure difference caused by the fan gives a suction that moves air through the products from one side of the container to the other, where the air is again blow through the curved duct in the module and back in to the area where the product is stacked. The products are stacked in boxes and placed on pallets in the container. To ensure that as much as possible of the cold air is moved through the product, a converging duct and an airflow barrier is included. The converging duct will be made of sheet metal that is shaped into a rectangular cross section at the intersection with the product pallets, and a circular cross section welded on to the evaporator and fan intersection. The airflow barrier that encases the products will be a plastic tarp with structural support beams along the edges, and a strap that can be tightened around the intersection with the converging duct and around the last pallet near the door. Two wood blocks with handles will be cut out in the dimensions of the open spaces where the pallets are picked up by forklifts, which can be inserted to restrict airflow here. It is crucial for optimal heat transfer that there are no holes in the tarp or other open areas for air to flow through other than through the boxes containing product to be cooled. Therefore it is important that the converging duct is fixed securely to the rest of the construction and that the tarp is strapped tightly around the converging duct and around the pallet closest to the door.

Pallet and product boxes

Special boxes designed for cooling will be used in the case of this cooling system. As shown by i.e Ngcobo et al. (2012), cooling in the typical transport boxes of cardboard with small vent holes gives a very large pressure drop across the geometry, which correspondingly will require a large energy input to the fan. Since the system will be reliant on only solar power for its energy, and the amount of area available for solar panels are restricted by the size and transportability of the container, it is crucial that the cooling provided is as energy efficient as possible. Therefore the boxes that will hold the products are designed to allow air to flow practically freely through the boxes at the airflow entry and exit, so that the only thing restricting airflow and thus giving a pressure drop is the bulk of products. The boxes will be made of a hard and durable plastic material, and have an opening and exit with many slits that looks like a mesh grid and will allow close to free airflow. Each box will be separated into two sections by a removable horizontal plate, so that the weight is more evenly distributed. The boxes will stack and fit into each other so that there is no gap between each box, thus forcing all airflow through only the open mesh grid in the boxes. The box design with sunken handles on each side and dimensions of the structure is shown in Figure 4.4.

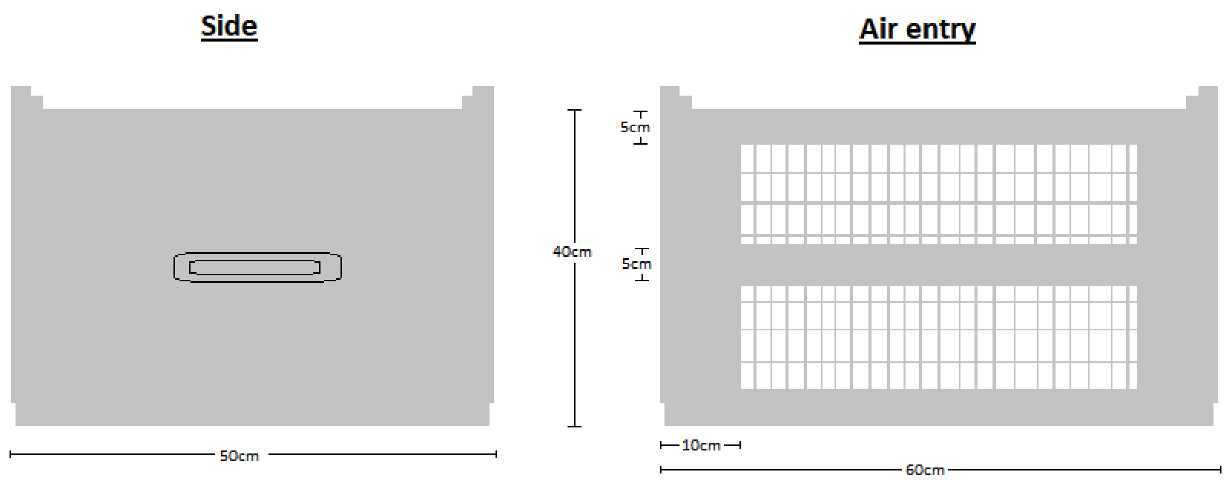


Figure 4.4: Simple sketch of the boxes that will hold products in the cooling system.

The boxes will be stacked on 162x1200x1000mm standardized wooden pallets that are commonly used in India (1001Pallets, 2019), where the longest part of the pallet is parallel to the width of the container. Each pallet will be stacked 4 boxes high and two boxes wide in width and length direction, meaning each pallet will have 16 boxes of products. The pallets will be placed close together in the container so little to no air will linger between the pallets when the system is operating, meaning there will be 8 rectangular ”ducts” for the air to flow through.

Airflow

The airflow through the system, or the mass flow rate of air, is related to the fan diameter, airspeed caused by the rotation, and the density of air. The fan work will counteract the pressure drop through the products and the geometry as determined by Equation 4.12, so that the mass flow rate is constant through the system. The density of air is considered constant through the entire geometry, this means there will be a constant volumetric flow rate through the system:

$$u_{fan}A_{fan} = u_s A_{entry}$$

Meaning that the superficial velocity of the air, i.e the velocity of air entering the boxes stacked with products, can be found when knowing the volumetric flow rate through the fan and the airflow entry area of the boxes. The volumetric flow of the fan is therefore the driving factor of the system, as the superficial velocity determines the pressure drop and thus the fan load, it also determines the heat transfer coefficient which in turn determines how fast the product heat is transferred and thus the product load.

4.1.2 Refrigeration system

The refrigeration system of the designed cooling system will be a single stage vapour compression cycle due to the relative small size of the cooler, and in order of designing a system that is low in cost and simple in operation. The heat exchangers will be bought from manufacturers with a requirement of a 5°C temperature difference in the unit. To ensure that there is no liquid entering the compressor and to increase the COP of the system, a liquid receiver is also included. Having no two phase refrigerant entering the evaporator will increase the COP due to state point 5 having a lower enthalpy than state point 4, making the enthalpy difference across the evaporator larger. The compressor is chosen to be a piston compressor due to the relative small size of the refrigeration system. The system is illustrated in Figure 4.5. Further theory about the system and its operation is later presented in subsection 4.3.4.

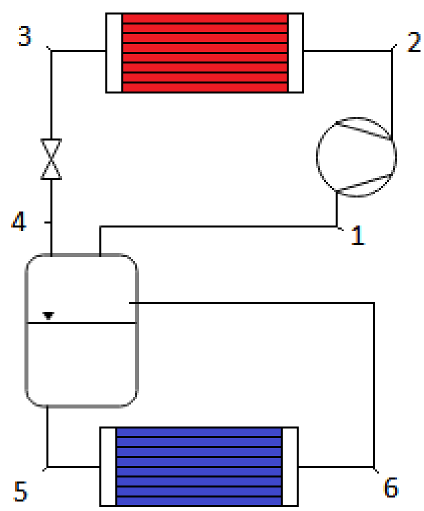


Figure 4.5: Sketch of the refrigeration cycle used in the cooling system, with state points.

4.2 Logistical solution

The system will facilitate for as early introduction to the cold chain as possible. It can be used so that it can connect rural farmers that would not otherwise be part of a cold chain at all, but it can also be used for facilitating larger producers with easy connection to a cold chain so losses are minimized. The cold chain for export of commodities that use the cooling system for initiating their cold chain is illustrated in Figure 4.6. The cold chain will be similar for domestic applications, with the only real change being that the transport of pallets and boxes after they have been packed in storage will be domestic.

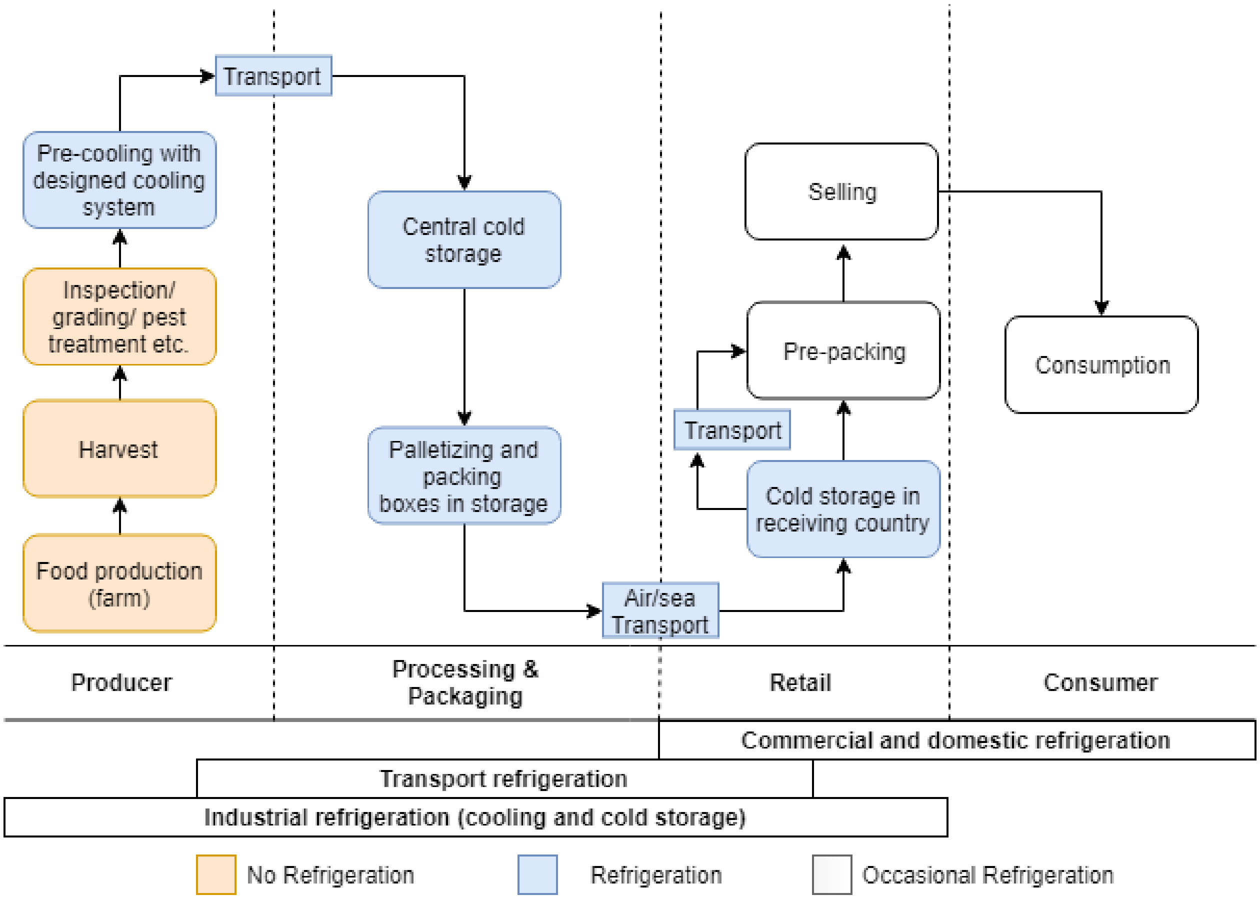


Figure 4.6: Cold chain for a commodity with use of the designed cooling system.

The cooling system will be transported out to areas of apple, grape and mango production according to the harvesting season. The local farmers in the area can then bring their product to the cooling system located in a short distance from the area of production, and sell their products to the operators responsible for the cooling system in the cold chain. Once cooled, the products should either be transported directly on refrigerated trucks to a centralized cold storage. Alternatively, a separate small cold storage can be used on site if available. A cold storage which is also portable and can follow the cooling system is highly relevant in this case, and a study into such a cold storage and its feasibility is done in the master thesis work by Bredesen (2019). Several cooling systems can be distributed to the areas of production during the harvesting season, and thus form a cold chain containing few intermediaries and prompt cooling after harvest. How a commodity will move from farm to a foreign country or a domestic retailer when the cooling system is used, is illustrated in Figure 4.7. This logistical system is similar for both export and domestic applications, but the transportation mode and distance after storage is in general shorter for domestic applications.

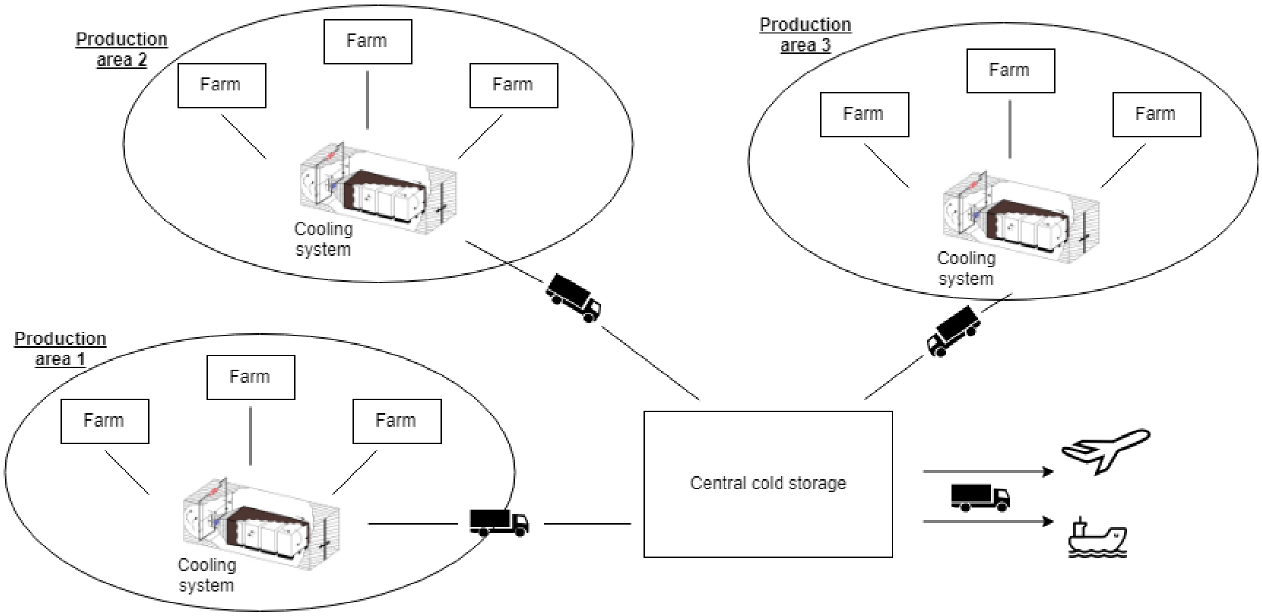


Figure 4.7: Commodity movement from farm to another country or domestic retailer with use of the designed cooling system.

When the designed cooling system and the corresponding cold chain and logistical procedure presented in Figure 4.6 and Figure 4.7 is applied for a commodity, said commodity will experience rapid cooling and shipment. The number of intermediary stakeholders is greatly reduced for the Indian scenario, as there is only a few crucial steps present and necessary in the cold chain. At the same time the introduction of designated cooling at such an early stage after harvest can greatly reduce loss and increase product value, while increasing storage life and allowing for a longer duration of transport.

4.3 Theory and simulation

The theory is based on information from the compendium by Eikevik (2018) and the book by ASHRAE (2018) unless otherwise stated and referenced. Some additional information about relevant important properties of food is given in section A.1.

The simulation is based on this theory and is made as a single coherent program in EES, and the code for this simulation can be found in Appendix B. An illustration of the functionality of the simulation program is shown in Figure 4.8. The relevant input for the operation of the system can be inserted, and the program will simulate the performance and behaviour of the complete cooling system under the given conditions. Functionality in EES such as plotting and parametric tables further allow for investigation of results for a variation of input situations and points in time. It is important to note that EES does not require equations and values to be listen consecutively, meaning that functions and equations can be solved simultaneously without being listen in a specific order. How the functions work and what they do are described in the following section.

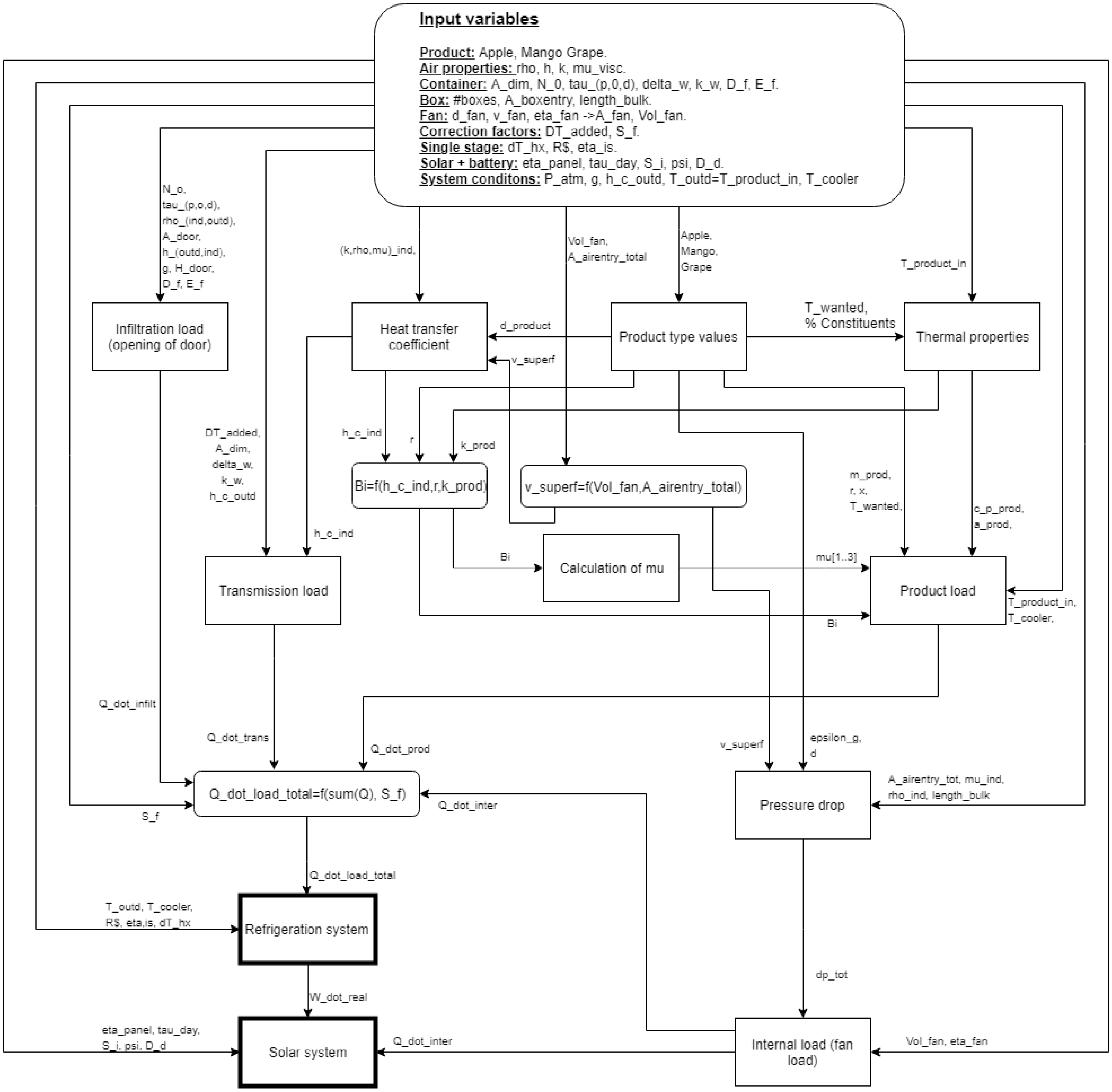


Figure 4.8: Block diagram illustrating the function and coherence of the cooling system simulation.

4.3.1 Products and airflow in the geometry

Product type

Each type of product considered for the design of the system will have different characteristics. The composition and freezing point of the selected important products explain what the product consist of and when crystallization of water will start respectively, these are listen in Table 4.1.

Commodity	Moisture content [%]	Protein [%]	Fat [%]	Carbohydrates		Ash [%]	Freezing point [°C]
				Total [%]	Fiber [%]		
Apple	83.93	0.19	0.36	15.25	2.70	0.26	-1.1
Grape	81.3	0.63	0.35	17.15	1.00	0.57	-1.6
Mango	81.71	0.51	0.27	17.00	1.80	0.50	-0.9
Onion	89.68	1.16	0.16	8.63	1.80	0.37	-0.9
Potato	78.96	2.07	0.10	17.98	1.60	0.89	-0.6
Tomato,green	93.00	1.20	0.20	5.10	1.10	0.50	-0.6
Tomato,ripe	93.76	0.85	0.33	4.64	1.10	0.42	-0.5

Table 4.1: Physical composition and freezing point of the selected Indian fruits and vegetables(ASHRAE, 2018)

The porosity of the product in bulk is important for later determining the pressure drop through this bulk. This porosity is a measure of the void space between the products in bulk, i.e the space where air can move through. This relationship is difficult to determine analytically, exemplified by grapes having a higher bulk porosity than other fruits due to their stems and how this increases the space between each grape. Experimental determination can and should be done by using Archimedes principle to find the volume of the products that fit in a box, and thus also the void space available in the volume of the box. Others have done such experiments to determine porosity of a few types of fruits, and these are used to approximate values for the porosity of apples, grapes and mangoes in this thesis work. Apples will be similar to oranges in shape and size, giving them an approximate porosity of $\epsilon_{apples} = 0.40$ (van der Sman, 2002), grapes have been found to have a bulk porosity of $\epsilon_{grapes} = 0.565$ (Ngcobo et al., 2012), and mangoes will have a slightly larger porosity than apples due to their larger diameter $\epsilon_{mangoes} = 0.45$. The measure of void space can again be used to determine how much product it is possible to have in each crate, by also considering the available volume of a box and the product density:

$$m_{product,box} = V_{box}(1 - \epsilon_{product})\rho_{product} \tag{4.1}$$

So if all the theoretically available space for products is used, the mass of product in each box as shown in Figure 4.4 will be $m_{apples,box} = 26[kg]$, $m_{grapes,box} = 19.2[kg]$, and $m_{mango,box} = 24.2[kg]$

The simulation is done by having the type of product considered for each simulation as an initial input in the program. The constituents of the products are known from Table 4.3 and the porosity, weight of product, and temperature required for storage are as found above and also summarized in Table 4.14. The program will set these values when the product type input is given.

Thermal product properties

The physical and thermophysical properties of a fooditem must be known if refrigeration related calculations are to be done. These will determine how the product will behave and interact thermally with its environment, and are dependant on the constituents of the fooditem.

The thermophysical properties c_p, ρ and k of a fooditem can be found from thermal property models given in ASHRAE (2018). Each of the product constituents will contribute to the total thermophysical property of the food, so that the value for each thermophysical property will be the sum of the contributions from each food constituent. The contribution from each food constituent will be the percentage of the given component present in the fooditem(Table 4.1) multiplied with the corresponding property model given in Table 4.2, where T is the food temperature and the model is valid from -40 to 150 °C.

Thermophysical property	Food component	Property model
k, Thermal conductivity, $W/(mK)$	Protein	k=1.7881*10^{-1}+1.1958*10^{-3}T-2.7178*10^{-6}T^2
	Fat	k=1.8071*10^{-1}-2.7604*10^{-4}T-1.7749*10^{-7}T^2
	Carbohydrate	k=2.0141*10^{-1}+1.3874*10^{-3}T-4.3312*10^{-6}T^2
	Fiber	k=1.8331*10^{-1}+1.2497*10^{-3}T-3.1683*10^{-6}T^2
	Ash	k=3.2962*10^{-1}+1.4011*10^{-3}T-2.9069*10^{-6}T^2
	Water	k=5.7109*10^{-1}+1.7625*10^{-3}T-6.7036*10^{-6}T^2
ρ, Density, kg/m^3	Protein	ρ =1.3299*10^3-5.1840*10^{-1}T
	Fat	ρ =9.2559*10^2-4.1757*10^{-1}T
	Carbohydrate	ρ =1.5991*10^3-3.1046*10^{-1}T
	Fiber	ρ =1.3115*10^3-3.6589*10^{-1}T
	Ash	ρ =2.4238*10^3-2.8063*10^{-1}T
	Water	ρ =9.9718*10^2+3.1439*10^{-3}T-3.7574*10^{-3}T^2
c_p, Specific heat, $kJ/(kgK)$	Protein	c_p =2.20082+1.2089*10^{-3}T-1.3129*10^{-6}T^2
	Fat	c_p =1.9842+1.4733*10^{-3}T-4.8008*10^{-6}T^2
	Carbohydrate	c_p =1.5488+1.9625*10^{-3}T-5.9399*10^{-6}T^2
	Fiber	c_p =1.8459+1.8306*10^{-3}T-4.6509*10^{-6}T^2
	Ash	c_p =1.0926+1.8896*10^{-3}T-3.6817*10^{-6}T^2
	Water (0 to 150 °C)	c_p =4.1289-9.0864*10^{-5}T+5.4731*10^{-6}T^2

Table 4.2: Thermophysical property model of food components for $-40 \leq T \leq 150°C$ (ASHRAE, 2018).

When these are know, thermal diffusivity a can be found from the correlation given in the same literature as:

$$\alpha = \frac{k}{c_p \rho} \tag{4.2}$$

The thermophysical properties of the specified fooditems at 20 °C is given in Table 4.3.

Commodity	c_p $[kJ/(kgK)]$	ρ $[kg/m^3]$	k $[W/(mK)]$	α $[10^{-7}m^2/s]$
Apple	3.730	1083	0.5427	1.344
Grape	3.658	1105	0.5335	1.320
Mango	3.670	1101	0.5348	1.324
Onion	3.876	1051	0.5646	1.386
Potato	3.604	1118	0.5247	1.302
Tomato, green	3.958	1034	0.5773	1.411

Table 4.3: Thermophysical properties of the introduced Indian fruits and vegetables at 20 °C (ASHRAE, 2018).

The simulation of the thermophysical property model illustrated is implemented to calculate the thermophysical properties of the chosen product. The properties are calculated by taking the product type constituents and wanted product temperature given by the product type function, and the temperature of the product when it enters the cooling system as an initial input value. The thermophysical properties are dependant on the temperature of the product at any given time, but this dependence is small in the temperature range that will be relevant. Therefore, a mean value between the wanted product temperature and the temperature of the product entering the cooling system is used.

Airflow

As described in the system design, the airflow and specifically the volumetric flow rate due to the fan work is the driver of the cooling system. The work done by the fan will counteract the pressure drop through the geometry, meaning that the volumetric flow of air through the system is considered to be constant.

The simulation of the airflow is modeled after this assumption. The diameter and the airspeed out of the fan, as well as the open area of each box and the number of boxes will be a chosen input, and the superficial velocity is then found as:

$$u_s = \frac{\dot{V}_{fan}}{A_{box} n_{boxes}}$$

Heat transfer coefficient

The convective heat transfer coefficient h_c is related to the fluid flow around a geometry, and can for a sphere be determined from relations given in the book by Kreith et al. (2012) as:

$$\frac{\overline{h_c} D_s}{k} = 0.37(\frac{\rho D_s u_s}{\mu_{visc}})^{0.6} = 0.37 Re_D^{0.6} \qquad for \quad 100,000 > Re_D > 25 \tag{4.3}$$

Where D_s is the sphere diameter, and u_s is the free-flow speed of surrounding fluid. The constraints for Re will hold for all practical applications relevant for this thesis work.

The simulation for the heat transfer coefficient is done by implementing Equation 4.3. The air properties are initial inputs found from inbuilt functions in EES when temperature and pressure is known, the diameter of the product is an input coming from the product type function, and the airflow velocity is the superficial velocity found above.

Pressure drop

Since the boxes are considered to have close to no pressure drop across them, the only pressure drop that will be considered is the one caused by the bulk of produce in the boxes. The pressure drop ΔP through a bulk of horticultural produce is generally modeled from the Ergun equation (Ergun, 1952) and its evolved equations, when these products are packed during cooling. The fruits or vegetables are considered to be a packed bed of large diameter particles with a specific bulk porosity ϵ that the fluid flows through. This method has been shown experimentally to provide appropriate results for bulk produce, and can with additional considerations for geometry also give relations for pressure drop through bulk produce in packaging (van der Sman, 2002; Ngcobo et al., 2012; Delele et al., 2008). The Ergun equation for fluid flow through a packed bed with spherical particles of diameter D_s and a bed porosity of ϵ can be described as (Ergun, 1952):

$$\frac{\Delta P}{L_{bed}} = \frac{150\mu_{visc}(1-\epsilon)^2 u_s}{\epsilon^3 D_s} + \frac{1.75(1-\epsilon)\rho u_s^2}{\epsilon^3 D_s} \tag{4.4}$$

The simulation of the pressure drop is done with Equation 4.4, where the fluid velocity u_s is the superficial velocity of the fluid, i.e the free flow velocity of the fluid through the empty geometry at the same volumetric flow rate. The porosity and product diameter are inputs coming from the product type function, the air properties and length of the bed, i.e total length of the pallets, are initial inputs.

4.3.2 Refrigeration loads

The refrigeration load is the amount of heat that must be removed from the system to maintain a certain temperature, and will be used to design the cooling system load and energy consumption. The different loads can be divided into subcategories as stated in Table 4.4, and it is calculated as follows(ASHRAE, 2018).

Load type	Load source
Transmission	Conduction through walls, roof and floor
Infiltration	Hot air infiltration from opening of door
Internal	Heat from fan
Defrost	Removal of ice when $T_{evap} < 0$ °C
Product	Sensible heat from cooling of product

Table 4.4: Specification of the refrigeration loads considered in the cooling system design.

Transmission load

Transmission loads are heat transferred through the surfaces surrounding a refrigerated space, such as walls and ceilings. It can be calculated at steady state as

$$\dot{Q}_{trans} = UA\Delta T \tag{4.5}$$

where all units are listed in the nomenclature, for this and for the following equations. Furthermore the overall heat transfer coefficient U can be determined as

$$U = \frac{1}{\frac{1}{h_{c,in}} + \sum \frac{\delta_w}{k_w} + \frac{1}{h_{c,out}}} \tag{4.6}$$

where the subscripts in and out of the convective heat transfer coefficient means inside and outside of the heat transfer surface respectively. Normal values are 1.6 for still air and 6 for an airspeed of 25 km/h, however if the walls are thick and well insulated(large δ_w and small k_w) the U value becomes so small that the impact of $1/h_{c,in}$ and $1/h_{c,out}$ becomes insignificant.

If the cooling unit is placed outside, the effects of solar radiation on the walls and roof must also be considered. Correlations have been made so that the temperature difference in Equation 4.5 is increased according to wall direction and surface material, this is shown in Table 4.5

Surface type	East/west wall [K]	South wall [K]	Flat roof [K]
Dark-coloured surfaces:			
Slate & tar roofing Black paint	5	3	11
Medium-coloured surfaces:			
Unpainted wood, brick, red tile, dark cement Red, gray or green paint	4	3	9
Light-coloured surfaces:			
White stone Light coloured cement White paint	3	2	5

Table 4.5: Temperature increase in calculation of transmission loads as a result of solar radiation(ASHRAE, 2018)

The simulation of the transmission load is found by considering each outer section of the container as:

$$\dot{Q}_{sec} = (UA\Delta T)_{sec}$$

The insulation layer is considered to be thick so that the contributions from convective heat transfer outside and inside the container is negligible. The conductivity of both the outer steel wall and the inner steel sheet metal layer are large so that $\frac{\delta_{layer}}{k_{steel}} \approx 0$, and the vapor barrier is so thin that its heat transfer is neglected. Meaning that the overall heat transfer coefficient U is found as:

$$U = \frac{1}{\frac{\delta_{ins}}{k_{ins}}}$$

The conductivity is given as initial input with a value as previously found to be $k_{ins} = 0.037[W/mK]$. The internal dimensions will be used to determine the area of heat transfer. The area for each section and the insulation layer thickness are initial inputs as given in Table 4.9.The temperature difference ΔT_{sec} is the temperature difference between ambient and internal cooling system air, which are initial inputs. The temperature in the cooling system must be lower than the wanted product temperature given from the product type function, and how much lower this temperature is greatly impacts how quick the product is cooled. The temperature difference equivalent when considering the effect of solar radiation on the cooling system is given in Table 4.6, where the wall is considered as white in colour. The floor and north wall is assumed to be in connection with only ambient temperature air. The solar panel will in reality block out most of the direct solar radiation on the east and west walls and on the roof, yet the addition is included to account for occasional direct and constant diffuse radiation.

Section	North/floor	East/West	South	Roof
Temperature increase $[°C]$	0	3	2	5

Table 4.6: Temperature increase equivalent due to solar radiation, for each outer wall section.

The total transmission load is the sum of the loads of each section:

$$\dot{Q}_{trans} = \sum_{i=1}^{i=6} \dot{Q}_{sec,i}$$

Infiltration load

Infiltration loads will be caused either by desired ventilation like in a fruit storage, airflow from the opening of doors, or through leakages. The heat coming from warmer infiltrated air can be calculated as

$$\dot{Q}_{inf.} = \dot{m}_{air}[\Delta h_{air} + (\zeta_{out} - \zeta_{in}) \cdot (h_{lf} + c_{p,ice}\Delta T_{ice})] \tag{4.7}$$

where the absolute humidity of air ζ can be found from a Mollier diagram, and subscripts out and in stand for outside and inside refrigerated space respectively. For airflow coming from the opening and closing of doors of a refrigerated storage the opening of the door must be considered, and the heat gain through doorways can be calculated as

$$\dot{Q}_{door} = \dot{Q}_{sl} D_t D_f (1 - E_f) \tag{4.8}$$

The sensible and latent heat load for fully established flow $\dot{Q}_{sl}$ can be calculated from

$$\dot{Q}_{sl} = 0.221 A_{door}(h_{out} - h_{in})\rho_{in}(1 - \frac{\rho_{out}}{\rho_{in}})^{0.5}(gH_{door})^{0.5}F_m \tag{4.9}$$

where

$$F_m = [\frac{2}{1 + (\frac{\rho_{in}}{\rho_{out}})^{1/3}}]^{1.5} \tag{4.10}$$

The doorway open-time factor D_t can be calculated as

$$D_t = \frac{N_o \tau_p + 60\tau_o}{3600\tau_d} \tag{4.11}$$

Where the time from initial door opening to closing τ_p is in seconds, the time for simple door stand open time τ_o is in minutes, the time period τ_d is in hours, and N_o is the number of door openings during the time period. Furthermore, the doorway flow factor value D_f in Equation 4.8 is recommended to be 1.1 for temperature differences below 11°C, and 0.8 for higher differences in temperature. The effectiveness of open-doorway protection equipment E_f is a value between 0 and 1, where 0 is a wide open door with no protection. The effectiveness of having simple plastic strips as an open-doorway protection has been found to be between 80 to 96 % (Downing and Meffert, 1993).

The simulation of the infiltration load of the cooling system will be from the opening and closing of the door when pallets are taken out and put in, and is calculated from Equation 4.8. $\dot{Q}_{sl}$ is dependant upon the door area and the air properties of ambient and outer chamber air as initial input. The air properties are found through the inbuilt property functions of EES, and the door area is given in Table 4.9. Further initial inputs are the time factors needed for calculating D_t(Equation 4.11), which are determined based on how often the door is opened. The rate at which the door is opened is dependant on how long it will take for one batch of palletized products to be cooled, but initially it is assumed that two batches of products are cooled per working day. The door should stand open as little as possible when when inserting and removing pallets, although some time must realistically be assumed and the process will be stated to give a total of 5 minute of open door time. This time of door opening still requires that the people working with the system are efficient in the pallet removal and insertion, and that they do so swiftly. The above considerations can in total be simplified to be equivalent to two door openings of 300 seconds each per 10 hour operational day. The temperature difference will for all products be higher than 11 °C, meaning D_f will be 0.8. It is further assumed that plastic strip open-doorway protection is used with an efficiency of 80%. These initial values are as stated in Table 4.7. However, they should vary based on the cooling time of the products which varies with area and product type, which will be the case for the later chosen optimized configuration.

N_o	$\tau_p[s]$	$\tau_o[min]$	$\tau_d[h]$	D_f	E_f
2	300	0	10	0.8	0.8

Table 4.7: Initial values for calculating the load coming from the opening of doors.

Internal load

Internal and equipment related loads are heat generated from equipment or personnel inside the refrigerated space, and heat generated from refrigeration equipment. This include electrical equipment such as fans and lights, processing equipment, trucks for large facilities, people present in the refrigerated space, and defrosting of evaporators due to ice formation. The electrical power consumption of a fan under given conditions can be found from the capacity diagram of the fan. When the fan type is not known, its power consumption can be determined as:

$$\dot{W}_{fan} = \frac{\dot{V}_{air}\Delta P}{\eta_{fan}} \tag{4.12}$$

This is typically in the order of 3 to 8% of the total evaporator capacity for a cold storage, and 15 to 20% for air blast freezers(Eikevik, 2018).

The simulation of the internal load will be the heat coming from the fan and potential defrost of the evaporator when the coils are below 0°C. The fan load will be equal to the energy input to the fan due to conservation of energy, and the fan load will therefore be the fan work calculated from Equation 4.12. The volumetric flow from the fan is found as described above, the pressure drop is given as an input based on the pressure drop function that is implemented, and the efficiency of the fan is an initial input set to be a standard value of 60%.

The heat required to defrost the evaporators when condensation on the evaporators form an ice layer is not added to the load. This is because the defrost of the evaporators can be done during unloading and loading of products. This means that the energy input to a defrosting unit will come when the product load is not present and the energy input from the solar panel is enough to power the defrost momentarily.

Product load

Product loads are heat generated from a product, or heat that must be removed from a product to bring it to storage temperature. The amount of heat removal needed to bring a product to a certain temperature during sensible heat transfer can be calculated as:

$$Q_{prod} = (mc_p\Delta T)_{prod} \tag{4.13}$$

This heat transfer will be done over a certain amount of time, and the temperature profile of the product will change during the process, transient heat transfer must therefore be considered for the product load when cooling is done. If the product will freeze the latent heat removed for freezing can be calculated as $Q = m_{product}h_{lf}$.

The simulation of the product load from a given amount of products will be determined by the properties of the product and the dimensioning temperature difference as in Equation 4.13. So if this heat is to be removed during a time period τ, the product load will be:

$$\dot{Q}_{prod} = \frac{(mc_p\Delta T)_{prod}}{\tau} \tag{4.14}$$

This load is found in the product load function, that also includes the transient considerations. The mass of products in the system is an input coming from the product type function which is based on the weight per box given in Table 4.14. The specific heat of the products is given from the thermal properties function, and the temperature difference between the product and the air in the cooling system are initial inputs. To determine the time dependant refrigeration load that is used to dimension the system, the transient heat transfer must be considered.

Total load

The total refrigeration load will be the sum of the above stated loads. However, because of possible uncertainties in the calculations a safety factor S_f of 10% is normally added to the total.

$$\dot{Q}_{load,tot} = (\dot{Q}_{trans} + \dot{Q}_{infilt} + \dot{Q}_{inter} + \dot{Q}_{prod})(1 + S_f) \tag{4.15}$$

The simulation of the total load is then determined as the sum of the above stated loads(Equation 4.15), with the addition of a 10% safety factor.

4.3.3 Transient considerations

This transient heat transfer theory and equations are based on the compendium section by (Tolstorebrov, 2018), and detailed derivations for the following equations can be seen there.

As the product temperature is decreased through cooling or freezing, the product will experience transient heat transfer due to a smaller temperature difference between the product and surroundings as time of cooling increases. This means that the temperature field and the heat flow from the product(Equation 4.13 when sensible heat) will be time dependant, meaning considerations must be made in this regard when a cooler is designed. Based on the Fourier-Kirchoff heat transfer equation and dimensional analysis, correlations for a variety of different geometrical shapes can be found for transient heat problems, which can be solved numerically. For the scope of this project work a spherical shape is considered, as this shape resembles many types of fruit and vegetables. Initially, the dimensionless temperature can be defined as the ratio of temperature difference between a product and its surrounding ambient to the temperature difference between product and ambient initially:

$$\theta = \frac{T_\tau - T_{amb}}{T_{\tau=0} - T_{amb}} \tag{4.16}$$

For cooling of a sphere, this dimensionless temperature at a given distance x radially away from the centre of the spherical product can be found as:

$$\theta = \sum_{n=1}^{n\to\infty} \frac{2(sin\mu_n - \mu_n cos\mu_n)}{\mu_n - sin\mu_n cos\mu_n} \frac{sin(\mu_n \frac{x}{r})}{\mu_n \frac{x}{r}} exp^{(-\mu^2 F_o)} \quad for \quad 100 \geq Bi \geq 0.1 \tag{4.17}$$

Boundary conditions in the sphere centre of $x = 0$ is so that the fraction $\frac{sin(\mu_n \frac{x=0}{r})}{\mu_n \frac{x=0}{r}} = 1$. The average dimensionless temperature of a sphere will be:

$$\overline{\theta} = \sum_{n=1}^{n\to\infty} \frac{6Bi^2}{\mu_n^2(\mu_n^2 + Bi^2 - Bi)} exp(-\mu^2 Fo) \quad for \quad Bi \geq 0.1 \tag{4.18}$$

The equations (4.17) and (4.18) can be solved by numerical methods on a computer, when the variables μ,Bi and Fo are known. The Biot number Bi is the dimensionless ratio of internal to external thermal resistance, and can be found as:

$$Bi = \frac{h_c L}{k} \tag{4.19}$$

Where L is the characteristic dimension of the geometry, and k is the products thermal conductivity. The Fourier number Fo is a dimensionless number stating the correlation between time wise length of the process, and the time of thermal wave distribution in the geometry. Due to its dependency on the time of the process τ, it will increase with increased cooling time, and can be found as:

$$Fo = \frac{a\tau}{L^2} \tag{4.20}$$

Finally, The roots of parametric equation μ can be found as[1]:

$$tan\mu = -\frac{\mu}{Bi - 1} \tag{4.21}$$

Once θ is determined, the temperature at a given time T_τ can be found from Equation 4.16, and the rate of heat transfer during the time period, i.e the product load, can be found as:

$$\dot{Q}_{prod} = \frac{(mc_p\Delta T)_{prod,\tau}}{\tau}$$

The simulation of the transient considerations are important as these determine how long it will take for a specific type of product to reach the desired temperature, which in turn determines the product refrigeration load as described in Equation 4.14. The transient behaviour of the product load will predict how the temperature profile of the product in a cold room changes with time as shown in Figure 4.9, which means that the product load function will solve iteratively and give an array of temperatures found from the transient theory previously given.

The product load and also the transient behaviour of the product is simulated in the product load function, where initial inputs are initial product temperature and temperature in the cooling system. Further inputs are the total mass of products, individual diameter of products, wanted product temperature, specific heat of product and thermal diffusivity of product, which are found

[1]Solving for small values of Bi can be troublesome, see section A.3 for clarification and alternative approach.

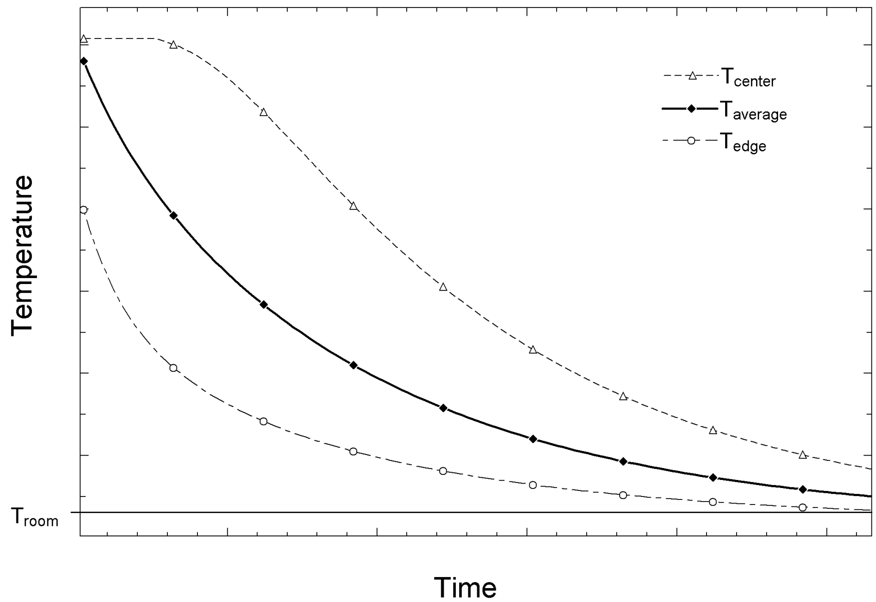


Figure 4.9: Transient temperature profile of a product of high temperature that is cooled in a room of lower temperature.

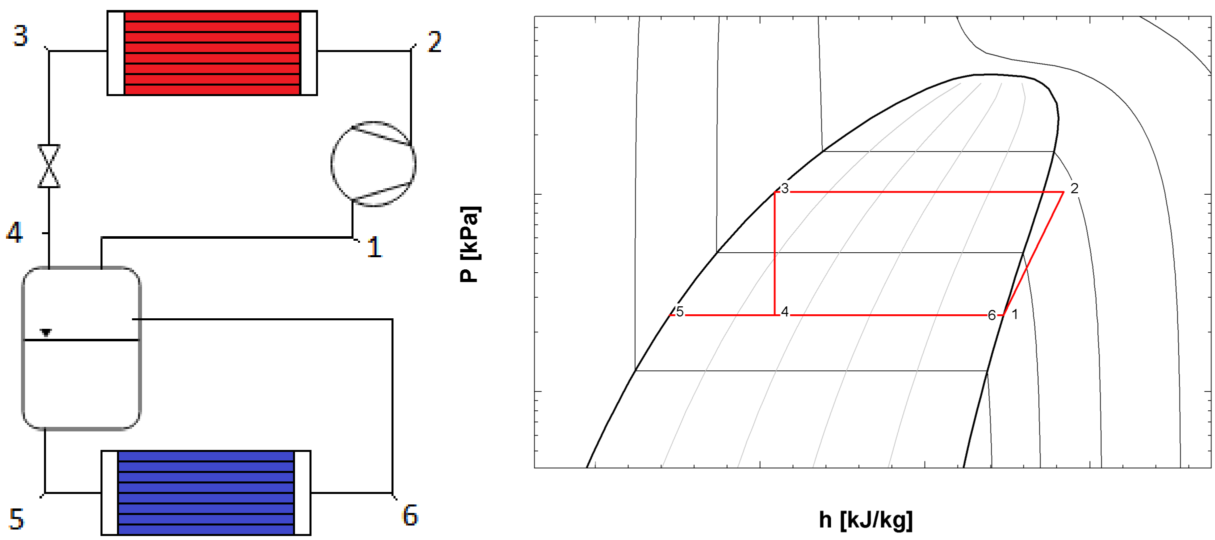
from the product type function and the thermal properties function. The dimensionless numbers Bi and Fo are calculated from the relations shown in Equation 4.19 and Equation 4.20 respectively. The Bi number will be a constant as the values for calculating it is considered constant when the cooling system is in operation, it is therefore found as a separate value and is given as input to the product load function. The Fo number is dependant on time and will increase with increasing time of cooling system operation, and is therefore included in the iterative product load function.

The roots of parametric equation μ is also not dependant on time, therefore it will be calculated separately and given as input to the product load function. It is a function of itself, and such functions can be solved with inbuilt functionality of EES with chosen initial guess-values and boundaries. After some experimentation with values that give stable answers, these are chosen to be $\mu[1] = 2$ with set boundaries between 0.4 and 3.0, $\mu[2] = 5$ with set boundaries between 4.0 and 6.5 and $\mu[3] = 8$ with set boundaries between 7.7 and 10. However, the inbuilt solver in EES is unable to give a solution of μ for low Bi numbers, due to the method that it uses in solving. An empirical function is therefore made and implemented for $Bi < 1.7$, which is explained in section A.3.

The dimensionless temperature at the center and edge of the product θ_c is found by setting $x = 0$ and $x = r$ in Equation 4.17 respectively, and solving the summation by numerical iteration. The dimensionless average temperature of a product is found by solving the summation in Equation 4.18 numerically through iteration. The numerical solving of the equations is as mentioned done by iteration, where three iterations are done. After three iterations the difference in the summations becomes negligibly small. The separate iterations are summed up, which gives a dimensionless temperature describing the change in temperature with respect to the given amount of time. This can then be used in Equation 4.16 to find the temperature at the center and edge of the product and also the average temperature of the product. The product load function will iterate over time and thus give an array with the transient temperature profile of the product. The iteration is time dependant and is done until the temperature of the product is equal to or just below the wanted storage temperature, which means that both the time of cooling and temperature difference achieved is known. This is in turn used to determine the product load in watts.

4.3.4 Refrigeration system

The refrigeration system is a heat pump that transfers thermal energy from a low to a high temperature reservoir, producing a cooling effect from the evaporator and a heating effect from the condenser. This is generally done by phase change of a fluid heat transfer medium, called a refrigerant or working fluid, inside the heat pump circuit. As previously stated the system will be a simple single stage vapour compression cycle with a liquid receiver, shown with a corresponding log P-h diagram in Figure 4.10.



(a) **(b)**

Figure 4.10: Refrigeration cycle of the cooling system **(a)** and corresponding log P - h diagram **(b)**

The cycle is powered by energy input to the compressor, and its degree of performance is measured by the amount of useful heating/cooling achieved compared to the work input, called the COP(Coefficient of performance).

$$COP = \frac{\dot{Q}}{\dot{W}} = \frac{\text{Useful heat supplied/removed by system}}{\text{Work required by system}} \tag{4.22}$$

The total refrigeration load is determined as the sum of the above described loads (Equation 4.15). This refrigeration load is the amount of energy that will be removed from the system via the heat pumping refrigeration system. An energy balance can be done between the state points, where they are denoted i and j, and where i is the high enthalpy state point and j is the lower enthalpy state point.

$$\dot{E} = \dot{m} * (h_i - h_j) \tag{4.23}$$

Furthermore, thermodynamic relationships can be used to determine the working fluid state points throughout the cycle. This information can be used to determine heat flows($\dot{Q}$) to and from the system, work rate($\dot{W}$) of the system compressor, mass flow($\dot{m}$) of the refrigerant, and thermodynamic properties of the state points(T_1,P_1 etc.).

The simulation of the refrigeration system is done by knowing the correlations previously explained, with initial inputs that must be given to simulate the refrigeration system. These are the isentropic efficiency, the type of refrigerant, temperature of air in the cooling system and in the ambient, and temperature difference between the heat exchanger and its surrounding air. The isentropic efficiency η_{is} of the compressor will depend on the pressure ratio of the system. This pressure ratio will change with changing ambient conditions, and so will the efficiency. The details of changing efficiency is not considered vital for the goal of the thesis, and a typical isentropic efficiency of $\eta_{is} = 0.8$ is assumed. The ambient and internal cooling system temperatures are determined from climatic data and the required product temperature after cooling. The temperature difference in the heat exchangers are as previously mentioned decided to be 5 °C.

Remembering that EES can solve set of equations even though they are not listed in consecutive order, the state points as shown in Figure 4.10 is found using the inbuilt functions of EES:

Point 1, the liquid receiver exit is on the saturated vapour line, at the same pressure level as the evaporator. Using the inbuilt functions of EES, the pressure, enthalpy, entropy and specific volume at this point can be found as functions of temperature and vapour content.

Point 2, the compressor exit is initially determined ideally, by assuming isentropic compression, and knowing the pressure of the condenser based on its temperature found in point 3. The real compressor work is found when knowing isentropic compressor efficiency and using the enthalpy difference over the compressor as:

$$\dot{W}_{ideal} = \dot{m}_{cond}(h_{2,ideal} - h_1)$$
$$\dot{W}_{real} = \frac{\dot{W}_{ideal}}{\eta_{is}}$$

Where the mass flow rate of the condenser is know from an energy balance of the liquid receiver as:

$$\dot{m}_{cond}h_4 + \dot{m}_{evap}h_6 = \dot{m}_{cond}h_1 + \dot{m}_{evap}h_5$$
$$\dot{m}_{cond} = \dot{m}_{evap}\frac{h_6 - h_5}{h_1 - h_4}$$

the real enthalpy and temperature of point 2 is found.

Point 3, the condenser exit is on the saturated liquid line, at the temperature of the condenser. This is then used to find the related pressure and enthalpy at the state point via inbuilt functions.

Point 4, the expansion device exit is found by assuming isenthalpic expansion and knowing that the pressure will be the same as for the evaporator. This can then be used to find the related property of vapor liquid fraction via inbuilt functions.

Point 5, the liquid exit of the liquid receiver will ideally give a flow to the evaporator of fully saturated liquid at the same pressure level as the evaporator. This can then be used to find the related property of enthalpy via inbuilt functions.

Point 6, the evaporator exit will ideally be fully saturated vapour that is sent to the liquid receiver with refrigerant properties identical to point 1.

The mass flow through the condenser loop will determine the volumetric flow through the compressor, which is used to determine the size of the compressor from a manufacturer. The specific volume for point 1 and the mass flow through the condenser loop is known, and the volumetric flow is found as:

$$\dot{V}_{compr.} = v_{specific}\dot{m}_{cond}$$

The heat released from the condenser is found as the mass flow multiplied by the entropy change over the condenser. And the COP of the system is found via Equation 4.22:

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{real}}$$

4.3.5 Refrigerant selection

The working fluid in a heat pumping refrigeration cycle is normally called the refrigerant, and is the fluid medium used for transferring heat in the heat pumping process. In most process the heat is transferred by phase transition of the refrigerant, where the latent heat is utilized. There are a large number of different refrigerants available, and the decision of which to use in a refrigeration cycle must be based on a comparative analysis of many factors to find the refrigerant most suitable to the specific refrigeration need. The deciding factors are mainly:

- Thermodynamic properties
  -Boiling point, critical temperature & pressure, thermal conductivity, viscosity, latent heat of evaporation & condensation, volumetric refrigeration capacity etc.
- Safety factors
  -Toxicity, flammability & explosiveness, material and refrigerant compatibility [2], working pressure of refrigerant and system.
- Environmental impact
  -GWP(Global Warming Potential) and ODP(Ozone Depletion Potential), other environmental damage such as causing smog and acid rain.
- Economical viability
  -Cost of refrigerant, taxation and fees [3], effectiveness of the system with the specific refrigerant.

The most ideal refrigerant for a heat pumping process is the one that has the most suitable thermodynamic properties for the refrigeration needs, have few or manageable safety factors, has the lowest GWP and ODP, and gives the most economically beneficial system. No refrigerant is the most ideal for all applications, and refrigerant selection will generally be a compromise between the deciding factors based on an educated analysis.

[2] It is important to avoid material deterioration in mechanical components and piping caused by e.g. corrosion, how the refrigerant is affected by oil and water contact is also important.

[3] Some countries and regions have implemented taxes on refrigerants with high GWP and ODP

Natural refrigerants

CFCs (Chlorofluorocarbons), HCFCs(Hydrochlorofluorocarbons) and HFCs (Hydrofluorocarbons) have been commonly used as refrigerants and are still prominent, but they have high GWP and ODP values and are therefore being phased out due to legislation such as the Montreal(1987) and Kyoto(1997) protocol. For this reason natural refrigerants have been reintroduced to refrigeration systems as more GWP and ODP friendly refrigerants, furthermore they are often abundantly available and comparatively lower in costs.

Air and water can be considered as natural refrigerant, however the most commonly used in industrial refrigeration systems are hydrocarbons, ammonia and CO_2.

Hydrocarbons have very good thermodynamic properties(as good as or better than HFCs and HCFCs) and low environmental impact, and are beneficial for use in small or compact systems.They consist of many different types of chemical combinations and blends, but the most common are propane(R290), isobutane(R600a) and propylene(R1270) (Danfoss, 2018). However they are highly flammable and explosive, and require attention to this safety aspect if it is to be implemented.

Ammonia(NH_3, R717) has some of the best thermodynamic properties and efficiency of all refrigerants, it has zero GWP and ODP, and is highly prominent in industrial applications. Challenges with ammonia include corrosion of copper if water is present, and it is poisoning and can be flammable[4]. Ammonia is rarely considered in smaller capacity systems below 100[kW].

Carbon dioxide(CO_2, R744) is non toxic and non flammable, has zero ODP and a GWP of 1, it is compatible with heat pump system materials, and gives high volumetric refrigeration capacity and energy density. This is due to its low critical temperature(31.1°C) and high pressure(73.8bar), resulting in comparatively very small compressor volumes and consequently smaller components and piping. However low critical temperature will give large expansion losses, and the system will also operate so called transcritically for ambient/surrounding temperatures above the critical temperature, where heat rejection must be done with a temperature glide. This can be utilized, especially in cold environments, but CO_2 application in warm climates are challenging and require somewhat complex and expensive system design to be competitive.

The simulation of the complete system is needed to determine which refrigerant will be the most efficient and viable in terms of system performance. This will be evaluated along with the information about refrigerants given above, and an informed selection can be made.

4.3.6 Energy supply

Solar cooling is the concept of using solar energy to power a refrigeration cycle, where the two main categories of commercially available systems are PV driven refrigeration units, and solar thermal refrigeration units. A PV driven systems uses electrical input from a PV panel generator to power the compressor in a heat pumping system, while a solar thermal unit uses a solar heat collector to provide energy to a heat driven refrigeration cycle(e.g. absorption systems). Newer analysis of such systems indicate that PV driven solar coolers perform close to or even better than solar thermal perform units in overall efficiency, require little space, and are comparatively more economically feasible than solar thermal for most applications (Lazzarin, 2017). The power delivered by an array

[4]The actual poisoning risk is small, due to the noticeable odor of ammonia at concentrations much lower than what is deadly. The concentration of ammonia in air must be 15-28% by volume for it to be flammable, reaching this concentration takes time and the area will be impossible for people to be in due to the high concentration.

of solar panels can in its simplest form be calculated as:

$$\dot{W} = S_i A_{tot} \eta_{panel} \tag{4.24}$$

where S_i is the solar irradiance in $[W/m^2]$. Typical efficiency is between 10-20% for standardized PV panels (McEvoy et al., 2003).

Renewable energy supply will also rarely be constant, and in the Indian scenario the most likely renewable energy supply will be solar power which is only present by day. For this reason it is necessary to have some sort of energy storage to power the refrigeration unit when solar power is not present, such as if it is used in the night or when it is blocked by clouds. Batteries provide the most natural solution if the generated energy is electrical and from a PV system. They are abundant and relatively cheap, but require proper handling and disposal. The battery size should be determined based on the daily average power consumption as:

$$B_s = \psi(\dot{W}\tau)_{lacking} D_d \tag{4.25}$$

where ψ is the inefficiency factor of the battery, $(\dot{W}\tau)_{lacking}$ is the power the system requires that is not being supplied directly from the solar panel in [kWh](WholesaleSolar, 2018). The depth of discharge is how far the battery can be discharged in a real scenario(50% for lead acid and 80% for lithium ion), and D_d is a corrections due to this depth of discharge. For two potential batteries, these values are as shown in Table 4.8.

Battery type	ψ	D_d
Lead-acid	1.2	2
Lithium ion	1.05	1.2

Table 4.8: Inefficiency factor and depth of discharge for lead-acid and lithium ion batteries(WholesaleSolar, 2018).

Thermal energy storage is a potential alternative that can be a low cost use of excess amount of energy during production hours, however it requires large storage areas and good insulation conditions.

The simulation of the energy supply is done as follows. The compressor and the inner chamber fan are the components that drive the system, and it is the work of these components that needs energy supply. Since the entire fan is placed inside the cooler, all the energy input to the fan will be released to the cooling system. To insure that there will always be enough energy supply, the PV panel is dimensioned for the month with the largest energy requirement. The area of solar panel needed can be found from Equation 4.24:

$$A_{tot} = \frac{\dot{W}_{sys}}{\eta_{panel} S_i}$$

The battery is chosen to be a lithium ion battery, and the size of the battery bank can be found from Equation 4.25 and Table 4.8:

$$B_s = 1.05(\dot{W}\tau)_{lacking} 1.2$$

4.4 Operating conditions

The operating conditions for the system will be the determining limits for the design. The geometry of the system has previously been described, and the dimensions of this geometry will be the fixed conditions that determine how much available space there is. These dimensions are given in Table 4.9.

Section	Height[m]	Width[m]	Length[m]
Container external dimension	2.59	2.44	6.05
Container internal dimension	2.39	2.35	5.9
Door opening	2.39	2.35	0.075
Insulation layer	0.150	0.150	0.150
Box external dimension	0.4	0.6	0.5
Box internal dimension	0.3	0.4	0.4
Pallet	0.162	1.2	1

Table 4.9: Dimensions of the cooling system geometry.

The local climate conditions will determine how the refrigeration system will have to work to remove heat from the products, and it will determine the requirements for keeping a constant temperature in the cooling unit. Where the system is located will also impact how much solar irradiation there is available, which will the amount of energy that can be supplied to the system from the solar panels and battery.

Apples, grapes and mangoes have different seasons and are grown in different areas as previously presented. The portable cooling system will be transported between the different areas so that cooling is available for each type of fruit when it is seasonally harvested. This means that the system operate over the entire year, but it will have different local climates and available solar irradiation depending of what type of fruit is cooled, and where the harvest of this fruit is. The three following areas will be considered for the three different types of fruits:

Apples - Dehradun in Uttarakhand, with average operating conditions as in Table 4.10.

Grapes - Mumbai in Maharashtra, with average operating conditions as in Table 4.11.

Mangoes - Kolkata in West Bengal, with average operating conditions as in Table 4.12.

These areas are chosen because they are major cities in areas where production of the fruits are significant. The system would in reality most likely be placed at a more remote farming area in proximity to these cities, so data from the real location should be used for exact implementation of the system. However, the differences in data will be minor, and the data used here will be sufficient for a general investigation of the system in each area of production.

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High temp. [°C]	19.3	21.5	26.4	32.1	35.6	34.8	30.5	29.4	29.7	28.5	25	21.1
Low temp. [°C]	6	7.8	12	16.7	20.7	23	22.8	22.4	20.8	15.7	10.4	6.8
Humidity [%]	72	66	57	46	48	66	85	86	81	69	68	71
Solar irradiance $[\frac{kWh}{m^2day}]$	3.53	4.32	5.80	6.70	7.24	6.30	5.08	4.72	4.97	5.28	4.29	3.59

Table 4.10: Monthly average climatic data and solar irradiation for Dehradun, Uttarakhand, India (Weather Atlas, 2002-2018; Synergy Enviro Engineers, 2018).

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High temp. [°C]	30.7	31.2	32.5	33	33.3	32.1	30	29.6	30.4	33.2	33.5	32
Low temp. [°C]	16.8	17.8	21	23.9	26.3	26	24.9	24.7	24.3	23.4	20.9	18.6
Humidity [%]	69	67	69	71	70	80	86	86	83	78	71	69
Solar irradiance $[\frac{kWh}{m^2day}]$	5.22	6.12	6.81	7.25	7.33	5.26	4.51	4.48	5.07	5.80	5.33	4.96

Table 4.11: Monthly average climatic data and solar irradiation for Mumbai, Maharashtra, India (Weather Atlas, 2002-2018; Synergy Enviro Engineers, 2018).

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High temp. [°C]	26.4	29.1	33.5	35.3	35.4	34	32.3	32.1	32.4	32.3	30.3	27
Low temp. [°C]	13.8	16.9	21.7	25.1	26	26.5	26.1	26.1	25.8	23.9	19.6	14.5
Humidity [%]	66	58	58	66	70	77	83	83	81	73	67	68
Solar irradiance $[\frac{kWh}{m^2day}]$	4.27	5.17	6.00	6.58	6.48	5.10	4.60	4.52	4.70	4.50	4.65	4.17

Table 4.12: Monthly average climatic data and solar irradiation for Kolkata, West Bengal, India (Weather Atlas, 2002-2018; Synergy Enviro Engineers, 2018).

The average operating conditions are used for compactly illustrating the trends of the monthly scenarios. For the real dimensioning of the system, collected weather data from 2005 is used for each of the locations (Meteonorm, 2005).

The type of product that will be cooled will change with the time of year. Because of the seasonal harvest, the system will be transported between areas of production so that it can operate through the year and maximize value output. The system will be considered for apples, grapes and mangoes as stated in Table 4.13, where the product is cooled throughout the last month (i.e. apples are cooled until the end of October). This accommodates for a large amount of peak season cooling of apples and mangoes that are otherwise rarely cooled, and an auxiliary lean season cooling of grapes which are already frequently cooled, as illustrated in Table 3.3.

The system behaviour will also depend on the type of product it should cool down. The considerations and assumptions relevant for the different products have been previously documented, and initial values for the different products are chosen as stated in Table 4.14. Here the cooling system has initially been chosen to have a 2 °C temperature difference between the product and the room

Fruit type	Apples	Grapes	Mangoes
Cooling season	Jul.-Oct.	Nov.-Jan.	Feb.-Jun.
Climatic region	Dehradun	Mumbai	Kolkata

Table 4.13: Season and region where the cooling system will be operated for the three different types of fruit.

to allow heat transfer, and the temperature in the cooler will be above 0 °C to avoid potential freezing of condensing vapour in the geometry and on the products. The wanted product temperature after cooling is also chosen to be slightly higher than optimal storage temperature, to avoid local cooling damage on products. Some of these choices will later be changed based on the results and corresponding justifications in the discussion.

Item of consideration	Apple	Grape	Mango
Shape	Sphere	Sphere	Sphere
Diameter [m]	0.08	0.03	0.12
Optimal storage temperature [°C]	-1 to 0	0 to 1	10 to 13
Cooler temperature [°C]	1	1	10
Product temperature after cooling [°C]	3	3	12
Porosity	0.4	0.565	0.45
Potential weight per box [kg]	26	19.2	24.2

Table 4.14: Initial conditions relevant for the products that will be cooled.

Chapter 5

Results and discussion

The results and the corresponding discussion will be an investigation into how a designed system will operate based on the simulated model that is made. The different factors of the system, their validity, and how they influence the rest of the system is presented. From the discussion around these factors, a suggested optimal solution and behavior of the system is presented, and this optimized system is further investigated to illustrate the workings of model, with discussions related to the Indian scenario. The results are found using the above specified methods, assumptions, and the simulation program in EES given in Appendix B, and will be discussed consecutively due to the large amount of factors impacting the system.

5.1 Products and airflow in the geometry

The products and the airflow in the geometry form the background for the heat transfer calculations. This is investigated and discussed to determine the foundation on which the cooling system must work. Furthermore, the validity and relative certainty of the different factors are discussed. It is found that the largest uncertainties are in the porosity and mass of products in the system, and that the volumetric flow of the fan will be the driving factor for heat transfer.

Product type

The results of the product type function is simply that the program sets the product constituents as in Table 4.3, and the porosity, product size, and wanted product temperature as in Table 4.14. Furthermore, the mass of product in each box and thus also the total mass of products in the system is calculated, from the relation in Equation 4.1.

The values of each of the respective product constituents is taken from credible sources, and their validity is certain enough for use in this work (ASHRAE, 2018). There may be minor variations in the percentages of each constituents for different types of crops and cultivars, and also minor variations due to physical changes during aging and processing (section A.1). These variations will however be negligibly small, and as seen from the values of the thermophysical properties in Table 4.2 even the differences in constituents between different types of fruit and vegetables are small.

As mentioned, the porosity has been found from sources where similar work has been done on equal or similar products, and its values in this thesis work is with some degree of uncertainty. This will be discussed further in relation to the pressure drop.

The mass of product in each box is initially determined as dependant on the previously discussed porosity, available volume of the box, and product density (Equation 4.1). This is a measure of the theoretical maximal amount of products that can be held by the boxes based on the stated porosity. In reality the mass of products in each box will vary depending on stacking arrangements, product size and how much a worker will fill the box with. With the amount of product per box being as stated in Table 4.14 and the amount of pallets and boxes as stated in subsection 4.1.1, the total weight of products in the cooling system will be around 1.5 tonnes for all product types. This will in turn cause a very large product load if the heat transfer rate is relatively high, which requires a very large solar panel for energy input. This issue will be further addressed and resolved in section 5.3.1.

Thermal product properties

The thermal product properties is set at a function of the specified products physical constituents found from the product type function. The product will for all relevant scenarios keep within the limits of the model implemented from Table 4.2. Since the temperature difference between ambient air and wanted product temperature after cooling is quite small and incurs no phase change, the thermal properties are calculated once for the mean between the ambient and wanted product temperature. This will be a sufficient approximation as neither of the thermal product properties will have large variations when cooled from ambient to wanted product temperature, as shown for each product property between 0 and 150 °C in Figure 5.1.

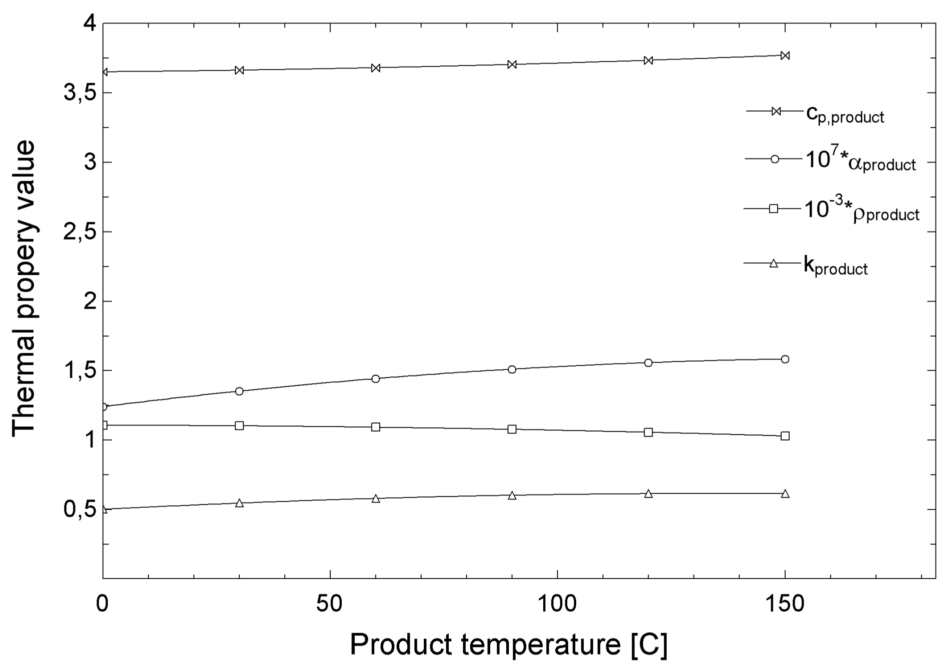


Figure 5.1: Change in thermophysical properties of grapes with changing product temperature.

Airflow

The airflow is as stated determined by the fan diameter and the airspeed out of it, i.e the volumetric flow through the fan. The volumetric flow of the fan is the driving factor for the cooling rate of the system, as this determines the air velocity and thus the rate of heat transfer from the products. The diameter of the fan is chosen to be fixed at $D_{fan} = 0.5[m]$, leaving the speed of air through the fan as the determining factor of the volumetric flow.

No specific fan has been chosen for the design and simulation of the system, as the airspeed of a fan will be varying with type and particular geometry of the fan blades, and the revolutions of the blades. An appropriate fan can be found and requested from a manufacturer once the maximal fan work is definitively determined. Although the volumetric flow rate is considered constant, the airspeed throughout the geometry is uncertain to some degree. The superficial velocity, i.e the speed of the air just before the inlet of the boxes, is known due to the fixed areas of both the fan diameter and the box areas. However, the other geometric cross sections in the geometry is more variable as the geometry is not uniform in the flow direction, meaning that the airspeed through the boxes of products will not be the same for all cross sections. It is therefore likely that there are higher air velocities due to smaller cross section area in parts of the geometry, and also some lower velocities due to physical restrictions in the air path. To determine a complete air velocity profile through the entire geometry, a comprehensive CFD simulation should be done.

For the scope of this thesis a CFD model is not implemented. This is because determining the volumetric flow through the fan is sufficient for determining the loads and the most crucial air velocities in the geometry.

Heat transfer coefficient

The heat transfer coefficient is modeled in relation to the superficial velocity and the diameter of each type of product, and will therefore have a degree of uncertainty. As previously discussed, the superficial velocity will not be the same as the local air velocity at all points of the geometry. The products will also not be fully uniform in diameter and spherical shape for the real case of each fruit type. For this reason, the local heat transfer coefficient around each one of the products will have some varying degree of certainty.

The modeling of the heat transfer coefficient is also done for one single fruit in an ideal non-restricted stream of air. The fruits will in reality be placed in a more randomly stacked pattern with minor size variations of each fruit, leading to some non-uniform flow of air around the products. This is counteracted by ensuring a stacking arrangement where air can flow as freely as possible around each product. Such a stacking arrangement will make the simulated heat transfer coefficient in this work more accurate in terms of the real scenario. The mass of products in each box will also be reduced due to larger spaces between each product.

A CFD model should also be implemented if the goal is to determine a precisely accurate local heat transfer coefficient, the same as for the local airspeed. The geometry can also be experimentally constructed and tested, and the heat transfer coefficient can be determined by reverse engineering from temperature measurements and the real cooling time. The simulation implemented in this work is however a sufficient approximation as it quite closely models the reality, with minor variations and idealized assumptions. The convective heat transfer coefficient for each type of fruit with diameters as previously stated are illustrated in Figure 5.2.

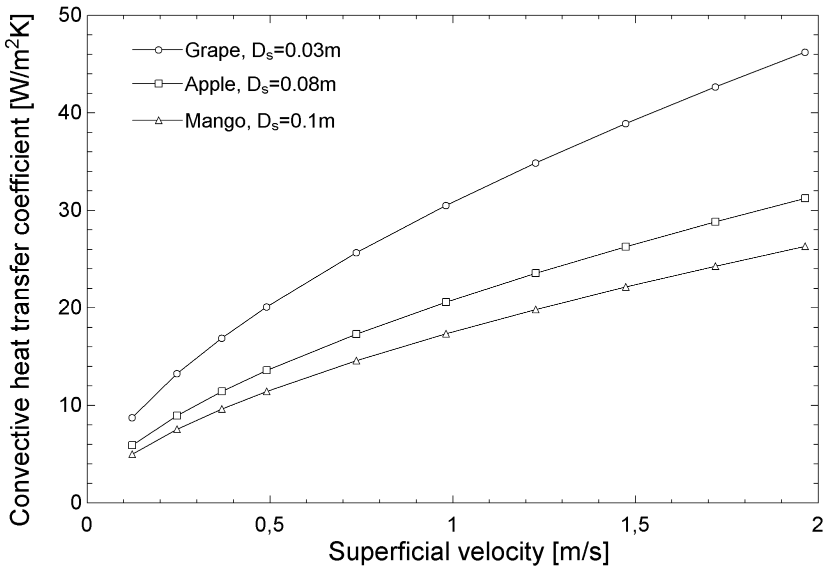


Figure 5.2: Convective heat transfer coefficient for one apple, grape and mango as a function of superficial air velocity.

Pressure drop

The pressure drop will have some uncertainty as a result of the uncertain porosity and variations in product diameter. The porosity will in reality be dependant on the stacking arrangement of products in the boxes, and on the geometry of the holding boxes of products. This is because the fluid flow around the products will not have fully uniform access to all the void space, and the geometry of a holding box will further change and obstruct fluid flow around the products. The porosity should be experimentally determined for a fully accurate result, as done by i.e (Ngcobo et al., 2012), or through precise a precise and comprehensive CFD simulation. The pressure drop calculated from the Ergun equation does however provide a reasonable result. This is validated by comparing the results to studies with similar theoretical results, which also investigate and state that predictions with comparative models are precise (van der Sman, 2002). The pressure drop per meter length of bulk produce for the three types of fruits, and the changes in pressure drop with changing porosity and product diameter for grapes is illustrated in Figure 5.3. The changing behaviour of the pressure drop will be the same for apples and mangoes. Since the porosity is a measure of the available void space where air can flow, a lower porosity implies a higher pressure drop. Furthermore, the pressure drop it inversely proportional to the product diameter.

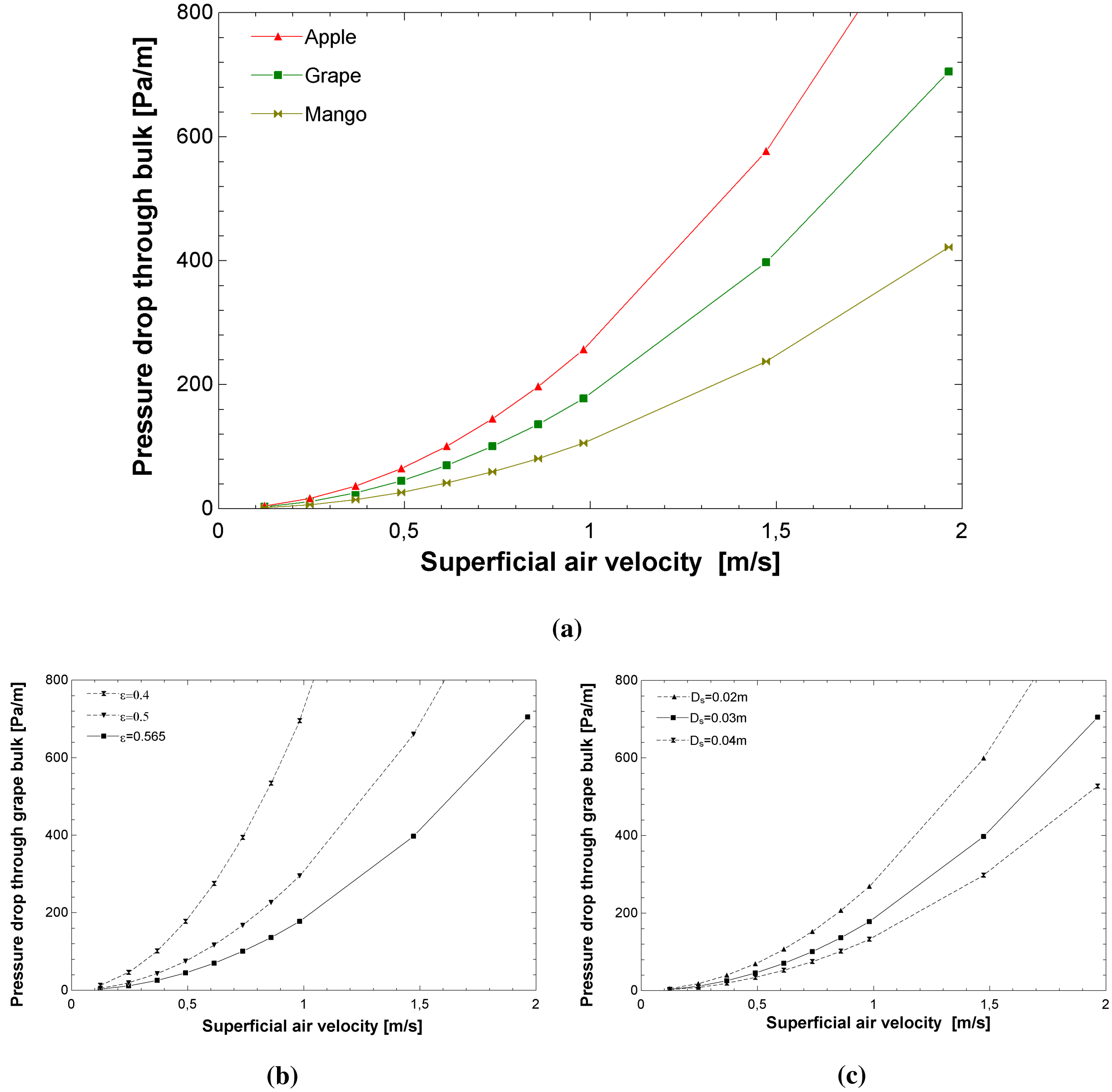
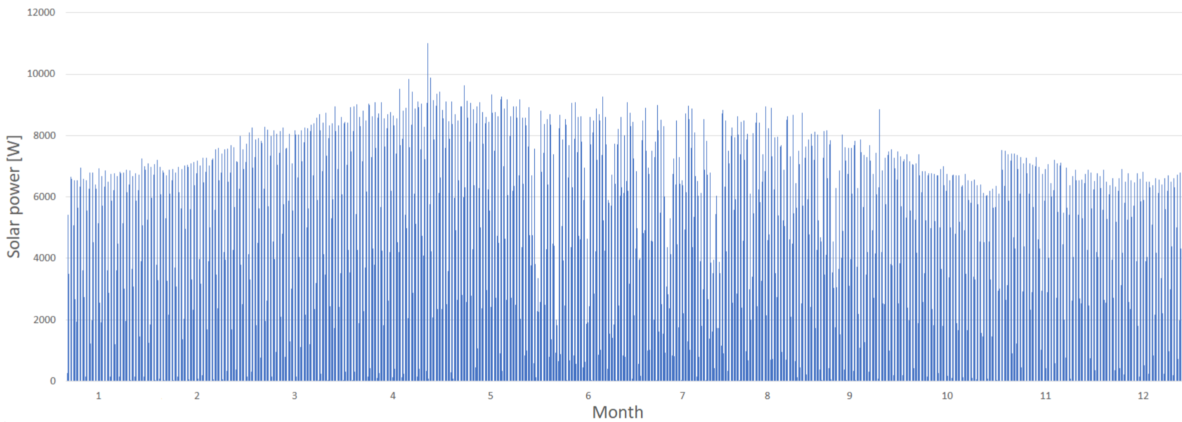


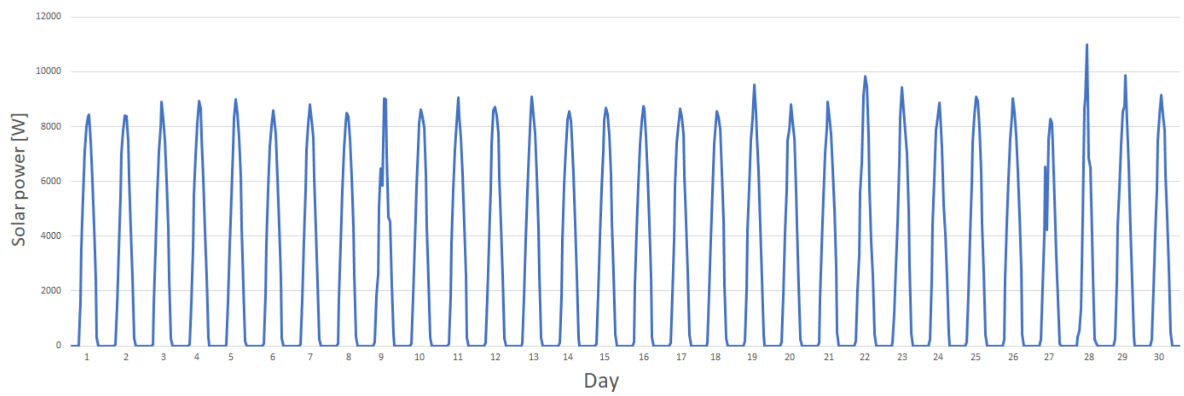
Figure 5.3: Pressure drop through a bulk of the three different fruits under the initial stated conditions **(a)**, change in pressure drop with changing porosity of grapes **(b)**, and change in pressure drop with changing diameter of each grape **(c)**.

5.2 Available energy

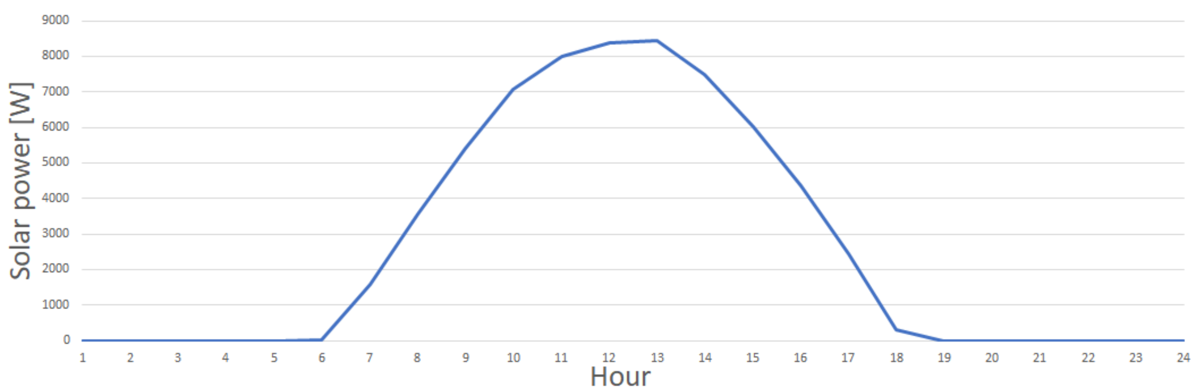
The amount of available energy coming from solar panel will determine how much energy the system can use, thus limiting the size of the cooling system. As illustrated in the design, the potential area of the solar panel is 47.3 m^2. The power accessible from this panel will vary throughout the year with the varying incoming solar radiation. For the system with 47.3 m^2 solar panel area at an efficiency of 15%, and with monthly regional placement as in Table 4.13, the yearly, monthly and daily available energy in kW is presented in Figure 5.4 (Meteonorm, 2005). The axis number 1-12 indicate the respective months from January to December.



(a)



(b)



(c)

Figure 5.4: Available energy from the solar panel of the cooling system throughout a year **(a)**, for the month of April in the same year **(b)**, and for the first day of April in the same year **(c)**.

The incoming solar energy will as shown fluctuate throughout the year and with the daily rise and fall of the sun.

5.3 Refrigeration loads

The load profile of the system throughout a year is investigated and discussed in order of optimizing the system for its intended use.

Transmission load

As the geometry of the cooling system is fixed, the only factors causing variations in the transmission load is the change in ambient temperature and the products being cooled - which determine the cooler temperature. The transmission load throughout a year will change according to the chosen operating season stated in Table 4.13 and the corresponding ambient and cooler temperature.

The transmission load of the cooling system for the average high temperatures over a year is illustrated in Figure 5.5, where the system is transported between the different regions and cools the different products.

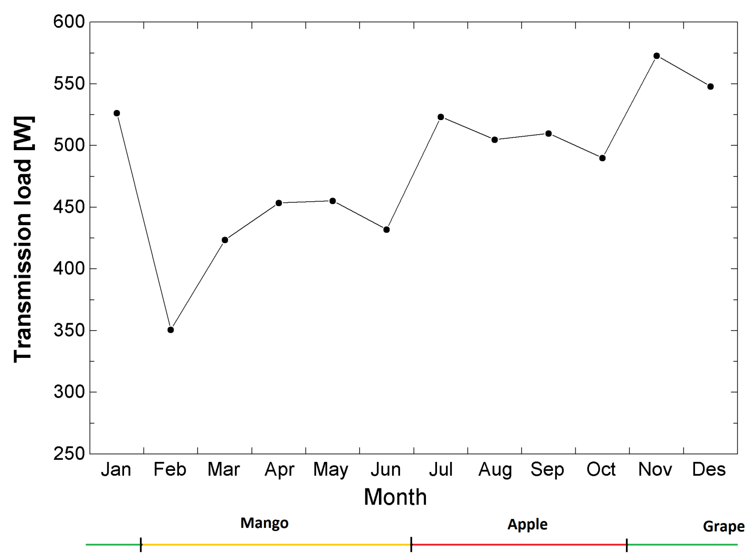


Figure 5.5: Average high transmission load of the cooling system throughout a year.

The added temperature differences due to solar radiation on the walls is here taken as stated in Table 4.6. However, the solar panel will provide shade to the walls, and the direct solar radiation will in reality be less. This shading will reduce the transmission load slightly, but the effect is so minor that the added temperature differences are kept the same to account for diffuse radiation. Increasing or decreasing the temperature inside the cooling system will decrease or increase the transmission load respectively. The change in the transmission load will again be very small for all feasible temperature changes.

The transmission load will consequently be determined mostly by the geometry of the container, and the insulation that is added. There is therefore little room for improving the transmission load energy wise by changing the way or operation.

Infiltration load

The infiltration load coming from the opening and closing of doors will change with ambient and cooling system temperature in the same manner as the transmission load, as the infiltration load is dependant on the air properties at these temperatures. The load profile throughout a year will therefore be equivalent to the transmission load, but with differences in the size of the load.

The opening of the door will be the largest impacting factor on the infiltration load. The open area of the door is part of the fixed geometry, and will not be changeable as there must be a large door opening to be able to move the pallets inn and out. The temperature difference between internal and external air will not be lower than 11 degrees for any ambient condition, making the doorway flow factor D_f fixed at 0.8. The remaining factors that then can be influenced are the number of door openings N_o, the amount of time the door is open τ_p, and the potential open-doorway protection E_f. The number of door opening will depend on the cooling time as this determines how many batches of produce that can be cooled in a day. The two remaining factors will be the easiest to influence to give a significant load decrease.

Reducing the time of the door being open can significantly reduce the infiltration load, and it only requires workers being knowledgeable and resolute in not allowing the door to be open unnecessarily. A value of $\tau_p = 300[s]$ per door opening is chosen, as this is likely to be possible if the doors are swiftly opened and closed between each time a pallet is inserted or taken out. The effect of changing the door open time is illustrated in Figure 5.6 for the average high infiltration load through a operational year. Furthermore, a layer of open-doorway protection will reduce the load directly related to how effective the protection is, i.e a doorway protection with an efficiency of $E_f = 0.5$ gives a 50 % load decrease. A simple plastic doorway protection will therefore be included, with an efficiency of $E_f = 0.8$ which will greatly reduce the load. The efficiency is on the low end of the spectrum for use of plastic strips, but is considered realistic due to the very frequent movement of workers and pallets in and out of the container when the door is opened.

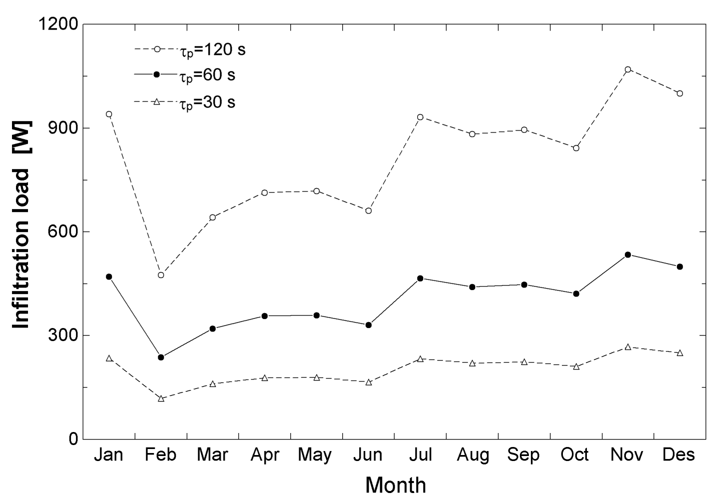


Figure 5.6: Change in average high infiltration load through a year with changing time duration of door opening, for a number of two door openings per working day with no open-doorway protection.

Internal load

The internal load of the fan will depend on the product type due to the difference in porosity and corresponding pressure loss. Furthermore it will naturally depend on the volumetric flow of the fan and its efficiency.

As previously discussed, the fan diameter is fixed at $D_{fan} = 0.5[m]$, and the porosity and resulting pressure drop model for each product is found as valid approximations. This means that optimization of the internal fan load will come from having an optimal airspeed, as this is the influencing factor on the pressure drop and also the volumetric flow. The change in the internal fan load and also the determining total pressure drop through the fruits, as a function of superficial velocity is illustrated in Figure 5.7a. The load throughout a year of cooling different products is illustrated in Figure 5.7b. The superficial air velocity is approximately 25% of the fan air velocity for the fixed geometry.

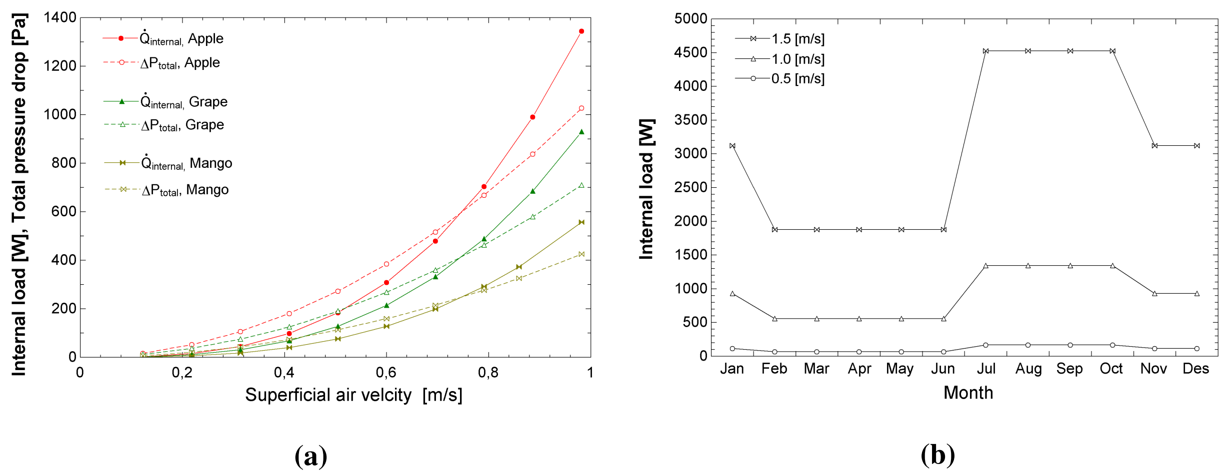


Figure 5.7: Change in pressure drop and resulting internal fan load related to superficial air velocity **(a)**, and internal fan load of the cooling system throughout a year with different superficial air velocities **(b)**.

Evidently, as the pressure drop through the bulk increases exponentially with increasing air velocity, so will the internal fan load increase. A dual effect on the size of the load will occur if the superficial air velocity is above 1.25, as this gives a volumetric flow of air above 1. Furthermore, the load from the fan will have a dual effect on the energy use of the system. An increase in the fan work will indirectly increase the energy consumption of the cooling system, as the refrigeration system will get an increase in its energy consumption, but the work is still done with a COP above 1. However, the increase in the fan work will at the same time increase the direct energy consumption as the fan uses electrical energy from the energy supply. In essence, this means that having a large fan load due to a high superficial air velocity will occupy a large amount of the available energy coming from the solar panel, with minor variations due to climatic conditions. It is therefore crucial that the superficial air velocity is kept low enough to have a feasible fan load, but still large enough to allow heat transfer from the products. This will finally be determined from the product load and its cooling time.

5.3.1 Cooling time

The transient profile will determine the cooling time of the products, which in turn will influence the product load. As the thermophysical properties model is valid, the ambient temperature is location dependant, and the shape and diameter of each fruit is as stated in Table 4.14, the factors that can be influenced to optimize the cooling time is the cooler temperature and Bi. If the temperature inside the cooling system is chosen to be higher than the lowest recommended temperature for storage of each of the products, there will be no local cooling damage on the products through the duration of the process. Bi is a function of the convective heat transfer coefficient, which again is a function of the superficial air velocity.

Increasing the air velocity will decrease the cooling time, but the scale of decrease in cooling time will reduce as the velocity increases. How the transient profile of each fruit will behave with increasing superficial air velocity, for operation of the system with a 2 °C temperature difference between the product and the cold room is illustrated in Figure 5.8.

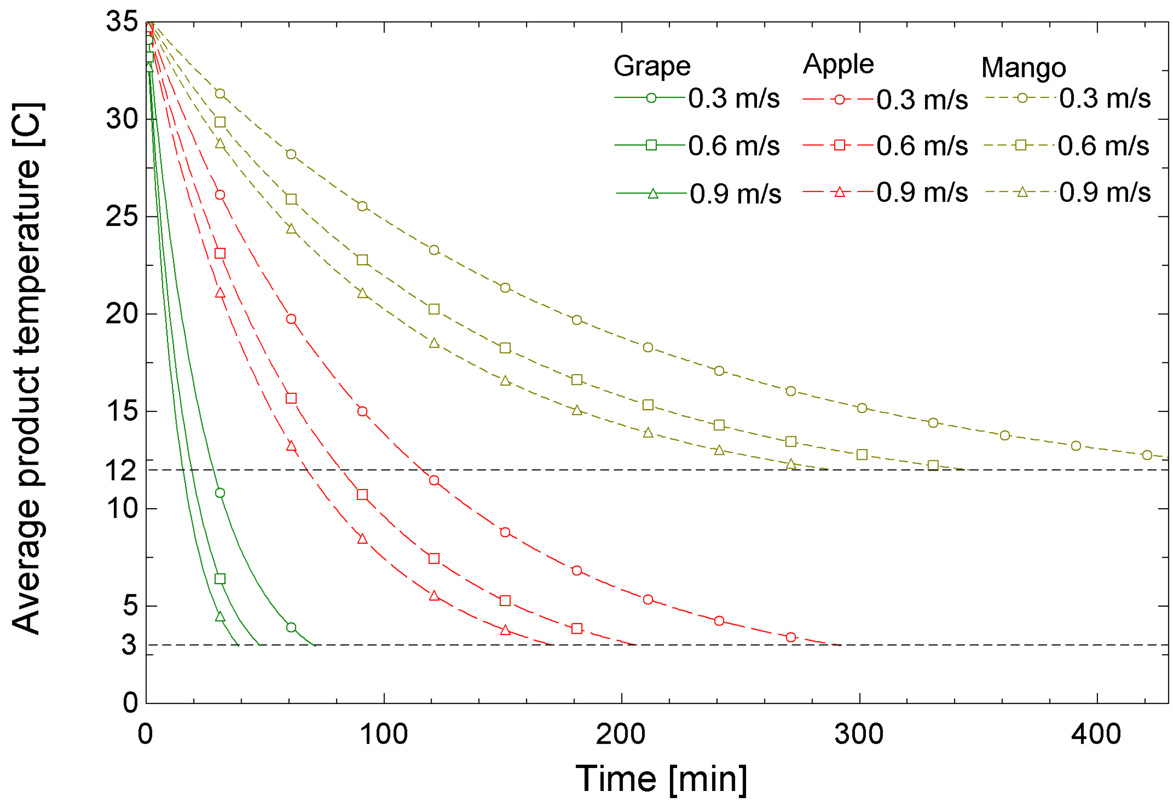
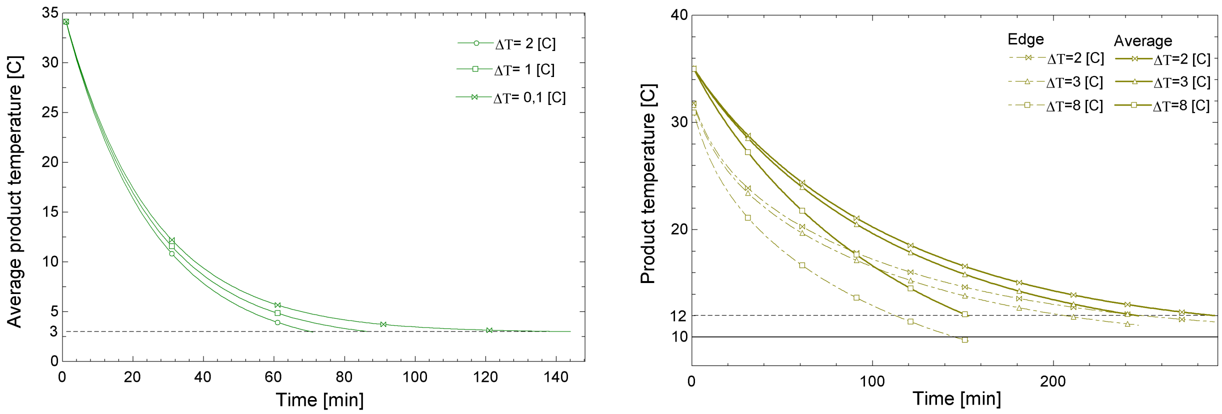


Figure 5.8: Transient profile for the average temperature of one grape, apple and mango in the cooling system with an initial product temperature of 35 °C, for a selection of different superficial air velocities at a 2 °C temperature difference between the product and the cold room.

Naturally, the transient temperature profile of each of the fruits is largely determined by the size of the product, as the model is a prediction for one single sphere in a fluid flow. As a result, grapes can be seen to have a very short cooling time, while mangoes will have a large cooling



(a) **(b)**

Figure 5.9: Transient profile of a grape in an airflow with superficial air velocity of 0.3 m/s **(a)**, and of a mango in an airflow with superficial air velocity 0.9 m/s **(b)**, with changing temperature difference between the product and the air in the cooling system.

time. The time it takes to cool down the product will greatly influence the product load, but also the infiltration load as the doors will have to be opened more frequently. The cooling time can be influenced by changing the air velocity as shown above, but also by changing the temperature in the cooling system, as exemplified for grapes and for mangoes in Figure 5.9. Since grapes are cooled so rapidly due to their small diameter, it may be necessary to extend this cooling time so that the infiltration load from frequent opening of the door is reduced, and so that the product load will not be excessively large. Reducing the temperature difference between the the product and the cooler achieves this goal as shown in Figure 5.9a. It is however worth noting the slope of the figure, as this illustrates that the grape will quite quickly achieve a low temperature even at very low temperature differences, but will not reach the desired temperature as quickly.

The cooling time of a mango is much longer due to its larger diameter, and increasing the temperature difference between the product and the cooler can be done so that more product can be cooled in a shorter time, as illustrated in Figure 5.9b. However, if the temperature of the cooler is decreased below the recommended storage temperature of the product, it is important to consider the possibility of cooling damage on the product. As shown in the figure, a temperature difference of 8 °C will reduce the cooling time by close to 50%, however the edge of the product will have a lower temperature than 10 °C and there may be local cooling damage of the product.

Product load

The product load is dependant on the temperature difference between the product and the ambient equivalently to the other discussed loads. This leaves the mass of product and the cooling time as the largest factors of influence on the load, and these are also the factors that can most easily be altered for optimization. The product load is proportional to the mass of product, and inversely proportional to the cooling time. The cooling time is as discussed largely dependant on the cooler temperature and the air velocity. The cooling time and corresponding product load for a selection of different superficial air velocities and temperature differences between the product and the cooler is presented in Table 5.1. The product load is presented for an ambient temperature of 35 °C and a mass of product per box of 20 kg. Changing these variables will linearly change the product load correspondingly, i.e a 50% reduction in the mass per box will reduce the load with 50%. It can be seen that the relative small variations in the velocity and the cooler temperature can greatly impact the load and the cooling time. The small diameter of grapes give a very short cooling time and correspondingly very large product load for high air velocities and large temperature differences, and the variables should be kept low to avoid an excessively large infiltration load. On the other side of the spectrum, mangoes will have a much longer cooling time and thus a lower product load. Increasing the variables will ensure that a larger amount of the available energy from the solar panel is used, and that a larger quantity of product is cooled through a working day.

	Apple			Grape			Mango		
$v_s[m/s]$	0.3	0.6	0.9	0.3	0.6	0.9	0.3	0.6	0.9
$\Delta T = 5°C$									
$\tau_{cooler}[min]$	205	145	120	49	34	28	324	233	195
$\dot{Q}_{product}[kW]$	12.4	17.6	21.2	50.1	73.8	90.1	5.6	7.7	9.3
$\Delta T = 2°C$									
$\tau_{cooler}[min]$	290	206	171	70	48	39	477	344	288
$\dot{Q}_{product}[kW]$	8.8	12.4	14.9	35.7	52.1	64.1	3.8	5.2	6.3
$\Delta T = 0.1°C$									
$\tau_{cooler}[min]$	593	421	350	142	98	79	1032	746	626
$\dot{Q}_{product}[kW]$	4.3	6.0	7.2	17.6	25.5	31.6	1.7	2.4	2.9

Table 5.1: Change in product load with variable superficial air velocity and temperature difference between the cooler and the product, for an ambient temperature of 35 °C and mass of product per box of 20 kg.

5.3.2 The total load

The total load will be the sum of the above discussed loads, and their dependence on different factors and each other has been described. The size and part load distribution of the total load is consequently a function of the all the different factors. As the intention of the cooling system is to reduce the temperature of the products, it is evident that an optimal system configuration is one that maximizes the size of the product load and minimizes the remaining loads accordingly. As discussed up until this point, there are variables that change throughout the year but are still pre-determined based on the operation of the system, and there are changeable variables that can be influenced to change the system behaviour. The pre-determined variables are the ambient temperatures, the geographical location, and the type of product cooled at each location with corresponding difference in product properties. Furthermore, the alterable factors that influence on the refrigeration loads is the temperature inside the system, the speed of airflow, the opening of the door, and the mass of product to be cooled. The previous discussion has highlighted the effects of all these variables on the system, and informed choices will be made to calculate an optimized total refrigeration load.

The loads will change with the changing temperature, and the dimensioning load will be the largest load for the given conditions, which will occur for the highest ambient temperature. The loads will be different for the different products, and it is therefore necessary to investigate the peak load for each of the products on the hottest day of their operation. Temperature data for the three different regional areas where apples, grapes and mangoes are to be cooled is presented in Figure 5.10. It can be seen that the highest temperature during cooling is 36.4 °C for apples, 38 °C for grapes, and 39.7 °C for mangoes.

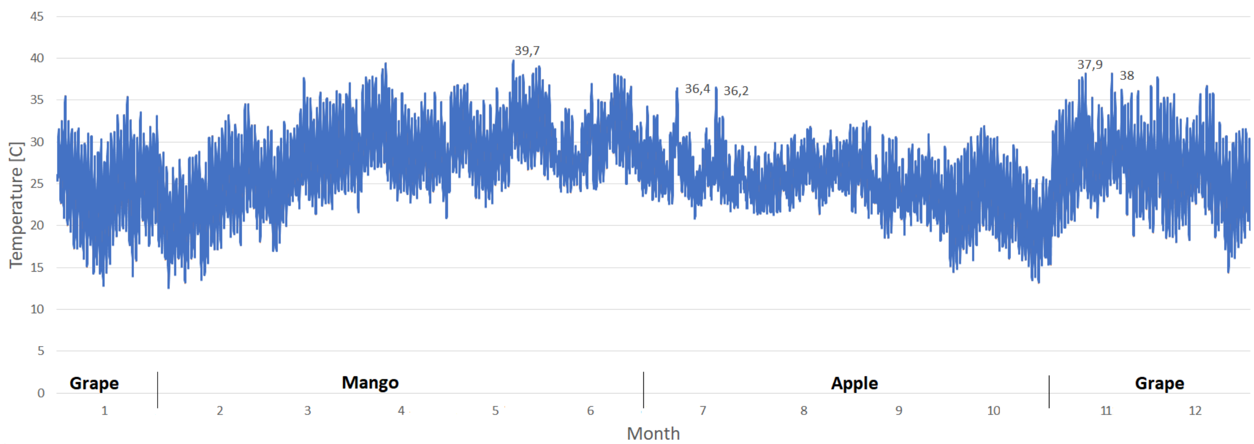


Figure 5.10: Ambient temperatures for operation of the cooling system throughout a year.

The optimal choice of values for the other variables will be a matter of opinion. For the further study of the cooling system, an optimal operation is considered one that is both practically efficient for workers, while at the same time attempting to maximize the product load in relation to the other loads. The mass of product per box should be large enough so that the cooling system is worth the effort, but still not as large as the potential maximum to ensure proper airflow and feasibility of the simulation model. The cooling time should be long enough so that workers have the time to stack new boxes and pallets with fruits, but still short enough to allow for a large amount of daily cooling and solar power utilization. From the previous discussion, this implies that the air velocity and temperature difference for small diameter grapes should be low in both cases so that the cooling time is long and the product load is feasible. The mango with its large diameter will have the opposite requirements, where a larger temperature difference and air velocity is needed to cool down the product in a short enough amount of time. The apple with a diameter in between will require an air velocity and temperature difference that are higher than for grapes but lower than for mangoes. The temperature in the cooler for the Indian scenario should however not be kept below 0 °C, this is because the high ambient humidity and the lack of humidity control in the cooler is likely to cause condensation and thus local ice formation in the system and on the products. The air velocity should not be higher than 1 [m/s] for apples and grapes and not much higher than 1.25 [m/s] for mangoes, based on the discussion of the internal load. The cooling times for these consideration will be around 150-200 minutes for apples and mangoes, and around 90-140 for grapes. The system will be operated for approximately 10 hour per day, based on the typical available solar energy. Allowing some extra time for the workers during loading and unloading to do tasks like moving pallets and securing structures etc. means that there in general will be time for three batches of apples or mangoes to be cooled, and four batches of grapes to be cooled in a day. It is preferable to have close to equal peak loads for the three different fruits to reduce the occurrence of off-spec performance of the system. These considerations and the peak temperatures relevant for cooling of each fruit will together form the optimized operation of the cooling system that will be used for further investigation and design. The simulation program is used to test reasonable guess values, and appropriate final values are found after a few runs to be as stated in Table 5.2.

Variable	Apple	Grape	Mango
$T_{cooler}[C]$	1	2.9	6
$v_s[m/s]$	0.9	0.5	1.2
N_o	4	5	4
$\tau_p[s]$	300	300	300
$m_{product,box}[kg]$	15	10	19
$T_{amb}[C]$	36.4	38	39.7

Table 5.2: Optimized variable input for operation of the cooling system in the three different cases.

With the optimized variable choices and the peak temperature for each product being as stated above, the dimensioning total refrigeration load can be determined as stated in Table 5.3. These loads are then used to determine the refrigeration system operation, and thus the size of the compressor.

Load [kW]	Apples	Grapes	Mangoes
Transmission	0.621	0.616	0.593
Infiltration	0.725	0.945	0.659
Internal	1.031	0.112	0.976
Product	11.522	12.417	11.935
Safety factor (10%)	1.390	1.409	1.416
Total	15.29	15.51	15.58

Table 5.3: Load distribution and total load for the refrigeration system at peak operation for cooling of the three different fruits.

5.4 Refrigeration system

The log P-h diagram of the single stage vapour compression cycle with liquid receiver is presented in Figure 5.11, for the three different loads related to the different operation. The refrigerant used is R600a, justification for the selection is later presented in subsection 5.4.1.

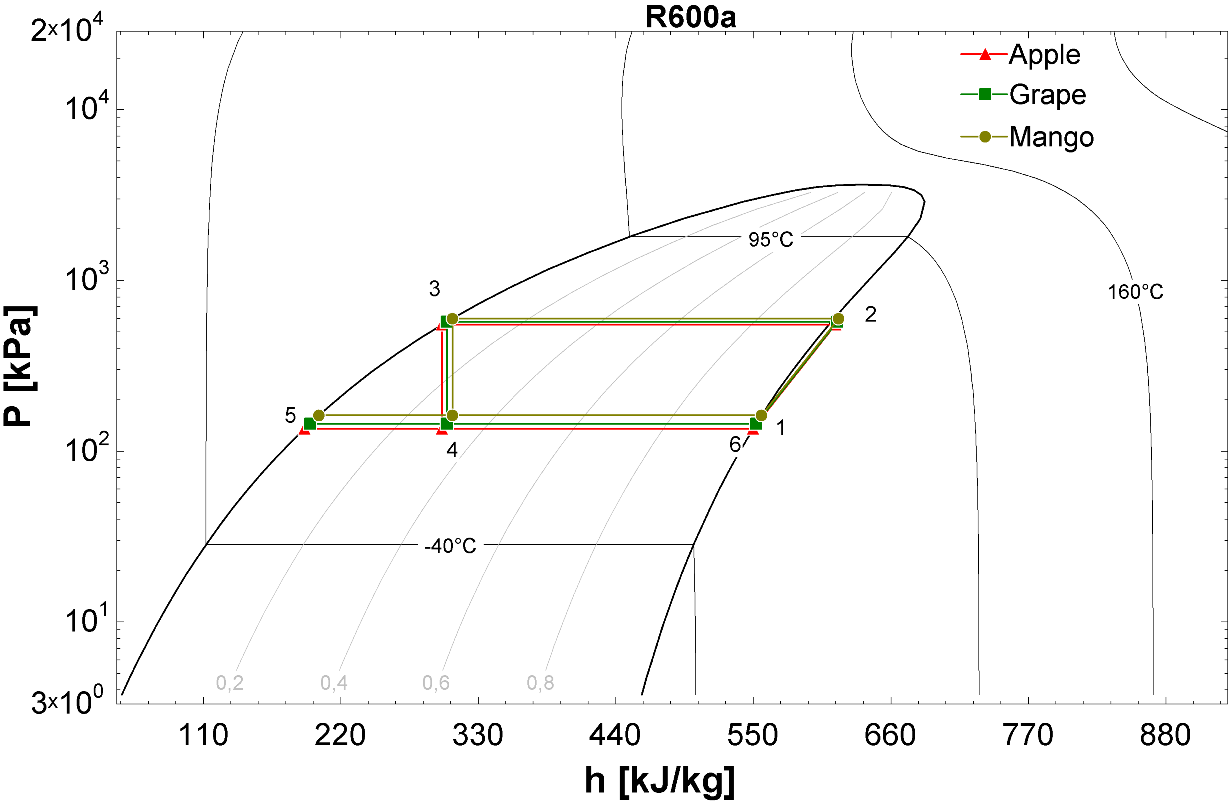
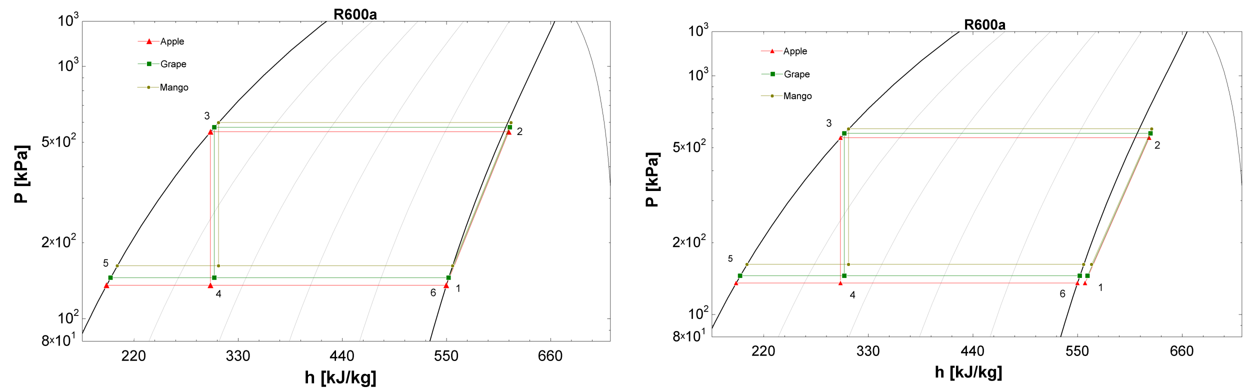


Figure 5.11: Log P-h diagram for the refrigeration cycles of the three peak loads for cooling of the different types of fruits.

The compression for these conditions are done very close the saturated vapour line of R600a, as the saturated vapour line moves almost parallel to the entropy at this section of the log P-h diagram. Although the liquid receiver in theory ensures that only gas enters the suction pipe, this can still cause severe implications for the compressor. When the compression is done so close to the liquid line there can be small local changes in pressure or temperature in the compressor that causes the very slightly superheated gas to form into liquid. As the compressor is a high velocity reciprocating machine, the introduction of a incompressible material such as a liquid in the machinery can quickly cause damaged. A 5 °C superheat of the refrigerant is therefore included before the compressor, thus ensuring compression of only superheated gas. The log P-h diagram of the refrigeration cycle with no superheat, and with a 5 °C superheat for the three different loads is presented in Figure 5.12.



(a) **(b)**

Figure 5.12: Enlarged view of the log P-h diagram for the refrigeration cycles, without superheat **(a)** and with the added 5 °C superheat **(b)**.

The cycles are naturally equivalent in behaviour, with minor size variations due to different evaporator and condenser temperatures related the cooling system and ambient temperatures respectively. The state points for the refrigeration cycle with a 5 °superheat is given in Table 5.4.

	Apple				Grape				Mango			
State point	$h_i[kJ/kg]$	$P_i[kPa]$	$T_i[C]$	X_i	$h_i[kJ/kg]$	$P_i[kPa]$	$T_i[C]$	X_i	$h_i[kJ/kg]$	$P_i[kPa]$	$T_i[C]$	X_i
1	557.7	135.6	1	-	560.4	145.3	2.9	-	564.6	162.3	6	-
2	625.2	550.7	49.04	-	626.6	573.9	50.23	-	627.8	599.5	51.35	-
3	300.6	550.7	41.4	0	304.7	573.9	43	0	309.1	599.5	44.7	0
4	300.6	135.6	-4	0.306	304.7	145.3	-2.1	0.307	309.1	162.3	1	0.302
5	190.8	135.6	-4	0	195.2	145.3	-2.1	0	202.3	162.3	1	0
6	549.7	135.6	-4	1	552.2	145.3	-2.1	1	556.4	162.3	1	1

Table 5.4: State points of the refrigeration system during peak load operation for cooling of the three different fruits.

The size of the components in the refrigeration system will be determined by the dimensional values during operation at the given conditions, these dimensional values are given in Table 5.5.

Product	$\dot{Q}_{evap}[kW]$	$\dot{Q}_{cond}[kW]$	$\dot{m}_{evap}[kg/s]$	$\dot{m}_{cond}[kg/s]$	$\dot{V}[m^3/s]$	$\dot{W}_{compr}[kW]$	COP
Apple	15.29	19.30	0.0426	0.05946	0.01637	4.013	3.81
Grape	15.51	19.53	0.04343	0.06066	0.01566	4.02	3.857
Mango	15.58	19.43	0.044	0.06098	0.01419	3.855	4.042

Table 5.5: Values of the dimensional variables for the refrigeration system during peak load operation for cooling of the three different fruits.

As can be seen, the compressor work is in similar size for all the three peak load, but highest for the cooling of apples. This also goes for the volumetric flow to the compressor, and these two values will determine the size of the compressor to be a 4 kW compressor with a volumetric flow rate of 0.01637 m^3/s which drives the refrigeration system.

5.4.1 Refrigerant selection

The designed cooling system is based on renewable energy both for practical and environmental reasons. The use of solar panels is practical due to the lack of proper electrical grid connections in rural areas, and with the impending development in technology and economical standard, the importance of having environmental development in India is crucial. Because of the importance of environmental development in India and similar economies, the system should be as environmentally friendly as possible, and the choice is made to only consider the natural refrigerants. Ammonia is excluded as the cooling system is relatively small in capacity. Furthermore, CO_2 is excluded as operation will be in high ambient conditions, and many modifications must be made for such a small CO_2 system to be viable. This leaves hydrocarbons, which consist of many different types of chemical combinations and blends, but the most common are propane(R290), isobutane(R600a) and propylene(R1270). The performance of the three hydrocarbons for the operating conditions of cooling mango is presented in Figure 5.13, where the performance of ammonia(R717) and a commonly used HFC gas(R134a) is also included for comparison. The refrigerants are listed in the legend based on how good they perform, and it can be determined that R600a gives the highest COP and thus the most efficient refrigeration system performance, it even outperforms R134 for all relevant temperatures and ammonia for low ambient temperatures. The COP behaviour will be the same for the cooling conditions of apples and grapes as well, and R600a is chosen as the refrigerant. As the refrigerant used is a hydrocarbon, it is susceptible for fire and explosions if the refrigerant is exposed to flames or other extremely high temperatures. It is therefore important that proper safety measures for the use of hydrocarbon refrigerants is followed (Danfoss, 2018).

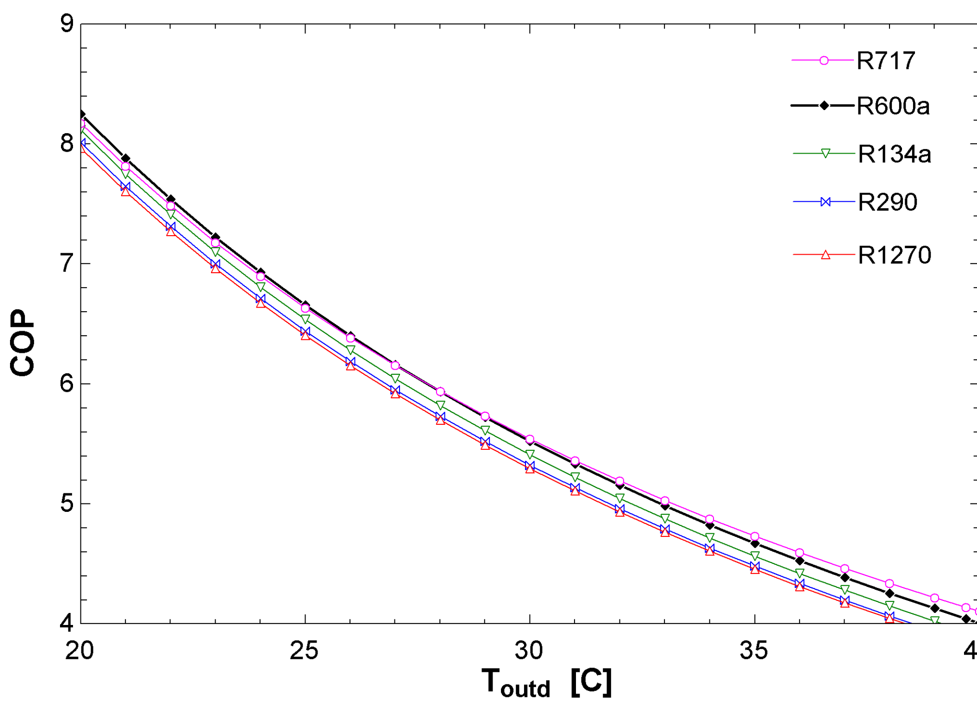


Figure 5.13: Performance of the refrigeration system with different choices of refrigerants.

5.5 Energy supply

The energy supply coming from the solar panel and battery must cover the needed energy consumption of the cooling system. This energy requirement is the work of the fan and the work of the compressor. The compressor work has been found from Table 5.5 for the three cases, and the fan work is the same as the internal load found in Table 5.3. For the cases of the peak loads, the highest value of the combined energy requirement of the system will be for the case of cooling apples and will be 5.044 kW, rounded off to a 5 kW energy requirement. The energy supply system must therefore ensure that this peak load is covered on the warmest day, but also make sure that sufficient operation is ensured through the rest of the day. The available energy for the system through the 47.3 m^2 solar panel area has been found as in section 5.2, and will also change through the day. The system is designed for peak conditions, however the real operation of the system will be dynamic throughout the day. How the energy requirements due to the refrigeration load will change throughout a day of cooling three batches of products with a peak operation of 5 kW is illustrated in Figure 5.14, where the daily energy supply is also included. The energy requirements caused by the load is the the amount of energy required to offset the original refrigeration load, through the COP of the refrigeration system.

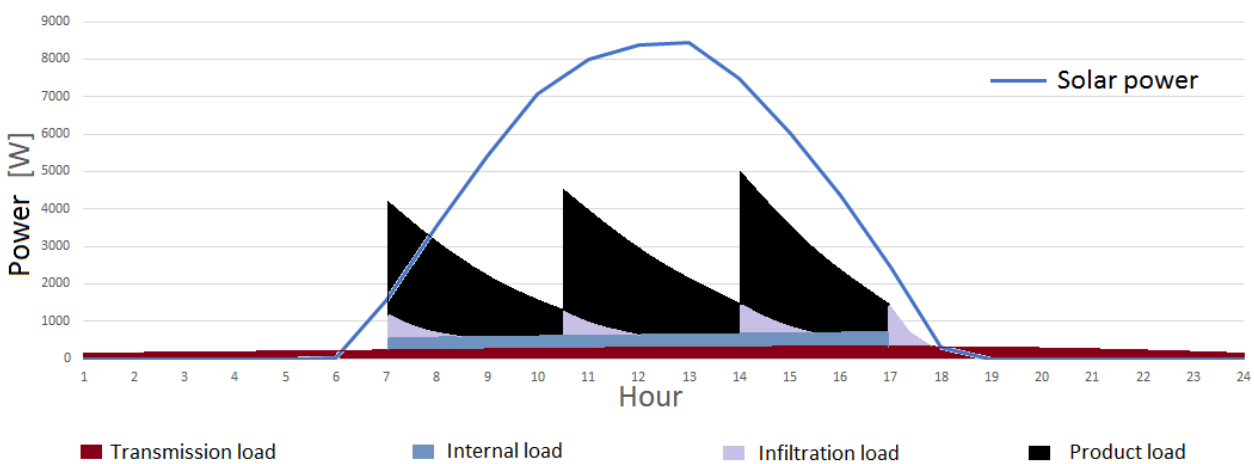


Figure 5.14: Real energy requirements due to the refrigeration load throughout a day of operation, related to the available energy from the solar panel.

As long as the area inside the bell shaped curve representing the available solar energy is larger than the highlighted load energy requirements, the solar system provides enough energy to supply the cooling system. This can be seen to clearly be the case, however a portion of the load is outside line of solar power, indicating that there is a larger energy demand than supply for these cases. This is where a battery must be implemented. The portion of the load outside the line of solar power is small, and consists of a small part of the product load for one hour in the morning when the system is started, and the transmission losses occurring through the night. Having the system remove the transmission load throughout the night ensures that the system can operate optimally at the start of the cooling in the morning. Summing these up gives an energy requirement of roughly 6 kWh, which in turn gives a required battery size of $B_s = 7.5[kWh]$ as the battery is a lithium ion one.

5.6 The optimized cooling system

In summary, the optimized cooling system that has been designed as the following:

It is a portable container fitted with a module based refrigeration system in the rear of the container, where geometry and door has been properly insulated for refrigeration. Inside the container is also a duct system channeling airflow over the evaporator of the refrigeration system, and a 1 kW adjustable speed fan creating a pressure differential that causes an airflow which only flows through boxes of products stacked on pallets. A foldable solar system with a PV-panel area of 47.3 m^2 is mounted on the container, while a machine room for the refrigeration system and a battery of size $B_s = 7.5[kWh]$ is placed on the roof underneath the solar panel. Boxes to hold the product is designed, and these will hold apples, grapes and mangoes that will be cooled related to their harvesting season. The system is dynamic and changes in the variables has been discussed. It will however be given setting related to which product is being cooled, so that the switch of a button will be enough for cooling the different types of fruit. As the system is dynamic, an increase in the other loads than the product load will simply mean that the cooling time of the product will increase. The total load will change throughout the year and throughout the day, and the total peak load calculated is the dimensioning extremity for the total system.

The optimized system will for the hottest day with peak refrigeration load cool each 960 kg palletized batch of apples in the climatic conditions of Dehradun from 36.4 °C down to 3 °C in 173 minutes, where three batches will be cooled during the 10 hour operation day giving 2880 kg of cooled apples per day. The 4 kW compressor will for these conditions of cooling apples work with a COP of 3.81 with the hydrocarbon refrigerant R600a. The settings for the cooling of apples will set the fan to give a superficial air velocity of 0.9 m/s and set the refrigeration system to have an evaporator temperature of -4 °C, which will give a temperature in the cooling system of 1 °C.

It will for the hottest day with peak refrigeration load cool each 640 kg palletized batch of grapes in the climatic conditions of Mumbai from 38 °C down to 3 °C in 110 minutes, where four batches will be cooled during the 10 hour operation day giving 2560 kg of cooled grapes per day. The same 4 kW compressor with the same refrigerant will for these conditions of cooling grapes work with a COP of 3.857. The settings for the cooling of grapes will set the fan to give a superficial air velocity of 0.5 m/s and set the refrigeration system to have an evaporator temperature of -2.1 °C, which in turn will give a temperature inside the cooling system of 2.9 °C.

It will for the hottest day with peak refrigeration load cool each 1216 kg palletized batch of mangoes in the climatic conditions of Kolkata from 39.7 °C down to 12 °C in 175 minutes, where three batches will be cooled during the 10 hour operation day giving 3648 kg of cooled apples per day. The same 4 kW compressor with the same refrigerant will for these conditions of cooling mangoes work with a COP of 4.042. The settings for the cooling of mangoes will set the fan to give a superficial air velocity of 1.2 m/s and set the refrigeration system to have an evaporator temperature of 1 °C, which in turn will give a temperature inside the cooling system of 6 °C. The edge temperature of the mango will not fall below 10 °C as long as it is taken out after 175 minutes.

As previously discussed, the choices made to reach an optimized system configuration will be a matter of opinion, and several other just as viable solutions can be presented. The method shown, theory presented, and the comprehensive simulation model developed, will form a foundation used to simulate the presented system configuration. The same model can be used to simulate and evaluate other configurations based on other choices of optimal system behaviour, and be used for the corresponding dimensioning and analysis of a cooling system fitted to these choices.

The off-grid cooling system will be transported between the three areas of fruit production throughout the year, and thus achieve year round operation. It will make cooling and the initiation of a cold chain substantially more accessible to rural and poor farmers, and allow access for new products that would otherwise be thrown away into the market. The use of the cooling system for the cooling of apples, grapes and mangoes in India throughout the year is shown in Figure 5.15. The figure is only for illustration purposes.

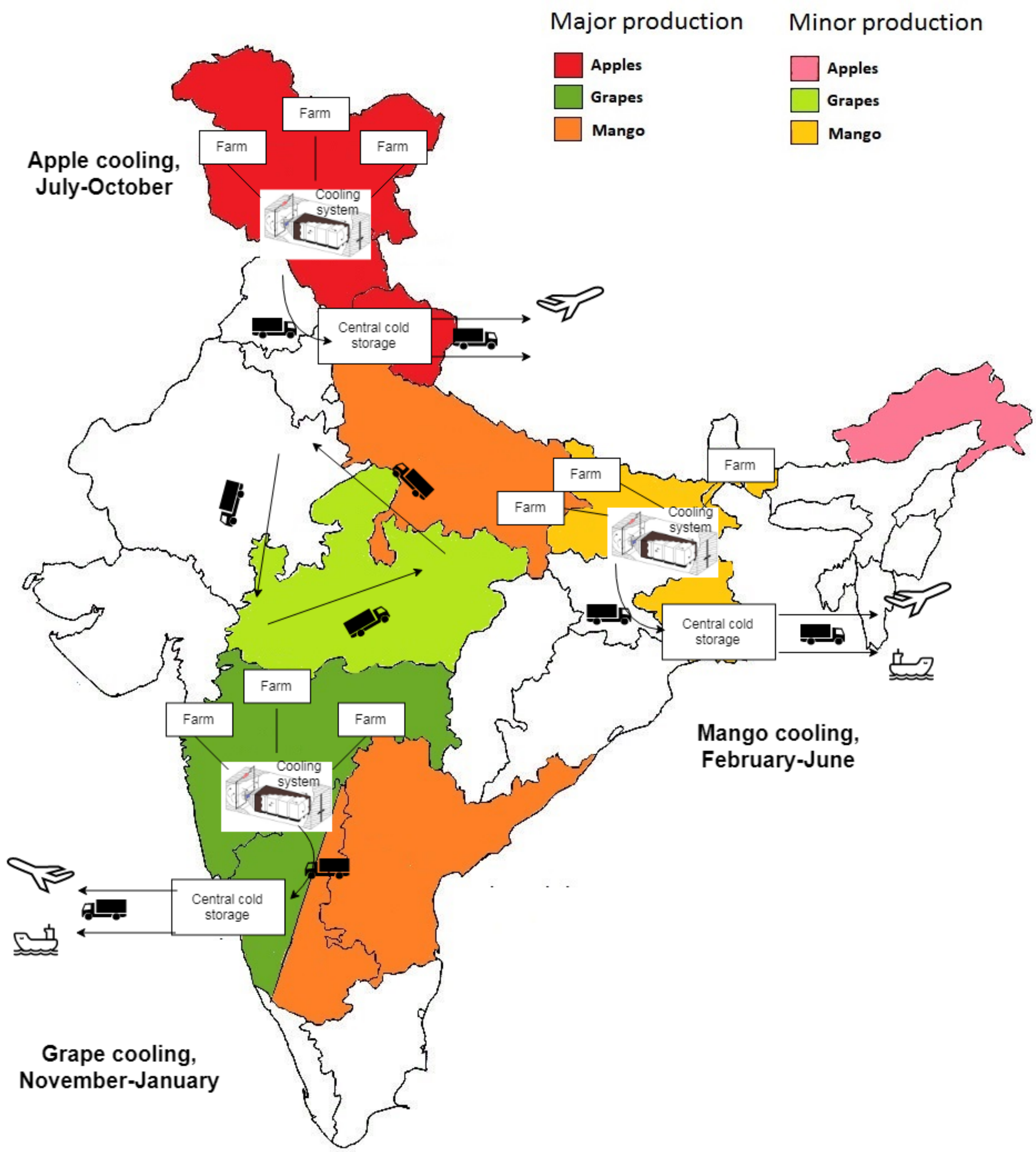


Figure 5.15: Regional use and movement of the designed cooling system throughout a year in India.

5.7 System viability

The use of the designed cooling system in the Indian scenario provides many possible advantages, there are however several obstacles present that may hinder proper or any utilization of it at all.

The practical aspect

Such a cooling system will be able to provide any producer of horticulture with cooling at the earliest stage possible. It can be used for more technologically developed industrial farming areas to give immediate cooling, or it can be used for rural and poor farmers that would otherwise struggle to reach other markets than the local middleman. Just the implementation of a designated cooling system will as stated by Kanlayanarat et al. (2009) be a massive benefit in terms of quickly reducing degradation, increasing shelf life, and give reduction of losses for the products. Furthermore, it will allow cold storages at later stages of the cold chain to be of smaller capacity. The typical standard of using cold storages to remove the field heat from the product, as implied by NCCD (2015) in Table 3.1, is both a challenge and an opportunity for the implementation of the cooling system. It will be more difficult to enter the Indian market as cooling is not a fully integrated part of both the horticultural cold chains and cold chains in general, but with implementation it will provide large benefits for both reduction of losses and increase in efficiency. Use of the cooling system in India with the logistical method in section 4.2 will also greatly reduce the amount of middlemen that provide no value addition, thus increasing the realized value given to the farmer, and avoiding consumers that has to pay inflated prices. Implementation of the entire cold chain of the different fruits, initiated with the cooling system, should therefore be done by one or a few stakeholders. This way the interconnectivity between the different stages of the cold chain is greater, and the responsible stakeholders can ensure proper operation. For this case, it would be advisable to utilize some of the technological tools described in Table 2.1 to achieve traceability of the cold chain, i.e sensors for tracking temperature and position in the logistical network.

From its design, the cooling system has been mostly aimed at rural farmers that produce apples, grapes and mangoes. Since these three fruits have different harvesting seasons throughout the year as documented in Table 3.3, and since these season match over the year, the cooling system is able to operate all year round. With this multi commodity operation, the system is much more feasible as it will have practically no down time with several application areas, and the cost of operation will be minimal as there will be no expenses for electrical power. This may further be of benefit to the rural farmers as they do not have to bear the high cost of electricity, which in subsection 3.4.1 has been seen to be a cause of concern for the rural poor in India. Furthermore, with the optimized settings and product weight per box chosen for cooling of each of the different types of products, the load on the compressor and system in general will be quite similar for all the cases. This gives a more steady refrigeration system operation, which is less of a strain on the components.

Since the system will be operated in rural farming areas, the sturdiness and transportability of the system is of concern. There has been documented a clear lack of infrastructure in India (M. and K., 2016), which is the case both for lacking cold chain infrastructure and for the lack of good road connections. Especially the solar panel fitted on the outside of the system is at risk during transportation, as the roads are often times of poor driving quality. The solar panel must be fixed tightly to the truck during transportation for safety reasons, and it would also be advisable to look into the possibility of having a tarp or similar fixtures that surround the panel, to avoid dust and road debris damaging the panels. The transportability of the container is also challenging with a solar panel mounted to the roof, as such containers generally are lifted from the roof with large cranes. The accessibility of such cranes in rural farming areas of India is however also doubtful, and the container should rather be fixed with wheels to accommodate for these challenges. The use of a fixed inner geometry that ensures an airflow that only goes through the product is highly beneficial, which gives a relatively low fan work compared to the rest of the energy requirements of the system as shown for the optimized system in Table 5.3. This ensures that a large amount of the limited amount of energy available is used for the product load, which is a majorly desirable functionality of having such a system.

The environmental aspect

The environmental benefits with the designed system are good not just for the sake of being idealistic, but the choices made are highly efficient and can also to a large extent be considered as being practical benefits. The use of off-grid solar panels is a definitive solution to the problem described by Palit and Bandyopadhyay (2017), where the rural Indian population often times have highly unstable electrical grids, or no electrical power at all. Furthermore, as the price of particularly PV-panels are decreasing they are now proving to be viable systems in economical and practical terms, and may even be more beneficial than having grid power connections for cooling in highly solar irradiated ares such as India (Lazzarin, 2017). With the inclusion of a natural refrigerant in the refrigeration system that gives a COP higher than many of the synthetic refrigerant, the system will be efficient and practical in use, without having to compromise on the environmental sustainability. Furthermore, as stated by SEforAll (2018) the introduction of sustainable and efficient refrigeration in these rural and poor areas is essential for the coming development of India, and other countries facing similar developments. This also includes avoiding the use of environmentally harmful refrigerants, since the management of these is the most influential factor available for reducing greenhouse gasses, as found by Hawken (2017). It is natural that the desire of the Indian people in the further development of their cold chain primarily will be to achieve a higher standard of living, and that environmental factors will be of secondary concern, just like it has been in currently developed countries in the last century. It is therefore vital that those who can impact this development do it so that the development will be a sustainable one. The designed system will provide an efficient solution for these considerations, and has the possibility of being a part of the further development of both efficient and sustainable cold chains in India.

Challenges and limitations in the Indian scenario

Some of the challenges and limitations have been briefly mentioned in the previous discussion of this section, and they will for the largest part be the ones illustrated in Figure 2.3. The lack of cooperation between stakeholders go hand in hand with the many middlemen and poor infrastructure present in the typical current chain, and can as discussed be mended if the cooling system is implemented according to the logistical solution presented. The current state of cold chain infrastructure in India is also a vital factor in the feasibility of the designed cooling system. As stated by NCCD (2015), only a fraction of the required cold chain infrastructure is currently available. Since the cooling system will only be one step in a functioning cold chain, and since the the most important factor of a cold chain is to maintain a constant low temperature (Ndraha et al., 2018), the use of the cooling system will be dependant on the rest of the infrastructure. Again, with the correct implementation of the cooling system and the logistical solution, this temperature level is much more easily achieved than in the current situation.

There is a mentality present in India that is part of the reason for not having cooling systems but rather using cold storages to pull down the product temperature, and also there is also a mentality of not needing more refrigeration in India at all (subsection 3.4.1). This may be a barrier for the introduction of the designed cooling system, as many may think it is unnecessary both to have a cooling system but also to cool fruits in general. The lack of cold chain infrastructure in light of this might be a further limiting factor, especially the access to refrigerated vehicles. The very limited and unorganized access to these vehicles stated by Singh (2019) and NCCD (2015) may pose a challenge for utilization of the cooling system, as the cold chain will be dependant on having such vehicles. Furthermore, it is natural that stakeholders in India will want to prioritize refrigerated transport of even more perishable items than fruit, as these are generally eaten fresh and the impression is that they do not need refrigeration as much.

The economical factors will be one of the biggest bottleneck, as the use of such a cooling system will require someone to invest the money needed for construction and operation of the system. There are several prospects of profit for a stakeholder with sufficient funds, which is later discussed, but a cooling system like the one designed will most likely not be affordable or practical to have for the horticultural producers that will get their products cooled. If the system is constructed and managed by a separate stakeholder than the farmers, the farmers should experience larger realized value of sale for their products, as the amount of middlemen that take their share is reduced and value addition from cooling is gained. The consumer should also get access to more products due to the reduction in losses, and these products should be of a cheaper price and be available for a longer time for the same reason. This gives a win-win-win situation for the farmer, cold chain operator, and consumer, where the profits will come at the expense of the previously present intermediary stakeholders. This will be the best case scenario, and the likelihood of non-optimal operation and cold chain implementation is highly present as a result of lacking economical will.

The value potential

The Indian cold chain industry is on a definitive rise as documented by i.e NCCD (2015) and Roy (2019), and will be a large sector for investments and improvements both by government and private players now and in the future. With India's vast production of food and central global location, the potentials for development and establishment of infrastructure here is inherently large for both national and international interests. The designed system with its multi commodity approach and off-grid environmentally beneficial operation is a concept with a potential for contribution in this development.

The potential win-win-win situation described for use of the cooling system by farmers, cold chain operators and consumers will be a major value potential for all the value creating players. Quantifying a general value addition from cooling is troublesome, but the use of cooling will be a vital factor in reduction of waste and thus increased saleable mass of products, and it will also increase the lifespan and potential value of the cooled product. Kanlayanarat et al. (2009) emphasizes the point of cooling horticulture promptly after harvest to be among the most efficient and largest contributors to value addition that can be used in its potential cold chain, a factor naturally achieved with the designed system. Since the cooling system is used for three different types of fruit, the output from yearly operation is also much larger than for a single commodity designed system. Furthermore, there has been documented economical benefits for refrigerating fruits both for domestic applications and for export applications, as seen in section 3.3. Especially the case of exporting the three types of fruit is likely to be economically viable uses of the system. The state of grape exports from India has been found to be a thriving business, while it is also one that demands immediate cooling after harvest (Aswaney, 2007). As the values found in Table 3.5 of exported mango and other types of fruit from India is similar to the value of exported grapes, and in some cases even higher, it is likely that there are markets for export that is not yet utilized, and that these markets could benefit from more cooling. The same is further stated by Aswaney (2007), which list apples and mangoes among many others as horticultural products of high potential and value for similar business and cold chain implementations. With Indias central geographical location in relation to the rest of the world, and its large production of horticulture, it has the possibility of being a vast global exporter to almost all parts of the world. For this to be achieved, it will however undoubtedly require efficient and large scale cooling promptly after harvest, and a well developed cold chain to accompany it.

With the implementation of cooling follows the need for a proper cold chain and stakeholder responsibility throughout this cold chain. This will further imply that implementation of cooling can be a catalyst for cold chain implementation and increased stakeholder cooperation, which again simplifies the logistics and reduces unnecessary stakeholder interactions. Furthermore, if proper implementation of efficient and beneficial cooling systems provide realizable value output to the stakeholders involved, this can cause a trickle down effect to other branches of the cold chain industry, where having designated cooling systems is seen as the vital and highly beneficial factor that it is.

Chapter 6

Conclusion

The conclusions made based on the work done in this thesis is stated in this chapter.

The Indian cold chain

The Indian cold chain is found to be riddled with inefficiencies and challenges, which in turn are responsible for the large amounts of post harvest food waste occurring. The issues are to a large extent interconnected and complex, and include lack of knowledge, poor infrastructure, little cooperation, and economical reasons as some of the most prominent factors. The current state of the cold chain industry in the country is as a result lacking in capacity and state of technology, where availability of infrastructure for shelf life extending temperature management of commodities is of little availability. The use of cooling for temperature reduction of food before storage is rarely used in India at the current state, a factor that limits the reach of the market and increases food losses.

The industry is however also found to be experiencing rapid growth, and it is a sector of the Indian economy with great potential for future revenue and productivity increase. Specific examples of well implemented cold chains further illustrate this point, as for the case of exported grapes where designated cooling systems are used to provide the foundation of a thriving sector of Indian cold chains. The vast production of food in India, along with its central location to other potential importing countries, gives rise to great opportunities for providing both its own people but also the world with high quality fruits and vegetables.

The cooling system

The designed cooling system is an approach for mitigating the many reasons of postharvest waste in India in a manner that is both implementable and sustainable. The system is a solution for allowing especially rural farmers a potential for connecting their harvest to a cold chain at an early stage, and from this reducing postharvest losses and increasing realizable value. The designed cooling system will when implemented along the lines of the proposed logistical solution have year round operation for cooling of apples, grapes and mangoes.

The background used for determining factors related to the products and airflow through the geometry is found to be valid and accurate to the degree relevant for the scope of the thesis, however they are also found to be highly influential on the total behaviour of the system.

The refrigeration loads are found to be highly dependant on the behaviour of the system, apart from the transmission load which is mostly determined by the geometry and ambient temperature. The infiltration load is largely determined by having door-way protection and the amount of door opening time. The internal load is directly related to the pressure loss and volumetric airflow, and thus also the porosity, airflow speed and product diameter. The product load is largely dependant on the mass of product and the cooling time, where the cooling time in turn is largely dependant on the airflow speed and temperature inside the cooling system.

The dependency of the loads is used for dimensioning of an optimized configuration for the cooling system, for cooling of apples, grapes and mangoes in the climatic conditions of Dehradun at 36.4 °C, Mumbai at 38 °C and Kolkata at 39.7 °C respectively. With the optimized variables as in Table 5.2, the cooling system will have a refrigeration system with a 4 kW compressor that uses R600a as a refrigerant, and a 1 kW fan that provides airflow through the geometry. The energy supply comes from a solar PV-panel of 47.3m2, and a battery with a size of 7.5kWh. The cooling system is set to operate for 10 hour per day, where it will cool a total 2880 kg of apples from 36.4 °C to 3 °C, 2560 kg of grapes from 38 °C to 3 °C, and 3648kg of mangoes from 39.8 °C to 12 °C during one day. The cooling will be done in three batches for apples and mangoes, and in four batches for grapes. For apples, grapes and mangoes the respective cooling time is 173, 110 and 175 minutes, and the respective COP of the refrigeration system at these dimensioning conditions is 3.81, 3.857 and 4.042.

The complete cooling system, with the suggested logistical solution, is found to reduce the amount of non value adding middlemen, and increase interconnectivity between links in the potential cold chain. The transportability is further found to be beneficial through allowing year round operation in the seasonal harvesting areas, and it facilitates for cooling close to the rural areas of production. The implementation of the solar panel further increases the accessibility to provide cooling in these rural areas with poor electrical grid connections, and with the use of a natural refrigerant the system will be a sustainable solution for cooling. There is found to be value addition for farmers and consumers with implementation of the system, and there is found several areas for potential economical profits.

Chapter 7

Further work

Based on the work done and the emphasis made, the following are the suggestions for further works of the thesis, and further work withing the subject.

The Indian cold chain

Further work should be done by local and international stakeholders to reduce the many inefficiencies present in Indian cold chains. This includes increased installment of cooling systems, cold storages and refrigerated transport vehicles. It further includes reduction of non value adding middlemen, improvement of logistical solutions, proper knowledge distribution, and greater implementation of efficient refrigeration technology.

The Indian cold chain industry should be further investigated in a search for opportunities by both government and private players, and with this seek to identify and utilize the large potential in the present and future parts of the cold chain and food industry.

Work must be done by both Indian government and local stakeholders to improve and develop the cold chain in a sustainable manner. Present and future international interests in the Indian cold chain should realize the potential for development, and also ensure that the future development is sustainable.

More emphasis by others doing work withing the Indian cold chain should in the future be placed on the benefits of using designated cooling systems, not only for horticultural products but also for other fooditems. Designated cooling systems should become a larger part of the cold chain industry in India, and should be implemented to a much greater extent.

The cooling system

The designed cooling system should be investigated in respect to a specific and pre-existing supply chains for the three fruits chosen in this thesis. This can be done by identifying currently farmed production areas in the different regions of harvest, and then investigate the implementation of the cooling system in that specific case.

The current simulated modeling of the cooling system should be accompanied by a CFD simulation of the airflow, this to reach a greater confidence in the details of the local airflow through the entire geometry of the system.

The components of the system and their interconnectivity could be investigated and determined in greater detail. This includes specific geometry of the fan and its rotary blades, specific geometry and area of the heat exchangers, pressure drop and refrigerant flow in the pipes, detailed investigation of the compressor and expansion valve, and detailed investigations of the electrical power interconnectivity between the solar panel and the battery.

Further economical considerations should be made to quantifying the viability of the system in the Indian scenario. A comprehensive economical model should be made to definitively determine the cost of construction and operation of the cooling system, and it should also include the cost of operating the other parts of the cold chain. This should be related to the potential profits of sale for domestic and export applications, so that a payback time of the system can be determined for the case of each type of fruit.

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Appendix A

Additional theory and methods

A.1 Food properties

Knowledge of the different properties of perishable foods can reduce the amount of waste and optimize refrigeration and storage conditions relating to quality and safety. The perceived quality of food is a complex combination of sensory inputs, and characteristics such as texture, taste, flavour, aroma, colour, shape and appearance all influence how edible a commodity is considered to be. Changes in these characteristics during handling, processing and storage, caused by different types of deterioration, highly influence the perception of quality and usefulness of a product. Furthermore the rheological properties of commodities, which is how an object deforms under influence of applied forces, contribute to changes in texture, appearance and quality.

Water activity, or relative vapor pressure, is an important factor when it comes to the rate of deterioration and microbiological activity in commodities, and is the measure of how available water is for microbial, enzymic and chemical processes to take place in foods. These processes are highly linked to food deterioration and its shelf life, and how water activity impacts these processes in food is illustrated in **Fig. A.1**. Water activity is defined as *"the ratio of the vapour pressure of water in a food to the saturated vapour pressure of water at the same temperature"*(**Eq. A.1**)

$$a_w = \frac{P_f}{P_{f,0}} \tag{A.1}$$

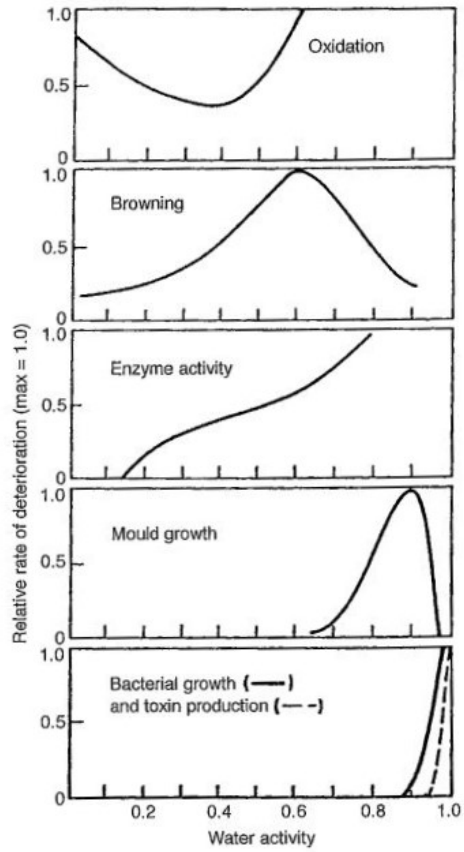

Figure A.1: How microbial, enzymic and chemical changes in food are affected by water activity.

A.1.1 Fruits and vegetables

Fruits and vegetables differ from most other commodities as they are living organisms at the point of entering the cold chain, giving rise to additional properties to be considered.

Respiration is the chemical process of combining sugar and oxygen to form CO_2, H_2O and energy for use in an organisms internal processes. Few internal cell developing processes occur after fruits and vegetables are harvested and stored, thus most of the released energy is in the form of heat, and must be considered when handling. The rate of respiration varies with the type of product considered, but conditions that impact plant respiration are general and listed in Table A.1.

High respiration rate	Low respiration rate
Young, actively growing	Dry plant produce
Fast-developing	Slow-developing
Newly harvested	Stored for several days
Does ripen in storage	Does not ripen in storage
High storage temperatures	Low storage temperatures

Table A.1: Factors impacting on respiration of fruits and vegetables.

The respiration rate can be classified relating to rate of carbon dioxide production per unit mass of the product, and some important examples are given in table Table A.2. Further calculations to determine the heat released is done as previously shown in Equation A.2.

	Respiration rate $(mgCO_2/kgh)$		
Class	10°C	20°C	Examples
Very low	<10	<40	Nuts, dates, dried fruit
Low	10	40	Potato, onion, grape, apple
Moderate	10-20	40-80	Citrus fruit, carrot, tomato, banana
High	20-40	80-120	Pear, apricot, papaya, cabbage
Very high	>40	> 120	Melon, mushroom, okra, strawberry

Table A.2: Respiration rate of a selection of fruits and vegetables (Rahman, 2007)

The heat generated from a product due to respiration, can be calculated as:

$$\dot{Q}_{resp} = \frac{10.7f_{resp}}{3600}(\frac{9T_{product}}{5} + 32)^{g_{resp}} \tag{A.2}$$

where f and g are respiration coefficients, and T is in °C. ASHRAE (2018) also provides tabulated values for respiration of a large selection of fruits and vegetables at different temperatures.

Transpiration in fruits and vegetables is the mass transfer of water from the commodity to the surroundings. Fruits and vegetables have a high content of water, some of which moves out through the skin and is removed from the commodity through evaporation on the surface and further convective mass transfer to the surroundings. Some moisture loss will always be present, but excessive moisture losses can cause shriveling, with resulting changes in product weight, texture, taste, shape and appearance. For this reason low temperature and high humidity environments are favorable for fruits and vegetables handling and storage. The moisture loss of transpiration($\dot{m}$) is driven by a difference in vapor pressure between the surface(p_s) and its surroundings(p_s), and can be calculated using Equation A.3, where k_t is the transpiration coefficient[1].

$$\dot{m} = k_t(p_s - p_a) \tag{A.3}$$

Ethylene production and sensitivity of fruits and vegetables are important factors that influence the many aspects of growth and development to increase ripening effect in the product itself, or in products surrounded by ethylene rich environments. It is a hormone formed as a product of plant metabolism and is formed at various rates for all types of plants. Ethylene can be both beneficial and unwanted when it comes to handling fruits and vegetables in a CC, especially when handling different types of fruits and vegetables together. Some illustrative examples are its uses as a ripening catalyst for fruits such as bananas and mangoes, and its degreening effect on citrus fruits. The ethylene production rates of a selection of fruits and vegetables, at 20°C, can be seen in table Table A.3.

[1]The coefficient can be found in tables, but these values are not always reliable, making calculations of the coefficient based on the specific conditions of the commodity necessary.

Class	Production rate ($\mu L/kg \cdot h$)	Examples
Very low	< 0.1	Potato, carrot, cabbage, onion
Low	0.1-1	Cucumber, okra, pineapple
Moderate	1-10	Grape, mango, tomato(green)
High	10-100	Apple, papaya, pear, apricot, tomato(ripe)
Very high	> 100	Cherimoya, passionfruit, sapota

Table A.3: Ethylene production of a selection of fruits and vegetables at 20°C (Rahman, 2007)

How sensitive certain products are towards ethylene concentrations in the surrounding air is also important, as their sensitivity increased the rate of ripening. Knowing the ethylene sensitivity of fruits and vegetables can be used to optimize product quality at end-user and avoid degradation during handling, some commodities and their respective sensitivity can be seen in Table A.4.

Class	Ethylene concentration (ppm)	Examples
Low	0.01-0.5	Onion(dry), grape, garlic, pineapple
Moderate	0.5-3	Potato,onion(green), okra
High	3-5	Banana, mango, tomato, apple, cabbage, cucumber

Table A.4: Ethylene sensitivity of a selection of fruits and vegetables (Rahman, 2007)

A.1.2 Processing

Processing can impact the perceived quality of food and its nutritional content by altering sensory characteristics and changing nutritional content or digestibility during processing, illustrated in Table A.5.

Characteristic	Determining components	Causes of characteristic change
Texture	Moisture content. Fat content. Structural carbohydrates. Proteins.	Loss of moisture or fat. Emulsion & gel formation/breakdown. Hydrolysis of carbohydrates. Coagulation/hydrolysis of proteins.
Taste, flavour	Saltiness, sweetness, bitterness, acidity & umami.	Respiratory changes. Food fermentation.
Aroma	Complex mixtures of volatile compounds.	Loss of these compounds. Volatile compound production due to e.g. heat. Enzyme activity on proteins, fat and carbohydrates.
Colour	Pigments.	Heat. Changes is pH. Oxidation during storage.
Nutritional properties	Protein, fat, carbohydrates vitamins, minerals.	Heat(e.g. coagulation of protein). Oxidation.

Table A.5: How processing impact food characteristics

A.2 Refrigerants in India

Sector	Current Refrigerants Used	Alternative Refrigerants	Low GWP Refrigerants (GWP < 750)	ISHRAE Assessment of Low GWP options for India
Domestic Refrigeration Single /Double Door	HC-600a , HFC-134a		HC-600a, HFC-1234yf, HFC-1234ze	HC-600a
Commercial Refrigeration Stand-alone units (Display Cabinet, Water Cooler, Bottle Cooler, Visi Coolers, Ice Cream Cabinets and Chest Freezers)	HC-600a, HC-290, HCFC-22, HFC-134a, R-404A, , R-744	HFC-134a , HC-600a, HC-290, R-404A, R-507A, R-407 (A, C or F)	HC-600a, HC-290, HFC-1234yf, HFC-1234ze, R-744	HC-600a, HC-290, R-744;
Room ACs (1 to 1)	HCFC-22, R-410A, HFC-32, HC-290	R-407C, R-410A, HFC-32, HC-290, HFC-161	HFC-32, HC-290, R-446A, R-447A	HC-290, HFC-32
Large ACs Multi-Split	HCFC-22, R-410A	R-407C, R-410A, HFC-32	HFC-32, R-446A, R-447A	None at the moment.
VRF ACs			HFC-32 , R-446A, R-447A	
Ducted, Packaged, Roof Top			HFC-32, HFC-1234yf, HFC-1234ze, R-450A, R-513A, R-451A, R-451B	
Mobile AC Car, Van	HFC-134a	HFC-152a, R-744, R-444A, R-445A	HFC-1234yf,R-744	HFC-1234yf, R-744
Bus, Truck, Train	HCFC-22, R-134a, R-407C	R-744, R-450A, R-513A,	HFC-1234yf,R-744	HFC-1234yf, R-744
Transport Refrigeration Refrigerated Transport Supply Chain	HCFC-22, HFC-134a, R-404A	*HFC-134a, R-407C, HFC-1234yf, R-744*		None at the moment.
Industrial Refrigeration Small and Medium Size	R-717, HCFC-22, HFC-134a, R-404A (for medium temperature)	R-717, HFC-134a, R-407A, R-407F	R-717, HFC-1234ze	R-717
Large Industrial Chiller	R-717, HCFC-22, HFC-134a	R-717, HFC-134a	R-717, HFC-1234ze R-717	R-717
Chillers Scroll	HCFC-22, R-407C, R-410A	R-410A, R-450A, R-513A	HFC-1234ze	None at the moment.
Screw	HCFC-22, HFC-134a	HFC-134a	HFC-1234ze, HC-1270	
Centrifugal	HFC-134a, HCFC-123	HFC-134a	HFC-1234ze, HCFO-1233zd, HFC-1336mzz	

Figure A.2: Currently used refrigerants for different refrigeration sectors in India, and potential alternatives (ISHRAE, 2015a).

A.3 Empirical model for roots of parametric equation

Solving for the roots of the parametric equation in Equation 4.21 will require solving μ as a function of μ, meaning it will be a iterated function. This means the function must be solved iteratively as:

$$\mu = -arctan(\frac{\mu}{Bi-1})$$

Where initial guess values, and an iterative solving method must be used.

EES has an inbuilt way of solving iterative equations automatically, with given guess values. However, for this specific equation EES is unable to find solutions of μ for low Bi numbers. This is because of the inverse trigonometric function $arctan$ and the method EES uses to solve iterative equations, making μ converge to 0. After some experimentation, it is found that the limit that causes convergence to 0 is for $Bi < 1.7$ when solving the equation in EES.

To overcome this, an empirical model is made and integrated in to the calculation of μ for low Bi numbers. The model is made by taking previously given values for μ for the given geometry at low values, and use nonlinear regression to make equations that fit the datapoints given in Table A.6. For calculation of θ it is sufficient to sum three solutions of Equation 4.17 to find an accurate solution, i.e three roots of the parametric equation is needed.

	Datapoints			Empirical model		
Bi	μ_1	μ_2	μ_3	μ_1	μ_2	μ_3
0.1	0.542	4.516	7.738	0.542	4.516	7.738
0.5	1.166	4.604	7.790	1.166	4.604	7.790
1	1.570	4.712	7.854	1.571	4.712	7.854
1.5	1.837	4.816	7.917	1.836	4.816	7.917
2	2.029	4.913	7.979	2.030	4.913	7.979

Table A.6: Values for μ at different low Bi numbers for a sphere, with known datapoints from Tolstorebrov (2018) and values from the empirical model.

The empirical relations are found by curve fitting the known datapoints as a symmetrical sigmoidal, this is suitable as $arctan$ is a typical sigmoid function. A symmetrical sigmoidal is given as:

$$y = d + \frac{a-d}{1+(\frac{x}{c})^b}$$

Using the datapoints from Table A.6 and curve fitting this as a sigmoid function gives the empirical relations in Equation A.4, this will be used for Bi numbers lower than 1.7 when the calculation is done in EES.

$$\left.\begin{aligned} \mu_1 &= 3.999142 + \frac{0.1360563 - 3.999142}{1+\frac{Bi}{2.115534}^{0.701822}} \\ \mu_2 &= 7.295802 + \frac{4.495916 - 7.295802}{1+\frac{Bi}{10.29459}^{1.063476}} \\ \mu_3 &= 16.11618 + \frac{7.724864 - 16.11618}{1+\frac{Bi}{64.34011}^{0.9986422}} \end{aligned}\right\} \quad \text{for } Bi < 1.7 \tag{A.4}$$

Appendix B

Simulation code in EES

Comprehensive simulation code for the dimensioning of the cooling system. Comments are written as: "*comment*".

```
$UnitSystem SI Radian Mass kJ kg C

" Calculation of thermal properties "
Procedure thermalprop( T_product_in ;T_wanted;Protein ;Fat ;Carb;Fiber ;Ash;Water:k_product ;
    rho_product ; c_p_product ; alpha_product )

T_m=(T_product_in+T_wanted)/2 "Mean temperature"


"Thermal conductivity , W/mK"
k[1]=Protein *(0,17881+1,1958*10^(-3)*T_m-2,7178*10^(-6)*T_m^2)
k[2]=Fat*(0,18071-2,7604*10^(-4)*T_m-1,7749*10^(-7)*T_m^2)
k[3]=(Carb-Fiber)*(0,20141+1,3874*10^(-3)*T_m-4,3312*10^(-6)*T_m^2)
k[4]=Fiber*(0,18331+1,2497*10^(-3)*T_m-3,1683*10^(-6)*T_m^2)
k[5]=Ash*(0,329620+1,4011*10^(-3)*T_m-2,9069*10^(-6)*T_m^2)
k[6]=Water*(0,57109+1,7625*10^(-3)*T_m-6,7036*10^(-6)*T_m^2)
k_product=sum(k[i]; i=1;6)

"Density ,kg/m^3"
rho[1]= Protein *(1,3299*10^3-5,1840*10^(-1)*T_m)
rho[2]=Fat*(9,2559*10^2-4,1757*10^(-1)*T_m)
rho[3]=(Carb-Fiber)*(1,5991*10^3-3,1046*10^(-1)*T_m)
rho[4]=Fiber*(1,3115*10^3-3,6589*10^(-1)*T_m)
rho[5]=Ash*(2,4238*10^3-2,8063*10^(-1)*T_m)
rho[6]=Water*(9,9718*10^2+3,1439*10^(-3)*T_m-3,7574*10^(-3)*T_m^2)
rho_product=sum(rho[i ]; i=1;6)

" Specific heat capacity , J/kgK"
cp[1]=Protein *(2,0082+1,2089*10^(-3)*T_m-1,3129*10^(-6)*T_m^2)
```

```
cp[2]=Fat*(1,9842+1,4733*10^(-3)*T_m-4,8008*10^(-6)*T_m^2)
cp[3]=(Carb-Fiber)*(1,5488+1,9625*10^(-3)*T_m-5,9399*10^(-6)*T_m^2)
cp[4]=Fiber*(1,8459+1,8306*10^(-3)*T_m-4,6509*10^(-6)*T_m^2)
cp[5]=Ash*(1,0926+1,8896*10^(-3)*T_m-3,6817*10^(-6)*T_m^2)
cp[6]=Water*(4,1289-9,0864*10^(-5)*T_m+5,4731*10^(-6)*T_m^2)
c_p_product=sum(cp[i]; i=1;6)*1000

"Thermal diffusivity , m^2/s"
alpha_product=k_product/( c_p_product*rho_product)
End

Procedure heattransfercoeff (k_ind;d;rho_ind;mu_ind;v_superf:h_c)
Re=(rho_ind*d*v_superf)/mu_ind

If (Re>25) and (Re<100000) Then
h_c=0,37*Re^0,6*k_ind/d
Else
return
Endif
End

"Transmission load"
Function transload (DT;A[1..6];DT_eastwest;DT_south;DT_roof;delta_w;k_w)

U=1/(delta_w/k_w) "Overall heat transfer of wall, only one insulating layer"


Q_t[1]=U*A[1]*(DT) "North wall"
Q_t[2]=U*A[2]*(DT+DT_eastwest) "East wall"
Q_t[3]=U*A[3]*(DT+DT_eastwest) "West wall"
Q_t[4]=U*A[4]*(DT+DT_south) "South wall"
Q_t[5]=U*A[5]*(DT+DT_roof) "Roof"
Q_t[6]=U*A[6]*(DT) "Floor"
transload=sum(Q_t[I]; I=1;6)
End

" Infiltration load"
Function doorload(N_o;tau_p;tau_o;tau_d;rho_ind;rho_outd;A_door;h_outd;h_ind;g;H_door;
    D_f;E_f)
D_t=(N_o*tau_p+60*tau_o)/(3600*tau_d)
F_m=(2/ (1+ (rho_ind/rho_outd)^(1/3) ) )^(1,5)
Q_dot_sl=0,221*A_door*(h_outd-h_ind)*rho_ind*(1-rho_outd/rho_ind)^(0,5) *(g*H_door)
    ^(0,5)*F_m
doorload=2*Q_dot_sl*D_t*D_f*(1-E_f)*1000
End
```

```
Procedure producttype(Apple;Mango;Grape;V_box;n_boxes;rho_product:epsilon_geometry;
    m_product;d;r;x;Water;Protein;Fat;Carb;Fiber;Ash;T_wanted)

If (Apple=1) Then
epsilon_geometry=0,40
d=0,08    "Diameter of product"
r=d/2
x=r       "Edge = r"
Water=0,8393   "Product constituents , %"
Protein=0,0019
Fat=0,0036
Carb=0,1525
Fiber=0,0270
Ash=0,0026
T_wanted=3 [C] "Wanted temperature of the product"
m_box=15 [kg]  "Chosen mass per box"
Endif

If (Grape=1) Then
epsilon_geometry=0,565
d=0,03
r=d/2
x=r
Water=0,813
Protein=0,0063
Fat=0,0035
Carb=0,1715
Fiber=0,010
Ash=0,0057
T_wanted=3 [C]
m_box=10 [kg]
Endif

If (Mango=1) Then
epsilon_geometry=0,45
d=0,12 [m]
r=d/2
x=r
Water=0,8171
Protein=0,0051
Fat=0,0027
Carb=0,1700
Fiber=0,018
Ash=0,0050
```

```
T_wanted=12 [C]
m_box=19 [kg]  "Wanted temperature of the product"
Endif
"m_box=V_box*(1−epsilon_geometry)*rho_product" " Potential  weight in each box"
m_product=m_box*n_boxes
End

"Pressure drop through produce in boxes"
Procedure pressuredrop (mu_ind; v_superf ; epsilon_geometry ; d ; rho_ind ; length_bulk : dp_tot ;
    delta_p_meter )
 delta_p_meter =(150*mu_ind*(1−epsilon_geometry)^2*v_superf) /( epsilon_geometry^3*d^2)
    +(1,75*(1−epsilon_geometry)*rho_ind*v_superf ^2) /( epsilon_geometry^3*d)
 pressuredropbulk = delta_p_meter * length_bulk

 dp_tot = pressuredropbulk

End

" Internal  load"
Function  fanload ( Vol_fan ; dp_tot ; eta_fan )
 fanload=Vol_fan* dp_tot / eta_fan
End

Procedure muoutput(Bi:mu [1..3])
 If  (Bi<1,7) Then
mu[1]=3,999142+(0,1360563−3,999142)/(1+(Bi/2,115534)^0,701822)                    "
    Empirical  solution  for  mu"
mu[2]=7,295802+(4,495916−7,295802)/(1+(Bi/10,29459)^1,063476)
mu[3]=16,11618+(7,724864−16,11618)/(1+(Bi/64,34011)^0,9986422)
Else
Call  mucalc(Bi:mu [1..3])
Endif
End

Subprogram mucalc(Bi:mu[1..3])
 Duplicate  k=1;3
   mu[k]=−tan(mu[k])*(Bi−1)
End
End

"Product load, includes the transient behavior profile and timespan of cooling"
Procedure  prodload(m_product; c_p_product ; r ; x ; T_wanted; alpha_product ; T_product_in ;
    T_cooler ; Bi ; mu [1..3]: Q_dot_prod ; t )
$Arrays  On
 t=0
```

```
Repeat
t=t+1
Fo[t]=alpha_product*t*60/(r^2)
tau_cooler[t]=t
t_stopcond[t]=t_wanted    "For plotting"

Duplicate i=1;3

Theta_avg[t;i]=(6*Bi^2/(mu[i]^2*(mu[i]^2+Bi^2-Bi)))*exp(-mu[i]^2*Fo[t])
Theta_e[t;i]=(2*(sin(mu[i])-mu[i]*cos(mu[i]))/(mu[i]-sin(mu[i])*cos(mu[i])))*exp(-mu[i
    ]^2*Fo[t])*(sin(mu[i]*x/r)/(mu[i]*x/r))
Theta_c[t;i]=(2*(sin(mu[i])-mu[i]*cos(mu[i]))/(mu[i]-sin(mu[i])*cos(mu[i])))*exp(-mu[i
    ]^2*Fo[t])

End

theta_avg[t]=theta_avg[t;1]+Theta_avg[t;2]+Theta_avg[t;3]
Theta_e[t]=theta_e[t;1]+Theta_e[t;2]+theta_e[t;3]
theta_c[t]=theta_c[t;1]+Theta_c[t;2]+theta_c[t;3]


If (theta_e[t]>=1) Then theta_e[t]=1
If (Theta_c[t]>=1) Then Theta_c[t]=1

T_avg[t]=theta_avg[t]*(T_product_in-t_cooler)+ T_cooler
T_e[t]=theta_e[t]*(T_product_in-t_cooler)+ T_cooler
T_c[t]=theta_c[t]*(T_product_in-t_cooler)+ T_cooler
T_temp_prod=T_avg[t]


Until (T_avg[t]<=T_wanted)
Q_dot_prod=(m_product*c_p_product*(T_product_in-T_temp_prod))/(t*60)
End

Subprogram refrigsystem( Q_dot_load_total ;dT_hx;T_outd;T_cooler;R$; eta_is :COP;
    W_dot_real;Q_dot_cond;m_dot_cond)
 $Arrays On
Q_dot_evap = Q_dot_load_total
T_cond = T_outd+dT_hx    "Temp condenser"
T_evap = T_cooler-dT_hx

"Compressor inlet"
T[1] = T_evap+5    "Temp point 1"
P[1]=P[6]
h[1]=enthalpy(R$; T=T[1];P=P[1])
```

```
s[1]=entropy(R$; T=T[1];P=P[1])
 v_specific =volume(R$;T=T[1];P=P[1])

"Compressor exit"
P[2] = P[3]
s[2] = s[1] "Assume ideal"
 T_2_ideal =temperature(R$;P=P[2];s=s[2])
 h_2_ideal =enthalpy(R$;P=P[2];s=s[2])   "Ideal enthalpy, real is calculated via the
    compressor efficiency"
W_dot_ideal=m_dot_cond*(h_2_ideal-h[1])
W_dot_real=W_dot_ideal/ eta_is "Compressor real work"
h[2]=h[1]+W_dot_real/m_dot_cond
T[2]=temperature(R$;P=P[2];h=h[2])

"Condenser exit"
T[3] = T_cond
x[3] = 0 "Saturated liquid"
h[3] =enthalpy(R$;T=T[3];x=x[3])
P[3] =pressure(R$;T=T[3];x=x[3])

"Expansion device exit"
h[4]=h[3]
P[4]=P[1]
x[4]= quality (R$;h=h[4];P=P[4])
T[4]=temperature(R$;P=P[4];h=h[4])

"Liquid receiver, liquid exit"
P[5]=P[4]
x[5]=0   "Saturated liquid"
h[5]=enthalpy(R$; P=P[5]; x=x[5])
T[5]=temperature(R$;P=P[5];h=h[5])

"Evaporator exit"
T[6]=T_evap
x[6]=1
P[6]=pressure(R$; T=T[6];x=x[6])
h[6]=enthalpy(R$; T=T[6];x=x[6])


m_dot_evap=Q_dot_evap/(h[6]-h[5])   "System mass flow"
m_dot_cond=m_dot_evap*(h[6]-h[5])/(h[1]-h[4])
V_dot= v_specific *m_dot_cond   "Volume flow to compressor."
Q_dot_cond=m_dot_cond*(h[2]-h[3])   "Heat release through condenser"
COP = abs(Q_dot_evap/W_dot_real) "COP of system"
```

```
End

Procedure solarsystem(W_dot_real; Q_dot_inter ; eta_panel ; tau_day ; S_i ; psi ;D_d:A_solar ;B_s)
W_dot_sys=W_dot_real+Q_dot_inter/1000
A_solar=(W_dot_sys*tau_day)/( eta_panel *S_i)
B_s=psi*(W_dot_sys*tau_day)*D_d
End

"Input"

"System conditions"
P_atm=101,325 [kPa]  "Atmospheric pressure, assumed inside and outside"
 g=9,81 [m/s^2]   " Gravitational constant"
T_outd=38[C]  " Initial temperature of outdoor air"
 T_product_in=T_outd  "Product temp equal to ambient"
T_cooler=T_wanted-0,1[C]  "Temperature of air in cooling unit"
"Month$='Jan'"

"Air properties"
rho_outd=density(Air_ha;T=T_outd;P=P_atm) "Density of outdoor air"
rho_ind=density(Air_ha;T=T_cooler;P=P_atm)  "Density of air inside refrigerated space"
h_outd=enthalpy(Air_ha;T=T_outd;P=P_atm) "Enthalpy of outdoor air"
h_ind=enthalpy(Air_ha;T=T_cooler;P=P_atm) "Enthalpy of indoor air"
k_ind=conductivity(Air_ha;T=T_cooler;P=P_atm)  "Conductivity of indoor air"
mu_ind=viscosity(Air_ha;T=T_cooler;P=P_atm) " Viscosity of indoor air"

"Product"
Apple=0 "Product used for calculation =1, the ones not used =0"
Grape=1
Mango=0

"Single stage process, conditions"
dT_hx = 5 [C]  "Temp difference in heat exchangers"
R$='R290'  "Working fluid"
 eta_is =0,8  "Compressor efficiency"

"Container"
A[1]=5,9*2,39[m^2]   "Longside"
A[2]=5,9*2,35 [m^2]  "Top"
A[3]=A[2]  "Other longside"
A[4]=A[1]  "Bottom"
A[5]=2,39*2,35[m^2]  "Shortside"
A[6]=A[5]  "Door"
A_door=A[6]
H_door=2,39 [m]
```

```
delta_w=0,15[m]   "Wall thickness"
k_w=0,037[W/(m*K)] "Thermal conductivity of wall material"
"Door opening info"
N_o=4 [-]   "Number of door openings per time period"
tau_p=300[-]   "Time it takes from initial opening to closing of door"
tau_o= 0[-] "Simple door stand open time"
tau_d=10[-] "Time period, in hours"
D_f=0,8 [-] "Doorway flow factor."
E_f=0,8[-]   " Effectiveness of open-doorway protection."

"Cooling box dimensions and correlations"
n_airentry_box =8  "Number of ducts that allow airflow through the boxes."
A_airentry_box=0,25*0,4 "Cross section area for air flow per box"
A_airentry_total =A_airentry_box* n_airentry_box
length_bulk =4
V_box=0,25*0,4*0,4
n_boxes=8*2*4

"Fan dimensions and correlations"
d_fan=0,5 [m] "Diameter of fan, from blade tip to tip"
v_fan=2 [m/s]  "Speed of air out of fan, must be descided."
eta_fan =0,6
A_fan=pi*(d_fan/2)^2
Vol_fan=v_fan*A_fan
v_superf=Vol_fan/ A_airentry_total     "Approach air velocity, i.e superficial velocity"


"Correction factors"
DT=T_outd-T_cooler "Ambient and outer chamber temp difference"
DT_eastwest=3 [C]     "Equivalent extra temp difference from raditation"
DT_south=2 [C]
DT_roof= 5[C]
S_f=0,1[-]  "Safety factor for refrigeration load"

"Solar and battery system factors"
eta_panel =0,15
tau_day=10 [h] "Operating hours of system per day"
S_i=6 [kWh/m^2*day] "Solar irradiance"
psi=1,05 "Li-ion battery"
D_d=1,2  "Li-ion battery"

Call  heattransfercoeff (k_ind;d;rho_ind;mu_ind;v_superf:h_c)

Q_dot_trans=transload(DT;A[1..6];DT_eastwest;DT_south;DT_roof;delta_w;k_w)
```

```
Q_dot_infilt =doorload(N_o;tau_p ; tau_o ; tau_d ; rho_ind ; rho_outd ; A_door;h_outd ; h_ind ; g ;
    H_door;D_f;E_f)

Call producttype (Apple;Mango;Grape;V_box;n_boxes;rho_product:epsilon_geometry ; m_product
    ;d ; r ; x ; Water; Protein ; Fat ; Carb; Fiber ; Ash;T_wanted)

Call pressuredrop (mu_ind; v_superf ; epsilon_geometry ; d ; rho_ind ; length_bulk : dp_tot ;
    delta_p_meter )

Q_dot_inter =fanload( Vol_fan ; dp_tot ; eta_fan )

Call thermalprop( T_product_in ; T_wanted; Protein ; Fat ; Carb; Fiber ; Ash;Water:k_product ;
    rho_product ; c_p_product ; alpha_product )

Bi=h_c*r/ k_product

Call muoutput(Bi:mu [1..3])

Call prodload(m_product; c_p_product ; r ; x ; T_wanted; alpha_product ; T_product_in ; T_cooler ; Bi
    ; mu [1..3]: Q_dot_prod ; t )

Q_dot_load_total =( Q_dot_trans + Q_dot_infilt +Q_dot_prod+Q_dot_inter ) *(1+S_f)/1000

Call refrigsystem ( Q_dot_load_total ;dT_hx;T_outd; T_cooler ; R$; eta_is : COP;W_dot_real;
    Q_dot_cond;m_dot_cond)

W_dot_system=W_dot_real+Q_dot_inter/1000

Call solarsystem (W_dot_real ; Q_dot_inter ; eta_panel ; tau_day ; S_i ; psi ; D_d:A_solar ; B_s)
```

Appendix C

Hazardous activity identification form

NTNU HSE	Hazardous activity identification process	Prepared by	Number	Date
		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
		The Rector		01.12.2006

Unit: Department of Energy and Process Engineering **Date:** 28.01.2019

Line manager: Terese Løvås

Participants in the identification process: Prof. Trygve Magne Eikevik – Norwegian supervisor , Prof. Maddali Ramgopal – Indian contact person.

Short description of the main activity/main process: Master project for student Benjamin Hammer Espedalen. Project title "Conceptual study of a portable cooling system based on renewable energy for cooling of fruits and vegetables", which includes a stay in India at IIT Kharagpur from 21.01.2019 to 05.04.2019.

Is the project work purely theoretical? (YES/NO): NO

Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If NO, briefly describe the activities below.

Signatures: *Responsible supervisor:* *Student:*

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment
1	Transport in India	Benjamin Hammer Espedalen		Seat belts, travel insurance		
2	Recreational activities	Benjamin Hammer Espedalen		Don't walk alone, listen to local students, use common sense		
3	Food and water	Benjamin Hammer Espedalen		Drink bottled water and be careful with hygiene		
4	Disease and general health	Benjamin Hammer Espedalen		Vaccines, travel insurance and common sense		
5	Visiting local farmers/cold storages	Benjamin Hammer Espedalen		Careful with hygiene, travel insurance, common sense		

NTNU	Risk assessment	Prepared by	Number	Date	
		HSE section	HMSRV2603E	04.02.2011	
		Approved by		Replaces	
HSE/KS		The Rector		01.12.2006	

Unit: Department of Energy and Process Engineering **Date:** 28.01.2019

Line manager: Terese Løvås

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Signatures: *Responsible supervisor:* *Student:*

Activity from the identification process form	Potential undesirable incident/strain	Likelihood:	Consequence:			Risk Value (human)	Comments/status Suggested measures
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		
Transport in India	Traffic accident	3	C	C	C	3C	See hazardous acitivity identification form
Recreational activities	Injuries, crime	2	A	A	A	2A	See hazardous acitivity identification form
Food and water	Food poisoning	4	A	A	B	4A	See hazardous acitivity identification form
Disease and general health	Disease, other health issues	4	A	A	B	4A	See hazardous acitivity identification form
Visiting local farmers/cold storages	Injury, desease	3	B	A	B	3B	See hazardous acitivity identification form

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

4. High *D. Critical*
5. Very high *E. Very critical*

Potential undesirable incident/strain

Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork

Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

Risk = Likelihood x Consequence

Please calculate the risk value for “Human”, “Environment” and, if chosen, “Economy/materiel”, separately.

About the column ”Comments/status, suggested preventative and corrective measures”:

Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE						
	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour		Description
Red		Unacceptable risk. Measures must be taken to reduce the risk.
Yellow		Assessment range. Measures must be considered.
Green		Acceptable risk Measures can be considered based on other considerations.