Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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# Design and simulation of a small cold storage with $NH_3$ refrigeration system and $CO_2$ as indirect cooling loop for storing of fresh fruits and vegetables

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# Preface

This Master Thesis has been completed at the Norwegian University of Science and Technology during the spring semester of 2019. In relation to the thesis, a stay at the Indian Institute of Technology Kharagpur in India from 22.01.2019 to 05.04.2019 was performed. The thesis consists of a literature study on Indian food cold chains and refrigeration systems, in addition to an investigation of typical existing food products and cold chains. The results of a survey conducted at IIT Kharagpur is presented and a thesis problem statement is decided. The use of a small cold storage for fruits and vegetables at the Indian mandis is investigated. The refrigeration systems considered and compared are a single stage $NH_3$ refrigeration system with and without a $CO_2$ based natural circulation loop.

The Master Thesis is done in cooperation with SINTEF Ocean and IIT Kharagpur, as a part of the Re-FOOD project, which is an international partnership between Norway and India to strengthen the global bioeconomy.

I wish to extend a huge thank you to my supervisor, Prof. Trygve Magne Eikevik, for the help provided. My co-supervisor, Dr. Ignat Tolstorebrov, deserves a thank for the technical assistance. I would also like to extend a thank to my supervisor at IIT Kharagpur, Prof. Maddali Ramgopal, for assisting me with my work in India. Dr. Kristina Norne Widell also deserves a thank for assisting me with supporting material and guidance prior to travelling to India. A great thank to Prof. Armin Hafner and Norsk Kjøleteknisk Forening is also extended, for trusting me with the Gustav Lorentzen Grant to support my stay in India. At last, I would like to show gratitude to all who assisted me with my thesis and my stay at IIT Kharagpur.

Simulation models were made and some key results are presented.

Tom André Bredesen

# Abstract

The objective of this Master Thesis is to investigate Indian food cold chains for fruits and vegetables and try to improve the cold chains with a small cold storage using a $NH_3$ refrigeration system with $CO_2$ in a Natural Circulation Loop (NCL). Performance of the $NH_3$ system with and without the NCL are compared. The fruits investigated are mangoes, grapes, apples, oranges and bananas. The vegetables investigated are potatoes, onions, tomatoes, cauliflowers, cabbages and okras. By studying how the monthly average wholesale prices for each product change, apples, mangoes and grapes are considered most suited for storage in terms of storage life and expected profit. The domestic and export cold chain, and the commodity flow through the Indian mandis, are investigated. The main findings are that lack of refrigerated transport and pre-cooling are major challenges in both cold chains. The domestic cold chain additionally need about twice the current cold storage capacity. The high number of intermediates in the mandis flow chain are highlighted as an issue, in addition to the total absence of refrigeration and cold storages. The Indian mandis is considered the weakest link and a cold storage is designed for use at mandis' or small markets. The results from a field investigation at IIT Kharagpur in India confirms the discussed conditions.

To design the evaporator, an I,x-diagram for moist air is used to decide maximum temperature difference and the resulting heat transfer area is 64.8 $m^2$. After investigating the effects of changing temperature difference in the intermediate heat exchanger (IHX), the resulting area is set to 0.97 $m^2$. To model the NCL, pressure losses through the entire loop are calculated. All investigated heights and circulation rates result in a positive driving force. For practical reasons, a height of 1 m and circulation rate of 2 are chosen. Refrigeration loads through an entire year are used to estimate the performance of the systems. The standard system operates with an average SCOP of about 6.5 during one year, while the NCL system operates with an average SCOP of about 5.6. Annual operating profits are estimated to be between 474 thousand and 479 thousand INR, depending on system configuration and electricity rate. In conclusion, both system solutions are considered competitive and feasible.

# Abstrakt

Målet med denne Masteroppgaven er å studere indiske kuldekjeder for frukt og grønnsaker, for å foreslå hvordan disse kan forbedres med et lite kuldelager som benytter seg av et $NH_3$ kjølesystem med $CO_2$ i ei naturlig sirkulasjonsløkke (NCL). Driftsytelse for $NH_3$ systemet med, og uten, NCLen sammenlignes. De undersøkte fruktene er mango, drue, eple, appelsin og banan. De undersøkte grønnsakene er potet, løk, tomat, blomkål, hodekål og okra. Ved å studere hvordan den månedlige markedsprisen for hvert produkt endrer seg, samtidig som mulig lagringstid og profitt tas i betraktning, blir eple, mango og druer vurdert som mest gunstige for kjølelagring. Kuldekjeden for innenlands salg og eksport, i tillegg til produktstrømmen gjennom den indiske mandien, er undersøkt. Hovedfunnene er at mangel på termobiler og forkjøling av mat er de største utfordringene i begge kuldekjedene. I tillegg er det behov for omtrent dobbel kapasitet av dagens kjølelagre i innenlands kuldekjeder. Antallet mellommenn og ledd i produktstrømmen gjennom mandien fremheves som et stort problem, i tillegg til den enorme mangelen på kjøling og kuldelagre. Den indiske mandien vurderes til å være det svakeste leddet og et kuldelager for bruk på mandiene eller andre små marked blir designet. Resultater fra en undersøkelse utført på IIT Kharagpur i India bekrefter mange av de diskuterte forholdene.

Når fordamperen designes, blir et I,x-diagram for fuktig luft brukt til å bestemme den maksimale temperaturforskjellen. Det resulterende varmeoverføringsarealet er 64.8 $m^2$. Ved å undersøke virkningene av endret temperaturforskjell i den mellomliggende varmeveksleren (IHX), blir det resulterende arealet satt til 0.97 $m^2$. For å modellere NCLen blir trykktapene gjennom hele løkka beregnet. Alle undersøkte høyder og sirkulasjonsrater resulterer i en positiv drivkraft. Av praktiske grunner blir en høyde på 1 m og en sirkulasjonsrate på 2 valgt. For å beregne driftsytelsen til systemene, blir kjølelasten gjennom hele året beregnet og brukt. Standardsystemet forventes å operere med en gjennomsnittlig SCOP på omtrent 6.5 gjennom et helt år, mens NCL-systemet forventes å operere med en gjennomsnittlig SCOP på omtrent 5.6. Årlig driftsprofitt for kjølelageret er beregnet til å være mellom 474 tusen og 479 tusen INR, avhengig av systemkonfigurasjon og strømpris. Det konkluderes med at begge systemløsninger er konkurransedyktige og gjennomførbare.

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# Nomenclature

| Symbol | Description | Unit |
|---|---|---|
| $A$ | Area | $m^2$ |
| $COP$ | Coefficient of Performance | - |
| $COP_{Ca}$ | Carnot Coefficient of Performance | - |
| $C_P$ | Specific heat capacity | $\frac{kJ}{kgK}$ |
| $D$ | Depth | $m$ |
| $D_f$ | Doorway flow factor | - |
| $D_t$ | Doorway open-time factor | - |
| $E$ | Doorway protective device effectiveness | - |
| $F_m$ | Density factor | - |
| $H$ | Height | $m$ |
| $P$ | Pressure | $bar$ |
| $Re$ | Reynolds number | - |
| $T$ | Temperature | $^{\circ}C$ or $K$ |
| $U$ | Heat transfer coefficient | $\frac{W}{m^2K}$ |
| $W$ | Width | $m$ |
| $\Delta P_{major}$ | Major head loss | $Pa$ |
| $\Delta P_{minor}$ | Minor head loss | $Pa$ |
| $\Delta P_{static}$ | Static pressure difference | $Pa$ |
| $\Delta T_{LMTD}$ | Logarithmic mean temperature difference | $K$ |
| $\dot{Q}$ | Heat flow | $kW$ |
| $\dot{Q}_C$ | Condenser heat flow | $kW$ |
| $\dot{Q}_D$ | Heat load through doorway | $kW$ |
| $\dot{Q}_L$ | Refrigeration load | $kW$ |
| $\dot{Q}_P$ | Product load | $kW$ |
| $\dot{Q}_S$ | Sensible and latent refrigeration load | $kW$ |
| $\dot{Q}_T$ | Transmission load | $W$ |
| $\dot{Q}_e$ | Evaporator heat flow | $kW$ |
| $\dot{Q}_{IHX}$ | IHX heat flow | $kW$ |

| Symbol | Description | Unit |
|---|---|---|
| $\dot{Q}_{eq}$ | Equipment load | $kW$ |
| $\dot{Q}_{resp}$ | Respiration load | $kW$ |
| $\dot{V}$ | Volume flow | $\frac{m^3}{s}$ |
| $\dot{W}$ | Work | $kW$ |
| $\dot{W}_{is}$ | Isentropic work | $kW$ |
| $\dot{m}$ | Mass flow | $\frac{kg}{s}$ |
| $\Theta_d$ | Daily time period | $h$ |
| $\Theta_o$ | Time door simply stands open | $min$ |
| $\Theta_p$ | Door open-close time | $\frac{seconds}{passage}$ |
| $\delta$ | Thickness | $m$ |
| $\epsilon$ | Absolute surface roughness | $m$ |
| $\eta$ | Efficiency | - |
| $\mu$ | Dynamic viscosity | $\frac{kg}{ms}$ |
| $\pi$ | Compressor pressure ratio | - |
| $\rho$ | Density | $\frac{kg}{m^3}$ |
| $d$ | Diameter | $m$ |
| $f$ | Friction factor | - |
| $g$ | Gravitational constant (9.81) | $\frac{m}{s^2}$ |
| $h$ | Enthalpy | $\frac{kJ}{kg}$ |
| $k$ | Thermal conductivity | $\frac{W}{mK}$ |
| $l$ | Length | $m$ |
| $m$ | Mass | $kg$ |
| $t$ | Time | $h$ |
| $v$ | Velocity | $\frac{m}{s}$ |
| $x$ | Gas quality | - |
| N | Number of doorway passages | - |

# Subscripts

| Subscript | Description |
|---|---|
| 1ph | Single-phase |
| 2ph | Two-phase |
| amb | Ambient |
| c | Condenser |
| Ca | Carnot |
| D | Door |
| e | Evaporator |
| eq | Equivalent |
| g | Gas |
| i | Initial |
| ins | Insulation |
| is | Isentropic |
| l | Liquid |
| R | Room |

# Abbreviations

**AC** . . . . . . . . . . . . . Air Condition

**CFC** . . . . . . . . . . . . Chlorofluorocarbone

**CFD** . . . . . . . . . . . . Computational Fluid Dynamics

**COP** . . . . . . . . . . . . Coefficient of Performance

**$COP_{Ca}$** . . . . . . . . . . Carnot Coefficient of Performance

**EES** . . . . . . . . . . . . Engineering Equations Solver

**FRISBEE** . . . . . . . . Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact and Energy optimisation along the cold chain in Europe

**GDP** . . . . . . . . . . . . Gross Domestic Product

**GWP** . . . . . . . . . . . Global Warming Potential

**HC** . . . . . . . . . . . . . Hydrocarbon

**HCFC** . . . . . . . . . . . Hydrochlorofluorocarbone

**HFC** . . . . . . . . . . . . Hydrofluorocarbone

**IHX** . . . . . . . . . . . . Intermediate Heat Exchanger

**IODSRR** . . . . . . . . . Indian Ozone Depleting Substances (Regulation) Rules

**IoT** . . . . . . . . . . . . . Internet of Things

**$LC_{50}$** . . . . . . . . . . . . The concentration of a chemical in air that kills 50% of test subjects during a given time period

**LCCA** . . . . . . . . . . . Life Cycle Cost Analysis

**LCCP** . . . . . . . . . . . Life Cycle Climate Performance

**LMTD** . . . . . . . . . . . Logarithmic Mean Temperature Difference

**NCL** . . . . . . . . . . . . Natural Circulation Loop

**ODP** . . . . . . . . . . . . Ozone Depletion Potential

**ODS** . . . . . . . . . . . . Ozone Depleting Substance

**ppm** . . . . . . . . . . . . Parts per million

**R404A** . . . . . . . . . . . HFC blend refrigerant

**R717** . . . . . . . . . . . . Ammonia refrigerant

**R744** . . . . . . . . . . . . Carbon dioxide refrigerant

**RFID** . . . . . . . . . . . Radio Frequency Identification

**SCOP** . . . . . . . . . . . Seasonal Coefficient of Performance

**TEWI** . . . . . . . . . . . Total Equivalent Warming Impact

**TTI** . . . . . . . . . . . . . Time-Temperature Integrators

**WSN** . . . . . . . . . . . . Wireless Sensor Networks

# Chapter 1

# Introduction

Correct management of refrigerants and refrigeration systems are considered the most important action to reduce greenhouse gases and harmful emissions to the atmosphere, with a potential of 89.7 gigatons reduced $CO_2$. Reducing the food waste is considered the third most important action to reduce global warming, with a potential of 70.5 gigatons reduced $CO_2$. Food waste is responsible for about 8% of global emissions (Drawdown 2019). In other words, improving and developing food cold chains to reduce food waste and have better management of refrigeration system can be considered the most important action to reduce global warming, greenhouse gases and harmful emissions.

The world population is expected to reach 8.6 billion people in 2030 and India are predicted to surpass China as the most populous country around 2024 (UN DESA 2017). The 2030 Sustainable Development Goals stipulated that zero hunger is the second global goal that needs to be fulfilled by 2030 (Guilpart & Clark 2018). It is estimated that global food production will have to increase 70% to meet the food demand by 2050 (UN DESA 2013). This is highly dependent on the food cold chain, in order to increase food security and decrease food waste (Shashi et al. 2017, Hernandez 2009). It is estimated that post-harvest losses account for 25% to 50% of the total food production in the world (Kitinoja 2013, Coulomb et al. 2015, Aung & Chang 2014). In other words, maintaining the desired temperature of the food during processing is crucial (Ndraha et al. 2018). Refrigeration stops or reduces changes in foods, those being microbiological, physiological, biochemical or physical. The most efficient cold chain is the one where the food is refrigerated to the temperature that inhibits these changes for as long as possible. This will, in turn, increase the quality and shelf life of the food (James & James 2010, Guilpart & Clark 2018, Ndraha et al. 2018).

## 1.1 Background and motivation

India is the among the world's largest producers of fruits and vegetables, yet the post-harvest losses can reach up to 40-50% of what they produce. Lack of cold storages is the main reason for the high waste and in order to meet the nutritional demands of the population, both food quality, quantity and shelf life must increase. Hunger is among the more urgent problems facing the Indian community, especially due to the large amount of poor people in the country. Some actions to develop cold chains in India have been taken, but the cold chain infrastructure is very fragmented. However, cold chain facilities can not solve the problem all alone. Poor logistics, numerous intermediates in food chains causing poor remuneration, lack of post-harvest management and processing and outdated technology and infrastructure are other challenges. Despite this, India have the potential to become the leading agricultural supplier in the world, if they harness and utilise this potential by, among other things, developing the post-harvest management and cold chain infrastructure.

The food cold chain is defined as:

> A cold chain for perishable foods is the uninterrupted handling of the product within a low temperature environment during the postharvest steps of the value chain including harvest, collection, packing, processing, storage, transport and marketing until it reaches the final consumer (Kitinoja 2013).

The food cold chain management consists of a set of supply chain practices, where the goal is to ensure an appropriate atmosphere for the perishable food products and defy microbial spoilage (Joshi et al. 2011, Aung & Chang 2014). From the moment of harvest or slaughter, the food will begin to deteriorate and this deterioration is highly dependent on the temperature at which the food is stored. Low temperatures slows down the metabolic processes in horticultural foods, and inhibit the growth of harmful bacteria in animal or fish products (Kitinoja 2013). Different types of food need different processing and storage temperatures, and it is important that the cold chain starts as early as possible and maintains the desired temperature for as long as possible (Shashi et al. 2017). The different stages of a typical cold chain are shown in Figure 1.1.1 on page 3.

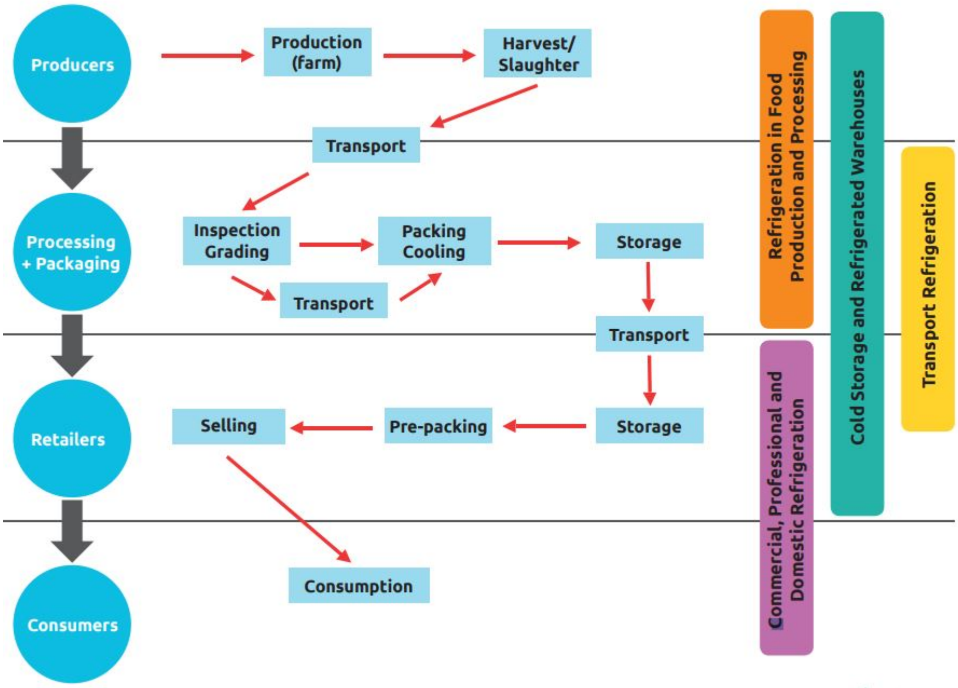



**Figure 1.1.1:** Typical cold chain stages for food (Guilpart & Clark 2018).

Food deterioration is just one of many issues related to too high supply chain temperatures (James & James 2010, Badia-Melis et al. 2018). There is a clear connection between food poisoning from salmonellosis and high ambient temperatures (D'Souza et al. 2004). To minimise the risk of food born illnesses, it is important to have strict control of the temperature throughout the food chain as cold storage reduces the growth rate of most human pathogens (Uçar & Özfer Özçelik 2013, Aung & Chang 2014). It is proved that food-born illnesses often are caused by temperature abuse in the food cold chain (Lediers et al. 2009). Additionally, many studies show that temperature abuse occur in all stages of the food cold chain, for almost all types of foods (Ndraha et al. 2018, Badia-Melis et al. 2018). This has a major impact on food quality and shelf life, as, according to the Q10 quotient, the degradation process double its rate for each increase of 10°C (Kitinoja 2013).

Developing efficient cold chain technologies and facilities is crucial if India, and the rest of the world, are going to have chance to meet the future food demand. Ammonia is an excellent refrigerant for cold storage and other refrigeration applications. However, due to its toxic and mildly flammable nature, there are safety concerns among users, especially in low-income countries like India. Use of a suitable secondary refrigerant, with ammonia as primary refrigerant, offers a safe solution as the charge of ammonia can be reduced and at the same time, ammonia can be confined to the plant room, away from the occupied zones. An addition of a secondary loop affects the cost as well as performance of the system. Selection of suitable secondary refrigerant is important to maintain a high efficiency and a good performance. $CO_2$ is considered an ideal secondary fluid and it can be used either in forced circulation loops or in natural circulation loops. For small cold storages useful for rural applications, a $CO_2$ based natural circulation loop along with an ammonia refrigeration system may offer a safe, reliable and simple solution.

## 1.2 Problem description

The objective of this Master Thesis is to investigate the Indian fruit and vegetable production and cold chains, and try to improve and develop the cold chains with a refrigeration system. Design, layout and theoretical performance of the refrigeration system at varying ambient conditions should be evaluated. The following tasks are to be considered:

- Literature review on the Indian food cold chain and ammonia refrigeration systems with $CO_2$ as secondary refrigerant.
- Map and investigate Indian fruit and vegetable cold chains, systems and products (regions, type of products, thermophysical properties, temperatures etc.) and suggest how to improve the food cold chain with the cold storage.
- Perform a thermodynamic analysis of the cold storage with an ammonia refrigeration system and $CO_2$ secondary loop and compare its performance with the baseline system (without secondary loop). Investigate the effect of magnitude of temperature difference needed for heat transfer between ammonia and $CO_2$ and $CO_2$ and storage room air. Estimate required $CO_2$ flow rates and effect of gas quality at the exit of the $CO_2$ heat source.
- Estimate the required heat transfer areas for $CO_2$-ammonia and $CO_2$-air heat exchanger and heat exchanger geometry. Identify practical problems that arise with the use of $CO_2$ based natural circulation loops and suggest a practical solution to address these problems.
- Make a simulation tool to calculate and design the cold storage with the refrigeration system and secondary loop.
- Preparation of a scientific paper from the main results of the Master Thesis.
- Make proposal for further work.

# Chapter 2

# Literature: Cold chains and refrigerants

## 2.1 Food temperature control

To get better control over the temperature abuse in the food cold chain, IT-integration can lead toward coherent demand measurement, avoiding over-production, reducing inventories and improving service quality (Shashi et al. 2017). By using wireless temperature-monitoring technologies, like Radio Frequency Identification (RFID) tags, Wireless Sensor Networks (WSN) and Time-Temperature Integrators (TTI), good time-temperature management and food safety can be achieved (Ndraha et al. 2018, Badia-Melis et al. 2018, Aung & Chang 2014). In addition, if these are integrated with the Internet of Things (IoT), real-time collection of temperature data is possible. A potential software available is the FRISBEE tool. The FRISBEE tool can optimise the quality of refrigerated food, energy usage and global warming impact of the refrigeration technology (Gwanpua et al. 2015). For applications where it is difficult to place a sensor, temperature estimation methods, thermal images and Computational Fluid Dynamics (CFD) can be used to monitor and predict temperatures (Badia-Melis et al. 2018).

Technology-wise, classic single-stage direct expansion systems are recommended for cooling in smaller facilities (Guilpart & Clark 2018, Kitinoja 2013). On larger facilities, single-stage systems with flooded evaporators for chilling, and two-stage refrigeration systems with flooded evaporators for freezing are recommended (Guilpart & Clark 2018). The energy consumption in the refrigeration sector is huge, consuming about 17% of the overall electricity used worldwide (Coulomb et al. 2015). Use of more energy efficient refrigeration technology is important, and companies should highly prioritise the use of carbon-free energy sources for sustainability purposes (Shashi et al. 2017).

There are several challenges relative to reliability, performance, environmental impact, regulations and economic concerns in the food cold chain. Major impediments are lack of required infrastructure, difficult agro-climatic conditions and absence of national focus and support due to social norms (Kitinoja 2013). In addition, consumers often lack knowledge about the food cold chain. Because of this, effective planning, integration and information sharing are important factors to overcome these barriers. By overcoming the barriers, consumers would get cheaper and healthier access to processed and unprocessed foods. Today, research on food cold chain management has shifted towards sustainable food cold chain management to save money, the environment, food and achieve social benefits (Shashi et al. 2017).

## 2.2 Indian food cold chain

The first step to properly develop cold chains in India was taken by the government in 1998 (NCCD 2015). This resulted in a substantial growth in larger standalone cold storages. Several measures were made in 2005-2006 and 2014 to further create more cold storages. However, only standalone cold storages were built and there was no focus on developing associated infrastructure to ensure a complete cold chain. Only 5% of the cold storage industry in India is organised and the country has negligible reefer transportation (Roy 2019, NCCD 2015). Perishable foodstuffs are transported without refrigeration, breaking the cold chain, leading to food waste and reduced quality. Currently, it exists cold storage space for 30.11 million tonnes of food. The required capacity, however, is more than 61 million tonnes, double the current amount (Roy 2019). There is also a need for refrigerated handling points like pack-houses and distribution centres. In fact, there is a need for 70 thousand refrigerated pack-houses, more than 50 thousand reefer vehicles and above 8 thousand ripening chambers (NCCD 2015).

In low-income countries, like India, refrigeration is still insufficient to satisfy vital needs and food safety for its inhabitants. One of India's greatest challenges in terms of food is its high and fast growing population. In order to meet their demands, food quantity and quality must increase, both in terms of nourishment and public health. One way to address this problem is to develop proper food cold chains, where the temperature is controlled from farm to consumer. A proper food cold chain will drastically decrease the food waste, increase food quality and prolong food shelf life (IIR-Billard & Dupont 2002). Lack of cold storages are among the main reasons for the high post-harvest losses in India, which reach up to 40-50% of the total production (Paul et al. 2016, Roy 2019).

India is the second largest fruit and vegetable producer in the world, with respectively 11.56% and 14.04% of the global production (Paul et al. 2016). During the recent years, the production has progressed rapidly, however, the post-harvest management and handling of the fruits and vegetables have not. The agriculture in India consists of over 1 840 000 square kilometres of gross cropped area, accounts for about 25-30% of the Gross Domestic Product (GDP), employs over 60% of the population and concerns the entire remaining population, making it a backbone in India's economy (Krishnan 2008). Most of the cold storages are therefore used to store fruits and vegetables. Being one of the worlds leading agricultural economies, India need to harness, develop and utilise this potential. If they do, they have a huge opportunity to become a global leader in feeding the world (ISHRAE 2018).

In addition to insufficient availability of cold storages and broken cold chains, India suffers from other problems as well. The cold storages are not evenly distributed, approximately 75% of the capacity exists in only five states (Andhara Pradesh, Gujarat, Uttar Pradesh, Punjab and West Bengal). The cold storages are not well maintained, making many storages out of operation, and as much as 80% of them run on old and outdated technology (Roy 2019). The cost of storing food in cold storages is very high, making it economically impossible for some farmers, or making the sales prices to high for some consumers. Cold storages generally exist as standalone units, making the integration into the cold chain difficult, in addition to making them inaccessible for poor and remotely placed farmers (Paul et al. 2016). The marketing system for agriculture and horticulture is also highly inefficient due to the presence of a large number of intermediates between farmer and consumer (Krishnan 2008). It is characterised by unorganised manual handling of food which leads to wastes (ISHRAE 2018).

The food supply chain and cold chain is currently experiencing a small and quiet revolution. Modern food retail has been estimated to have grown by 49% annually from 2001 to 2010. The processing sector grew 7% from 2002 to 2006. Indians are steadily adopting frozen and processed foods and many new start-ups are focusing on healthy premium foods like fresh meat, fish and dairy, which heavily rely on temperature-controlled logistics (Roy 2019). In addition, India experienced a rapid increase in ownership of white goods, like refrigerators, in urban households (Reardon et al. 2011). A very ambitious program launched in India is to double farmers' income by 2022. This will appeal to, and offer opportunities to, the refrigeration and cold chain industry (ISHRAE 2018). Studies estimate that India's cold chain market was valued at about $167 billion in 2016, reaching

$234 billion by 2020 (Roy 2019).

## 2.3 Refrigerants in India

Prior to the Montreal Protocol, Chlorofluorocarbones (CFCs) and Hydrochlorofluorocarbones (HCFCs) were extensively used for refrigeration purposes. After the adoption of the Montreal Protocol, India was classified under the A5 country group 2, giving them the longest time span for phase out of Ozone Depleting Substances (ODSs) (UNEP 2018). Consequently, the Indian Ozone Depleting Substances (Regulation) Rules (IODSRR) came into force in July 2000, leading to the phase out of CFCs ahead of target date of 2010. A5 countries have to phase out HCFCs by 2030, however, through comprehensive phase out management plans, manufacturers in India plan to phase out HCFCs by 2025 (ISHRAE 2015).

In need of good alternatives to CFCs and HCFCs, Hydrofluorocarbones (HFCs) were considered as a long term solution in India. They are ozone friendly with zero Ozone Depletion Potential (ODP). However, due to their relatively high Global Warming Potential (GWP), the Kyoto Protocol came into effect in 1997 to abate the use of, among others, HFCs. Despite being reliant on HFCs, India submitted a proposal to phase down HFCs under the Montreal Protocol in 2015. One of the key elements in their proposal is the continuous use of HCFCs, HFCs and blends as transitional substances during the phase out of HCFCs, due to lack of adequate technology and other alternatives. Technologies equivalent to that used in high-income countries are currently not available, nor economically possible, in India. Thus, the suggestion included a grace period of 15 years, to ensure availability of safe, efficient, environmentally friendly, commercially and economically viable technologies. HCFCs and HFCs are still used to great extent in India. Phase down should be completed by 2050 (ISHRAE 2015).

Figure A.1.1 in Appendix A shows current and alternative refrigerants in different sectors in India. One can see that HFC-134a and HCFC-22 is most used and they are not currently regulated in India. However, due to phase down and difficulty with export to other countries, their future is uncertain. Another thing worth noting is that most of the considered alternative refrigerants still are HFCs, like R-410A and R-407. Use of alternative natural refrigerants, like $CO_2$, is restricted to only mobile Air Condition (AC) and transport refrigeration. It is, however, identified as one of the most promising natural refrigerants, but climate conditions and lack of technology and knowledge makes it difficult in India. Hydrocarbons (HCs) are more used, but still only considered as promising alternatives in some niche areas due to the flammability and explosion risk. Ammonia has been used for a long period of time, but there are still uncertainties around ammonia due to its toxicity and flammability. It requires proper training for service and maintenance and appropriate safety codes. Currently used HFCs and HCFCs are non-flammable and non-toxic, and service personnel are often careless with safety issues. It is important to change this attitude and train technicians to handle the more difficult natural refrigerants. Owing to this, natural refrigerants have yet to find their golden age in India (ISHRAE 2015).

## 2.4 $NH_3$ refrigeration systems

### Environment and energy efficiency

Ammonia is among the most energy efficient refrigerants still in use, 15-20% more efficient than R404A (Danfoss A/S 2018a). In addition, it covers a large temperature range, from AC to low temperature freezing application (Ayub et al. 2011). Ammonia is classified as a natural refrigerant and it is among the most environmental friendly refrigerants on the market (Eikevik 2018). The ODP and GWP of ammonia are equal to zero (The Linde Group 2018) and it has excellent Life Cycle Climate Performance (LCCP) and low Total Equivalent Warming Impact (TEWI) (Rule et al. 2017).

### Safety

Ammonia is a toxic refrigerant. However, it has a characteristic and irritating odor that is easy for humans to detect at very low concentrations, making the risk of poisoning very small. The harmful concentration of ammonia is much higher, as seen in Table A.2.1 in Appendix A. Ammonia is flammable and explosive in mixtures with air at concentrations between 15-28%, but it is impossible for humans to stay at this concentration. In addition, the ignition temperature is relatively high, at 630°C, and it will not support combustion after the ignition source is removed (Rule et al. 2017). In case a leakage of ammonia, the vapour will rise and quickly be diluted in the air. If necessary, water scrubbers can be installed to absorb and drain a possible leakage. This should not necessarily present any barriers, as proper maintenance and training of personnel should be performed. If such is provided, the dangers of ammonia systems are no different from most other refrigerants (Ayub et al. 2011).

### Compressors and sizing

Ammonia is not compatible with copper and brass if there is air or water present in the system, as ammonia will corrode these materials (Rule et al. 2017). Semi-hermetic or hermetic compressors with special motor coatings or aluminium motor wires have to be used (Danfoss A/S 2018a). Semi-hermetical ammonia compressors exist on the market and they are used in smaller facilities (Ayub et al. 2011). Compared to other refrigerants, ammonia has a high volumetric capacity and thermal conductivity, in addition to low molecular weight and density, so it requires smaller equipment and pipe diameters. The high volumetric refrigeration capacity results in smaller compressors, while the high thermal conductivity leads to smaller heat exchangers. The pressure levels are also about equal to HFC systems (Danfoss A/S 2018a).

Despite having excellent thermodynamic properties, ammonia is rarely used in small capacity systems. At first, this was due to lack of compatible compressors and components designed for small ammonia systems, as most small compressors were hermetic with copper windings (Lobnig 2009). However, now it exists open compressors and separating hood compressors designed for small ammonia systems. One example is the separating hood compressor developed by Frigopol. It has a wide operating range, from -30°C to 50°C, and it can provide a cooling capacity of 1 kW to 95 kW, with capacity control ranging from 20-100% of the chosen capacity (Frigopol 2019).

### Costs

The cost of ammonia refrigerant is considerably lower than most other refrigerants. Operating costs are low, due to the high efficiency, and reduced equipment and pipe sizing will contribute to a reduced investment cost. However, since specific materials have to be used, the total costs might eventually eclipse those of other commercial systems. Despite these disadvantages, through Life Cycle Cost Analysis (LCCA), even relatively small ammonia systems are deemed competitive due to the increased efficiency and lowered operational costs (Rule et al. 2017, Danfoss A/S 2018a).

There are many sources estimating the COPs of different applications. COP will vary depending on the system and conditions and Table 2.4.1 on page 11 shows typical COPs for some cooling applications.

| Description | COP | Reference |
|---|---|---|
| Above typical efficiencies of cooling technology | Above 4.8 | Sefaira (2013) |
| Efficient large scale, water cooled chiller | 3.9 - 4.8 | Sefaira (2013) |
| Efficient small scale, water cooled chiller | 2.7 - 3.9 | Sefaira (2013) |
| Efficient large scale, air cooled chiller | 2.4 - 2.7 | Sefaira (2013) |
| Efficient small scale, air cooled chiller | 2.0 - 2.4 | Sefaira (2013) |
| Inefficient cooling equipment | 0.9 - 2.0 | Sefaira (2013) |
| Absorption cycle chiller | 0.5 - 0.9 | Sefaira (2013) |
| Domestic refrigerator | 2.7 | Taib et al. (2010) |
| $NH_3$ plate in shell chiller package | 5.0 | Boone (2013) |
| $NH_3$ direct expansion chiller package | 3.3 - 5.6 | Boone (2013) |
| $NH_3$ combined plate in shell chiller package | 3.6 | Boone (2013) |

**Table 2.4.1:** Typical COPs for cooling applications.

## 2.5 $CO_2$ as secondary refrigerant

$CO_2$ is a non-toxic, non-flammable, non-explosive, natural refrigerant, which can be employed in areas where the toxic ammonia or the flammable hydrocarbons can't be used. However, one should be aware that $CO_2$, in case a leakage, is undetectable for human senses and can cause suffocation at higher concentrations. It has zero ODP, GWP of one, low TEWI and good LCCP. The price of $CO_2$ itself is also low, though the general cost of $CO_2$ systems tend to be higher than other commercial systems. $CO_2$ is not known to interact with any common materials (Danfoss A/S 2018b). Compared to other secondary fluids, like glycol, alcohol based fluids or other brine solutions, $CO_2$ has some advantages and disadvantages when used as a naturally circulated secondary fluid:

### Advantages

- Due to the high working pressure and the fact that $CO_2$ is a volatile fluid, it has a volumetric refrigeration capacity much higher than R22, ammonia and glycol. Consequently, the size of pipes, heat exchangers and other equipment can be reduced (Sawalha et al. 2000).

- The saturation temperature for $CO_2$ changes very little with pressure and the viscosity is low, so the pressure drop in pipes and heat exchangers will be low (Emerson 2015).

- In addition to the viscosity, the surface tension is relatively low, which is beneficial for efficient heat exchangers and flow through pipes. The heat transfer in heat exchangers is also high due to the high pressure and density, allowing for either a lower temperature difference in the heat exchanger, or smaller heat exchangers (Emerson 2015).

- $CO_2$ has a very high volumetric expansion coefficient, which additionally increases with higher temperature. This is very beneficial for natural circulation loops (Kumar 2017).
- A study by Kumar & Ramgopal (2009), comparing $CO_2$ to other secondary fluids, found out that for the same geometry and heat input, $CO_2$ required the smallest temperature difference across heat exchangers.

**Disadvantages**

- The operating pressures are high, increasing the leakage potential and wall thickness of pipes and other equipment (Emerson 2015).
- $CO_2$ has a low critical temperature, restricting the temperature to a maximum of 31.06°C to operate conventionally.

# Chapter 3

# Horticulture in India

## 3.1 Highlights

In this chapter, the production amount, production location and harvest season of the most important fruits and vegetables are investigated. In addition, the wholesale price fluctuations through the last four years are presented together with some short info on the current situation for each crop with regards to export and cold chain management. At last, storage recommendations are presented.

### Fruits

The most important fruits are, in listed order, identified as mangoes, grapes, apples, oranges and bananas. India is the fifth largest producer of apples in the world, the largest of bananas, ninth largest of grapes, the largest of mangoes and sixth largest producer of oranges. Southern India is the most productive region. Bananas are the only fruit produced throughout the entire year, while the remaining fruits are seasonal. As a consequence of this, the price of bananas stay relatively constant through the year. The remaining fruits, especially mangoes, experience large fluctuations in price depending on the season. The only fruit with a noteworthy cold chain are grapes. Grapes are pre-cooled in modern packhouse facilities and exported. Mangoes are handled and treated in packhouses as well, but lack cold chain facilities, causing post-harvest losses of up to 34%.

### Vegetables

The most important vegetables are, in listed order, identified as potatoes, onions, tomatoes, cauliflowers, cabbages and okra. India is the world's second largest producer of cabbages, cauliflowers, onions, potatoes and tomatoes, while it is the largest producer of okra. Eastern and central India are the most productive regions. Cabbages, cauliflowers and onions are seasonal crops, while okra, potatoes and tomatoes are produced throughout the entire year. Cabbages, cauliflowers, okra and tomatoes experience some price fluctuations through the year, though inferior to the large variations in price for fruits. The remaining vegetables have a more or less constant price. Compared to fruits, none of the vegetables are deemed competitive for storage, either due to short storage life or unfavourable prices. Modern packhouses for sorting and grading onions are available in production zones, but cold chain facilities are lacking. Potatoes are the only vegetable stored in cold storages, where about 75% of cold storages in India are used to store potatoes.

## 3.2 Background

India is the largest producer of fruits and second largest producer of vegetables in the world (NCCD 2015, Paul et al. 2016). 90.2 million tonnes of fruits are produced over 63 thousand square kilometres of land and 169.1 million tonnes of vegetables are produced over 101 thousand square kilometres of land (APEDA 2018). This employs about 150 million farmers across the country. Due to the warm and diverse climate, a wide variety of horticultural products are grown. Production statistics are available for about 30 different fruits and 20 different vegetables. The most important crops, with regards to production and consumption, are listed below (APEDA 2018, NCCD 2015). The selected fruits and vegetables will be further investigated.

**Fruits:** Mango, grape, apple, orange, banana.

**Vegetables:** Potato, onion, tomato, cauliflower, cabbage, okra.

India is composed of 29 states and seven union territories, but in this study they will all be referred to as states. The states are divided into six six geographical regions, illustrated in Figure 3.2.1 on page 15.

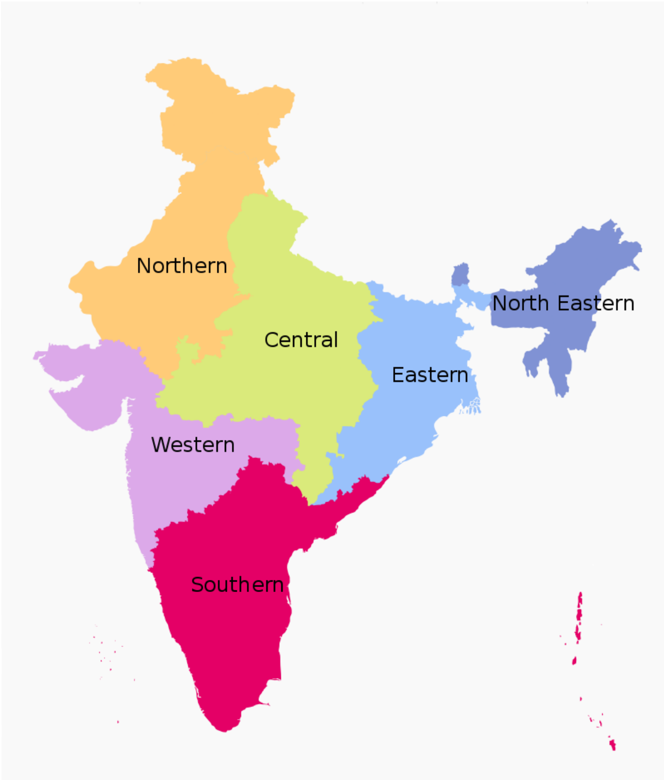



**Figure 3.2.1:** Regions of India (Wikipedia 2018).

**Northern India:** Chandigarh, Dehli, Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, Rajasthan.

**North-Easthern India:** Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura.

**Central India:** Chhattisgarh, Madhya Pradesh, Uttarakhand, Uttar Pradesh.

**Eastern India:** Bihar, Jharkand, Odisha, West Bengal.

**Western India:** Dadra and Nagar Haveli, Daman and Diu, Goa, Gujarat, Maharashtra.

**Southern India:** Andaman and Nicobar Islands, Andhra Pradesh, Karnataka, Kerala, Lakshadweep, Puducherry, Tamil Nadu, Telangana.

## 3.3 Fruits

The production location and amount for the selected fruits are shown in Table 3.3.1 on page 16. Production statistics are from the 2015-2016 season, as statistics for recent years still are provisional or estimated numbers.

| Region/State | Apple | Banana | Grapes | Mango | Orange |
|---|---|---|---|---|---|
| **Northern** | **2 449 850** | **7 260** | **9 120** | **347 110** | **1 424 890** |
| Haryana | - | - | 160 | 89 970 | - |
| Himachal Pradesh | 777 130 | 420 | 130 | 37 630 | 13 030 |
| Jammu and Kashmir | 1 672 720 | - | 320 | 23 740 | 4 210 |
| Punjab | - | 6 430 | 8 490 | 113 500 | 1 140 310 |
| Rajasthan | - | 410 | 20 | 82 270 | 267 340 |
| **North-Eastern** | **9 290** | **1 503 730** | **23 050** | **113 130** | **437 550** |
| Arunachal Pradesh | 7 280 | 31 640 | - | - | - |
| Assam | - | 882 710 | - | 46 150 | 210 140 |
| Manipur | - | 93 950 | - | - | 43 340 |
| Meghalaya | - | 88 710 | - | - | 42 840 |
| Mizoram | - | 141 030 | 22 550 | 4 180 | 41 340 |
| Nagaland | 2 010 | 108 510 | 500 | 3 740 | 51 690 |
| Sikkim | - | 3 560 | - | - | 16 800 |
| Tripura | - | 153 620 | - | 59 060 | 31 400 |
| **Central** | **61 940** | **5 406 680** | **2 200** | **5 454 530** | **1 126 270** |
| Chhattisgarh | - | 587 420 | - | 420 610 | - |
| Madhya Pradesh | - | 1 758 050 | 2 200 | 371 480 | 1 126 270 |
| Uttar Pradesh | - | 3 061 210 | - | 4 512 710 | - |
| Uttarakhand | 61 940 | - | - | 149 730 | - |
| **Eastern** | **-** | **3 203 630** | **-** | **3 330 710** | **39 210** |
| Bihar | - | 1 535 300 | - | 1 464 930 | - |
| Jharkhand | - | 33 280 | - | 393 670 | - |
| Odisha | - | 462 710 | - | 778 720 | - |
| West Bengal | - | 1 172 340 | - | 693 390 | 39 210 |
| **Western** | **-** | **7 210 670** | **2 048 110** | **1 704 760** | **768 990** |
| Gujarat | - | 4 185 520 | - | 1 241 590 | - |
| Maharashtra | - | 3 025 150 | 2 048 110 | 463 170 | 768 990 |
| **Southern** | **20** | **11 749 330** | **507 560** | **7 665 280** | **315 820** |
| Andhra Pradesh | - | 3 570 620 | 14 640 | 2 803 660 | 217 040 |
| Karnataka | - | 2 370 950 | 429 780 | 1 725 670 | 92 050 |
| Kerala | - | 1 292 410 | 15 500 | 382 520 | 30 |
| Tamil Nadu | 20 | 4 331 650 | 34 100 | 975 110 | 6 260 |
| Telangana | - | 183 700 | 13 540 | 1 778 320 | 440 |
| Others | - | 53 550 | - | 27 000 | 60 |
| **Total** | **2 521 100** | **29 134 850** | **2 590 040** | **18 642 520** | **4 112 790** |

**Table 3.3.1:** Production of fruits in India 2015-2016 (Datanet India 2015-2016a). Values in tonnes.

### Apple

India is the worlds fifth largest producer of apples, with about 2.5% of the world share (NCCD 2015). Export values are 6.07 million US$, mainly to Nepal and Bangladesh (APEDA 2018). Northern India is the main producer of apples with about 97% of the national production, where Jammu and Kashmir and Himachal Pradesh are the producing states. Uttarakhand in Central India is the third largest producer. North-Eastern India has some production, though inferior to the mentioned states. The harvest season for apples varies from June to November, depending on the location, as can be seen in Table 3.3.2.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Himachal Pradesh | | | | | | | | | | | | |
| Jammu and Kashmir | | | | | | | | | | | | |
| **North-Eastern** | | | | | | | | | | | | |
| Arunachal Pradesh | | | | | | | | | | | | |
| **Central** | | | | | | | | | | | | |
| Uttarakhand | | | | | | | | | | | | |

Peak season    Lean season    Throughout year

**Table 3.3.2:** Harvest season of apples (APEDA 2018, NCCD 2015).

Figure 3.3.1 on page 18 shows the average price each month at wholesale markets in India for the last four years. During season there is high availability and the price is consequently low. After the short season, the price increase each month and reaches almost double the value in June before the season begins again. The short season and large price variations makes apples an economically ideal product for storage.

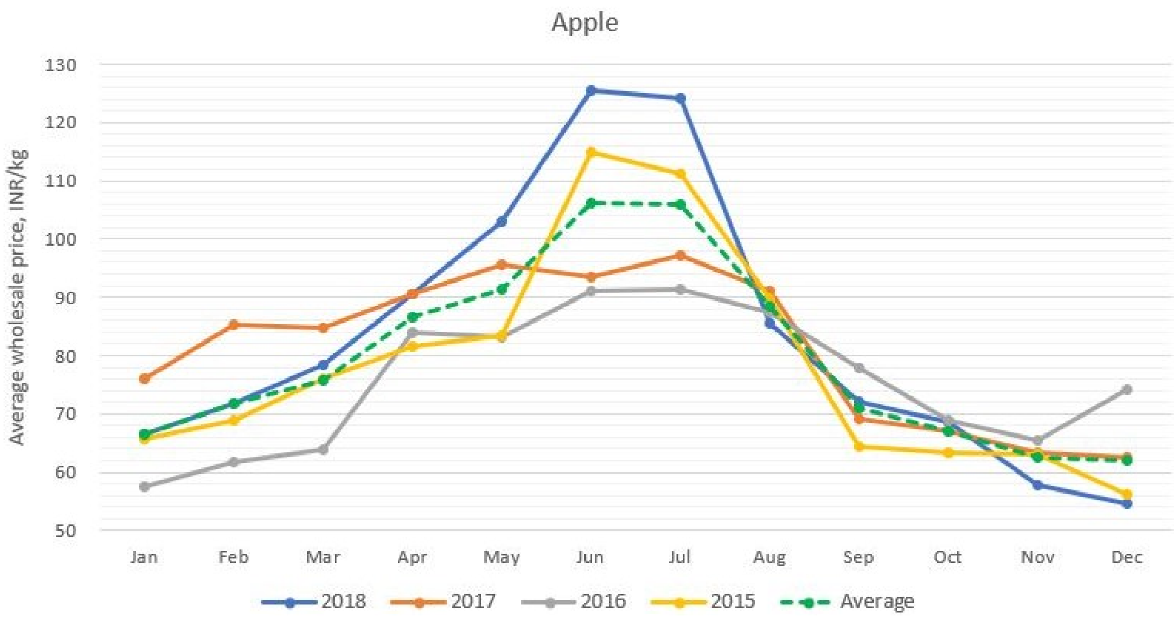



**Figure 3.3.1:** Monthly average wholesale price for apples (NHB 2019b).

### Banana

India is the world's largest banana producer, with about 25.6% of the world share (NCCD 2015). Export values were about 12.8 million US$ in 2011-2012, mainly to the United Arab Emirates, Saudi Arabia and Iran (APEDA 2012a). Banana are the most produced fruit in India and they are grown in almost the entire country. Southern India produce about 40% of the national production, where Tamil Nadu and Andhra Pradesh are the biggest contributors. Western India produce about 25% of the national production, with Gujarat and Maharashtra as the producing states. Central India is contributing with about 18%, where Uttarakhand is the most productive state.

The harvest seasons for bananas are changing with the location, as can be seen in Table 3.3.3 on page 19. Northern and Southern India have production during the entire year in all states. Western India have production roughly during the entire year for almost all states. The harvest period in North-Eastern and Eastern India is annual in some states, while others have harvest in the second half of the year. Central India is more varying, with either harvest in February to April, or June to November.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Rajasthan | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| Manipur | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| Meghalaya | | | | | | Peak | Peak | Peak | | | | |
| Mizoram | | | | | | Lean | Lean | Peak | Peak | Peak | Lean | Lean |
| Nagaland | | | | | | | | Lean | Peak | Lean | | |
| Tripura | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| **Central** | | | | | | | | | | | | |
| Chhattisgarh | | Lean | Peak | Lean | | | | | | | | |
| Madhya Pradesh | | Lean | Peak | Lean | | | | | | | | |
| Uttar Pradesh | | | | | | | | | Peak | Peak | Peak | |
| Uttarakhand | | | | | | Lean | Peak | Peak | Lean | | | |
| **Eastern** | | | | | | | | | | | | |
| Bihar | | | | | | | | Lean | Peak | Peak | Peak | Lean |
| Jharkhand | | | | | | | | Lean | Peak | Peak | Peak | Lean |
| Odisha | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| West Bengal | | | | | | | Lean | Peak | Peak | Lean | | |
| **Western** | | | | | | | | | | | | |
| Gujarat | Lean | Lean | Lean | | | | | Lean | Peak | Peak | Peak | Lean |
| Maharashtra | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| Karnataka | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| Tamil Nadu | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |

Peak season   Lean season   Throughout year

**Table 3.3.3:** Harvest season of bananas (APEDA 2018, NCCD 2015).

Figure 3.3.2 on page 20 shows the average price each month at wholesale markets in India for the last four years. Since bananas are available throughout the year, the price stays more or less constant, only varying with about 3 INR/kg. The high availability and low price variation makes bananas economically unfavourable for storage.

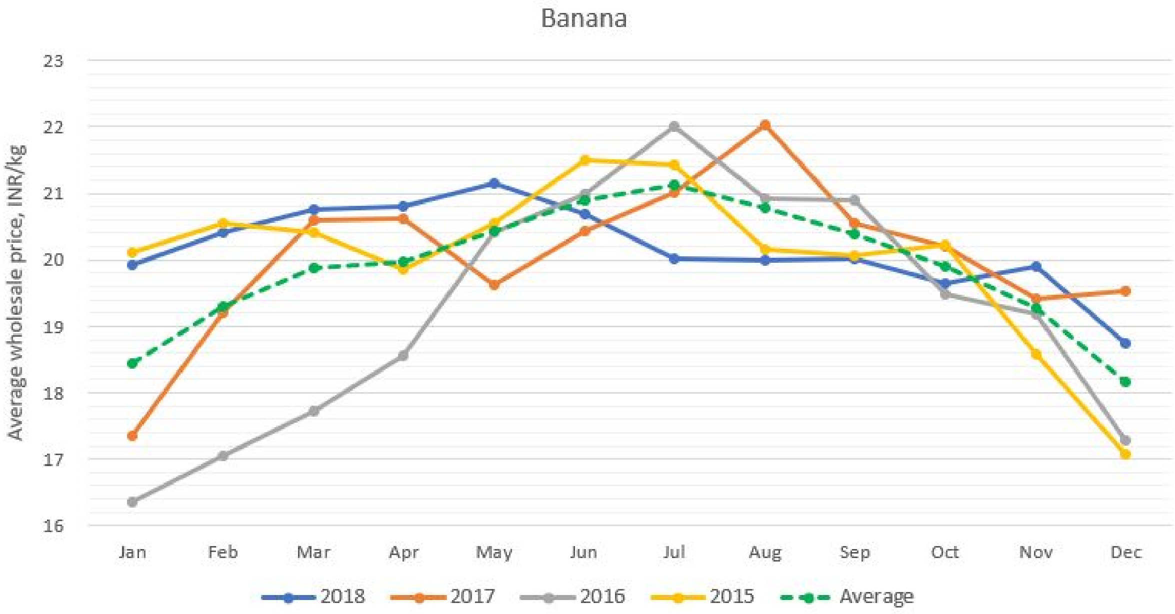



**Figure 3.3.2:** Monthly average wholesale price for bananas (NHB 2019b).

### Grapes

India is the world's ninth largest producer of grapes, with about 3.6% of the world share (NCCD 2015). Hot and dry climate is ideal for growing grapes, but temperate and warm regions in general are productive. Grapes are one of the fruits in India with the most complete cold chain. Modern packhouse facilities with automatic forced air systems for pre-cooling are available in all commercial production. Traceability systems are also currently used for grapes. Due to this, grapes are a high-value export product. Export values were about 294.6 million US$ in 2017-2018, mainly to Netherland, Russia, UK, Germany and the United Arab Emirates (APEDA 2018).

Maharashtra in Western India represent about 79% of the national production. Most of the remaining production takes place in Southern India, in Karnataka, which produce about 19% of the grapes. The harvest seasons vary throughout the country, as seen in Table 3.3.4 on page 21. Northern India harvest grapes fram May to July. Western and Southern India have more or less similar harvest periods, with total season from December to May and peak season in February and March. Southern India additionally harvest twice a year, with the second harvest in July. The only exception is Tamil Nadu which follows the same harvest season as Northern India.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Haryana | | | | | Peak | Peak | Peak | | | | | |
| Punjab | | | | | Peak | Peak | Peak | | | | | |
| **Western** | | | | | | | | | | | | |
| Maharashtra | Lean | Peak | Peak | Lean | Lean | | | | | | | Lean |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | Lean | Peak | Peak | Lean | Lean | | Peak | | | | | Lean |
| Karnataka | Lean | Peak | Peak | Lean | Lean | | Peak | | | | | Lean |
| Tamil Nadu | | | | | Peak | Peak | Peak | | | | | |

Peak season  Lean season  Throughout year

**Table 3.3.4:** Harvest season of grapes (APEDA 2012b).

Figure 3.3.3 shows the average price each month at wholesale markets in India for the last four years. During season, the availability is high and the price consequently hits a low point in March. The price between March and September vary a lot between the different years, but most years have a minimum point in September. In October to December, right before the season begins, the price is at its highest. The seasonal price variations makes grapes an economically ideal product for storage.

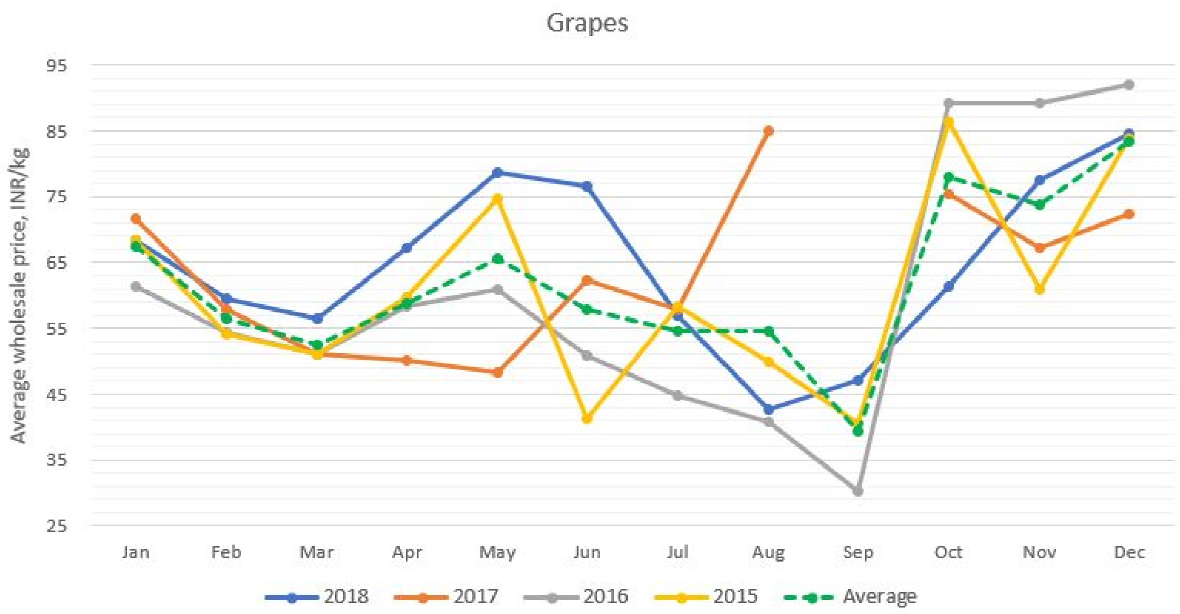



**Figure 3.3.3:** Monthly average wholesale price for grapes (NHB 2019b).

## Mango

India is the world's largest producer of mangoes, with about 40% of the world share (NCCD 2015). Mangoes are usually grown in tropical and subtropical regions, making

India an ideal country. The Indian mangoes comes in many different shapes and sizes, with different flavour, aroma and taste. However, only a few varieties are cultivated and they keep a high quality in terms of both taste and nutritional value. Mangoes are treated relatively good in India to maintain the high quality. Modern packhouses exist in all major producing zones and they are treated according to international requirements, with irradiation facilities, identification systems and traceability systems. However, post-harvest losses of mangoes can still be as high as 34% due to lack of appropriate cold storage facilities (Sab et al. 2017). Because of the relatively high quality and high production of mangoes, India is a prominent exporter to the world. Export values were about 59.3 million US$ in 2017-2018, mainly to the United Arab Emirates, United Kingdom, Saudi Arabia and Qatar (APEDA 2018).

Mangoes are the second most produced fruit in India, after bananas. It is grown to a large extent in more or less the entire country, although the production in the Northern and North Eastern parts of India are inferior to the remaining regions. Southern India has the highest production with about 41% of the national production. Andhra Pradesh, Karnataka and Telangana are South Indias most productive states. Central India comes second with about 29% and Eastern India is third with about 18%. Uttar Pradesh in Central India is the most productive state and Bihar is the most productive state in Eastern India. The harvest season in Northern, Eastern and Central India are usually a little bit later compared to Southern and Western India, as seen in Table 3.3.5. Western and Southern India have harvest season from January to July, with peak around April to May. Central and Eastern India has its main season from June to August, with peak season in June to July.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Central** | | | | | | | | | | | | |
| Uttar Pradesh | | | | Lean | | Peak | | | | | | |
| **Eastern** | | | | | | | | | | | | |
| Bihar | | | | | | Peak | Peak | Lean | | | | |
| **Western** | | | | | | | | | | | | |
| Gujarat | | | | Lean | Peak | Lean | Lean | | | | | |
| Maharashtra | | | Lean | Peak | Peak | Lean | | | | | | |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | Lean | Lean | Lean | Peak | Peak | | | | | | | |
| Karnataka | | | | Peak | Peak | Peak | Lean | | | | | |

Peak season   Lean season   Throughout year

**Table 3.3.5:** Harvest season of mangoes (NCCD 2015).

Figure 3.3.4 shows the average price each month at wholesale markets in India for the last four years. During the season, from March to July, there is high availability of the product and the price consequently drops to a low point in June. However, after the season ends, the price increase with over 40 INR/kg to September. The price for the different years vary and the profile for 2015 is opposite the other years, as it starts high and ends low. The 2018 season also lasted two months longer than the other years. Still, the short season and large price variation makes mangoes an economically ideal product for storage.

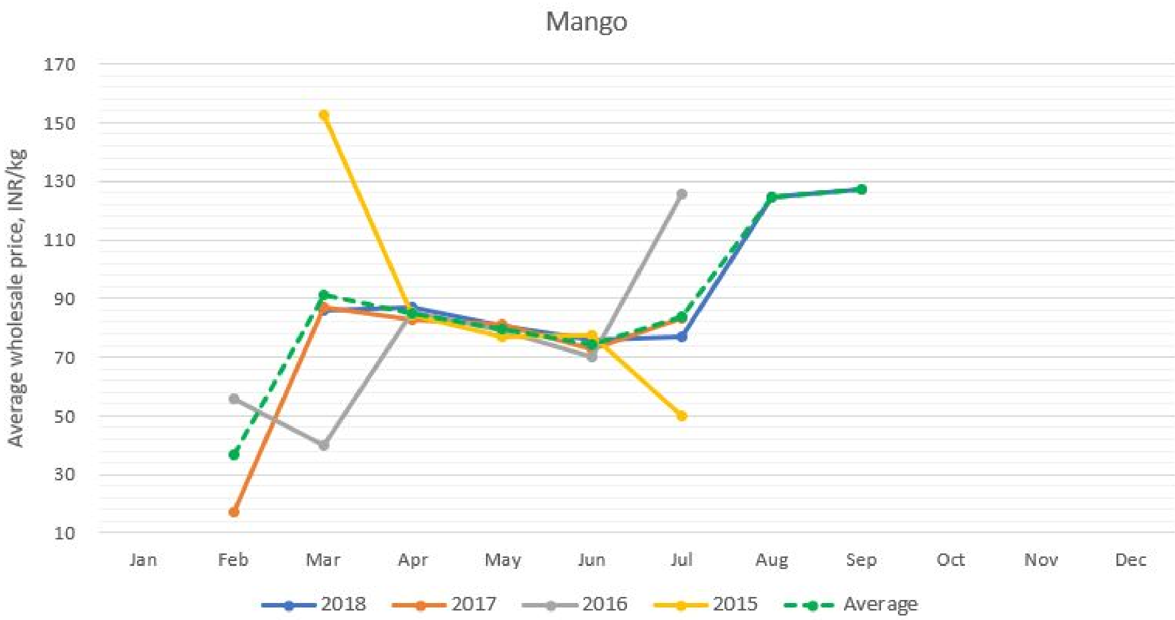



**Figure 3.3.4:** Monthly average wholesale price for alphonso mangoes (NHB 2019b).

### Orange

India is the world's sixth largest producer of oranges, with only 4% of the world share (NCCD 2015). Oranges are the most common citrus fruit in India, occupying nearly 40% of the total area used for citrus cultivation (NHB 2012). Export values for oranges were about the same as for apples, about 5.4 million US$ in 2017-2018, mainly to Bangladesh and Nepal (APEDA 2018). Oranges are usually transported to the neighbouring countries by road, without cooling or other treatment, often leading to large losses (NHB 2012).

Most of the oranges are produced in Northern and Central India, with about 35% and 27%, respectively, of the national production. Punjab accounts for most of the production in Northern India, while Madhya Pradesh produce the entire amount in Central India. Maharashtra comes third and accounts for the entire production in Western India. The harvest seasons are roughly around the new year in most of India, as seen in Table 3.3.6 on page 24. In Northern, North-Eastern and Central India, the season last from October to March, with peak season in November to February for most states. Eastern India is slightly later, with season from December to March and peak season in January and February. Western India has production the entire year, except for July and August, with peak season from March to May. Southern India has two harvest periods, one around February/March and one around September or November/December.

| **Region/State** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Himachal Pradesh | Peak | Peak | Lean | | | | | | | | | Lean |
| Jammu and Kashmir | Lean | | | | | | | | | Lean | Peak | Peak |
| Punjab | Peak | Lean | | | | | | | | | | Peak |
| Rajasthan | Lean | Lean | Peak | | | | | | | Lean | Lean | Lean |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | Peak | | | | | | | | | Lean | Peak | Peak |
| Manipur | | | | | | | | | Lean | Lean | Peak | Peak |
| Meghalaya | Peak | Peak | | | | | | | | | | |
| Mizoram | Lean | Peak | | | | | | | | Lean | Lean | Peak |
| Sikkim | Peak | Lean | Lean | | | | | | | | Peak | Lean |
| Tripura | | | | | | | | | | Lean | Peak | Lean |
| **Central** | | | | | | | | | | | | |
| Madhya Pradesh | Peak | Lean | | | | | | | | | Lean | Peak |
| **Eastern** | | | | | | | | | | | | |
| West Bengal | Peak | Peak | Lean | | | | | | | | | Lean |
| **Western** | | | | | | | | | | | | |
| Maharashtra | Lean | Lean | Peak | Peak | Peak | Lean | | | Lean | Lean | Lean | Lean |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | Lean | Peak | | | | | | | | Lean | Peak | Peak |
| Tamil Nadu | | Lean | Peak | Lean | | | | Lean | Peak | Lean | | |

Peak season Lean season Throughout year

**Table 3.3.6:** Harvest season of oranges (APEDA 2018, NCCD 2015).

Figure 3.3.5 on page 25 shows the average price each month at wholesale markets in India for the last four years. The price varies considerably between the different years and oranges were generally very expensive in 2018. During the season, from November to March, the price is low due to the high availability. When the season ends, around March, the price increase with an average of 12 INR/kg to May. The seasonal variations and price variations makes oranges somewhat suited for storage, however, not to the same extent as mangoes, grapes and apples.

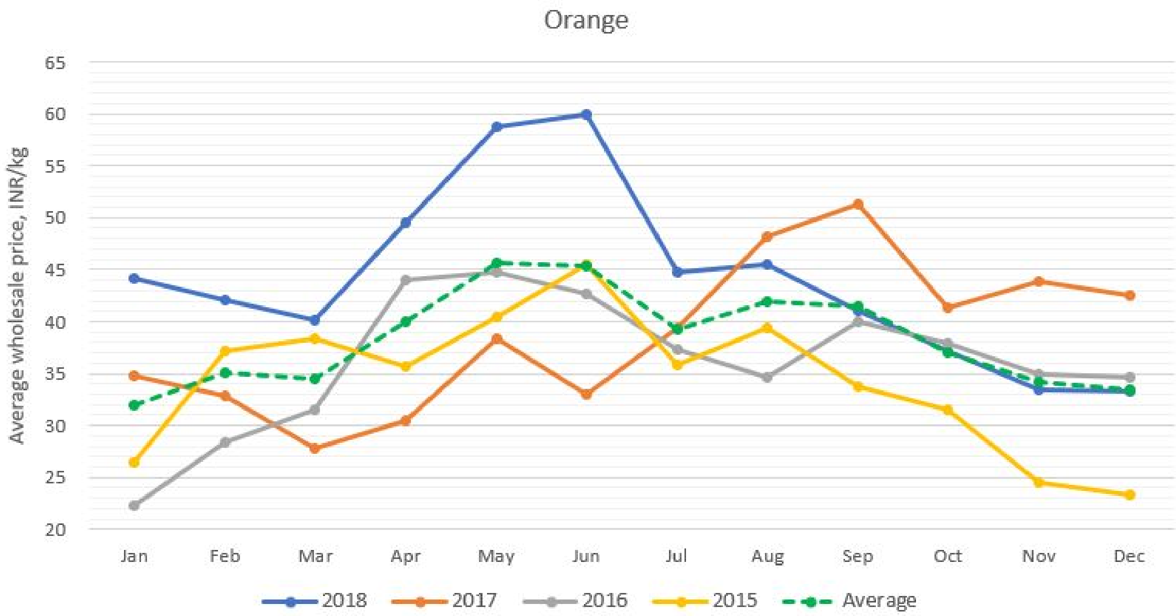



**Figure 3.3.5:** Monthly average wholesale price for oranges (NHB 2019b).

## 3.4 Vegetables

Most vegetables in India are grown from temperate to humid tropics. The production location and amount for the selected vegetables are shown in Table 3.4.1 on page 26. Production statistics are from the 2015-2016 season, as statistics for recent years still are provisional or estimated numbers.

| Region/State | Cabbage | Cauliflower | Okra | Onion | Potato | Tomato |
|---|---|---|---|---|---|---|
| **Northern** | **655 910** | **1 080 770** | **328 520** | **2 447 850** | **3 779 390** | **1 523 480** |
| Haryana | 310 550 | 578 950 | 193 820 | 705 800 | 853 810 | 675 380 |
| Himachal Pradesh | 160 740 | 119 010 | 38 770 | 47 960 | 183 250 | 485 540 |
| Jammu and Kashmir | 73 230 | 85 260 | 42 990 | 65 270 | 127 240 | 88 090 |
| Punjab | 104 410 | 248 450 | 42 600 | 193 710 | 2 385 260 | 191 180 |
| Rajasthan | 6 980 | 49 100 | 10 340 | 1 435 110 | 229 830 | 83 290 |
| **North-Eastern** | **1 176 150** | **572 450** | **238 930** | **108 760** | **1 471 170** | **602 330** |
| Arunachal Pradesh | 9 620 | 2 670 | 170 | - | 5 650 | 3 320 |
| Assam | 754 980 | 443 950 | 183 290 | 80 310 | 1 037 260 | 445 020 |
| Manipur | 96 980 | 32 600 | 1 530 | 5 170 | - | 31 610 |
| Meghalaya | 41 570 | 20 470 | 3 440 | 4 600 | 183 820 | 34 020 |
| Mizoram | 48 900 | 1 080 | 25 000 | 8 430 | 1 440 | 10 200 |
| Nagaland | 135 670 | 4 950 | 1 550 | 7 140 | 60 940 | 20 100 |
| Sikkim | 5 380 | 3 350 | 6 870 | 1 730 | 53 550 | 4 250 |
| Tripura | 83 050 | 63 380 | 17 080 | 1 380 | 128 510 | 53 810 |
| **Central** | **1 178 380** | **1 707 110** | **958 790** | **3 688 330** | **18 015 830** | **4 107 470** |
| Chhattisgarh | 374 370 | 433 300 | 291 270 | 375 990 | 644 830 | 908 980 |
| Madhya Pradesh | 444 420 | 842 060 | 342 050 | 2 848 000 | 3 161 000 | 2 285 900 |
| Uttar Pradesh | 292 020 | 393 260 | 301 210 | 422 750 | 13 851 760 | 819 370 |
| Uttarakhand | 67 570 | 38 490 | 24 260 | 41 590 | 358 240 | 93 220 |
| **Eastern** | **4 511 500** | **3 766 110** | **2 678 590** | **2 425 100** | **15 678 280** | **3 726 620** |
| Bihar | 719 810 | 1 003 900 | 763 000 | 1 247 340 | 6 345 520 | 1 001 010 |
| Jharkhand | 475 990 | 258 640 | 452 120 | 254 630 | 627 010 | 230 190 |
| Odisha | 1 057 670 | 614 530 | 566 170 | 378 580 | 278 750 | 1 290 990 |
| West Bengal | 2 258 030 | 1 889 040 | 897 300 | 544 550 | 8 427 000 | 1 204 430 |
| **Western** | **787 370** | **731 710** | **978 560** | **7 885 120** | **3 800 840** | **2 295 690** |
| Gujarat | 608 160 | 544 710 | 859 470 | 1 355 780 | 3 549 380 | 1 319 110 |
| Maharashtra | 179 210 | 187 000 | 119 090 | 6 529 340 | 251 460 | 976 580 |
| **Southern** | **496 080** | **183 900** | **643 060** | **4 358 600** | **656 090** | **6 462 200** |
| Andhra Pradesh | 40 580 | 36 010 | 225 470 | 885 420 | 38 860 | 2 236 560 |
| Karnataka | 231 210 | 83 320 | 90 820 | 2 695 990 | 455 450 | 2 046 140 |
| Kerala | 21 190 | 6 440 | 31 860 | 280 | 17 920 | 58 800 |
| Tamil Nadu | 143 860 | 36 220 | 123 220 | 380 950 | 72 230 | 645 700 |
| Telangana | 59 240 | 21 910 | 171 690 | 395 960 | 71 630 | 1 475 000 |
| Others | 560 | 47 720 | 22 120 | 17 490 | 15 450 | 14 200 |
| **Total** | **8 805 950** | **8 089 770** | **5 848 570** | **20 931 250** | **43 417 050** | **18 731 990** |

**Table 3.4.1:** Production of vegetables in India 2015-2016 (Datanet India 2015-2016b). Values in tonnes.

## Cabbage

India is the world's second largest producer of cabbages, with about 12% of the world share (NCCD 2015). Export values are relatively low compared to fruits, with about 131.5 thousand US$ in 2017-2018, mainly to Mauritius, Nepal, Qatar and the United

Arab Emirates (APEDA 2018). Over 50% of the cabbages are produced in Eastern India, with West Bengal and Odisha as the biggest producers in the country. Central and North-Eastern India are the second and third largest producers, with about 13% of the national production each.

The harvest season is roughly around new year in most of the country, as seen in Table 3.4.2. Central, Eastern and Western India have harvest period from around November to March/April, with peak season in January and February. Most of Northern and North-Eastern India follows the same harvest season, however, Nagaland has peak season in July and August. Southern India differs even more, with two harvest seasons through the year.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Rajasthan | | | | | | | | | Lean | Peak | Lean | Lean |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | Peak | Peak | Lean | | | | | | | | Peak | Lean |
| Manipur | Peak | Lean | | | | | | | | Lean | Lean | Peak |
| Meghalaya | Peak | Lean | Lean | | | | | Lean | Lean | Peak | Peak | Peak |
| Mizoram | Peak | Lean | | | | | | | | | | Lean |
| Nagaland | | | | | | Lean | Peak | Peak | Lean | Lean | | |
| **Central** | | | | | | | | | | | | |
| Chhattisgarh | Peak | Lean | Lean | | | | | | | | | Lean |
| Madhya Pradesh | Peak | Lean | Lean | | | | | | | | | Lean |
| Uttar Pradesh | Peak | Peak | Peak | Lean | | | | | | | | Lean |
| Uttarakhand | Peak | Peak | Lean | | | | Lean | Peak | Lean | Lean | Lean | Peak |
| **Eastern** | | | | | | | | | | | | |
| Bihar | Peak | Peak | Lean | Lean | | | | | | | Lean | Lean |
| Jharkand | Peak | Peak | Lean | Lean | | | | | | | Lean | Lean |
| Odisha | Peak | Peak | Peak | Lean | | | | | | | Lean | Peak |
| West Bengal | Peak | Peak | Lean | | | | | | Lean | Lean | Peak | Peak |
| **Western** | | | | | | | | | | | | |
| Gujarat | Peak | Peak | Lean | | | | | | | Lean | Lean | Peak |
| Maharashtra | Peak | Peak | Lean | | | | | | | | | Lean |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | Peak | Lean | | | | | | | | | Peak | Lean |
| Karnataka | Lean | Peak | Lean | | | | | Lean | Peak | Lean | | |
| Tamil Nadu | Lean | | | Lean | Peak | Lean | | | | | Lean | Peak |

Peak season   Lean season   Throughout year

**Table 3.4.2:** Harvest season of cabbages (APEDA 2018, NCCD 2015).

Figure 3.4.1 shows the average price each month at wholesale markets in India for the last four years. Compared to the selected fruits, the general price level is considerably lower. Still, at the end of the season in March, when the average price is at its lowest, the price more than doubles until July. Then, it stays high until November when the season starts again. This increase in price makes cabbages somewhat ideal for storage, but considering that the increase is only about 8 INR/kg over four months, it's uncertain whether it is economically feasible or not.

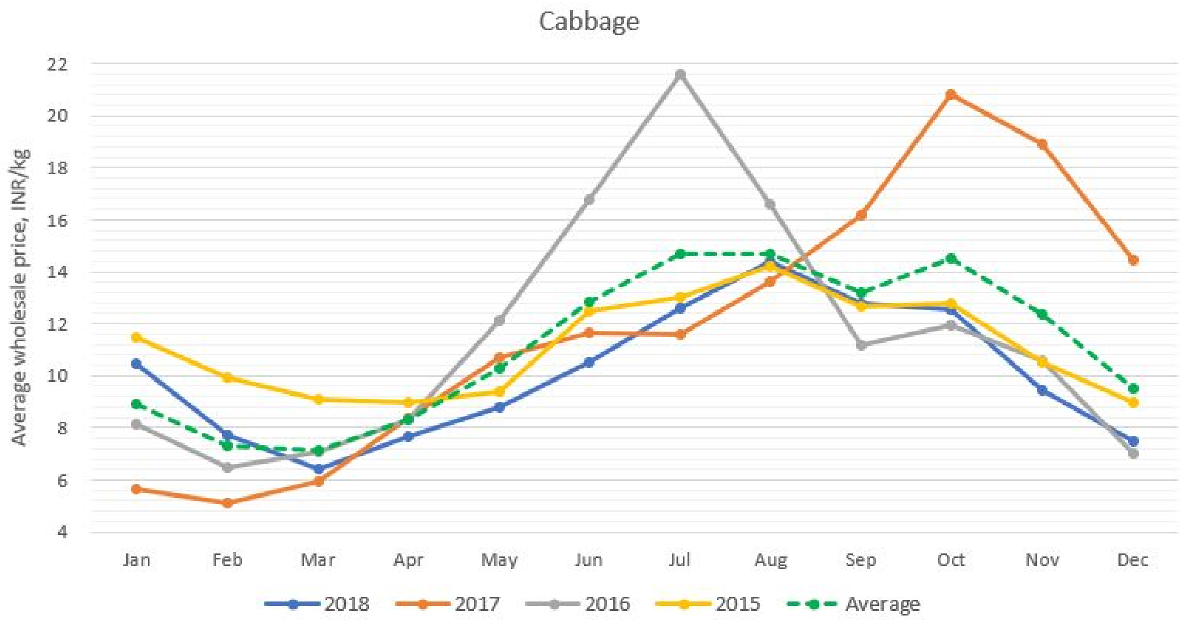



**Figure 3.4.1:** Monthly average wholesale price for cabbages (NHB 2019b).

### Cauliflower

India is the world's second largest producer of cauliflowers, with 36% of the world share (NCCD 2015). Export values are about the same as cabbages, 148.2 thousand US$ in 2017-2018, mainly to United Kingdom, Nepal and Japan (APEDA 2018). Eastern India is the largest producer of cauliflowers with about 47% of the national production. West Bengal and Bihar in Eastern India are the largest contributors both regional and national. Central India is the second largest producer with about 21% of the national production, and Madhya Pradesh is the biggest contributor. Northern India is third, with about 13% of the national production volume.

The harvest season is generally around the new year in most regions, as can be seen in Table 3.4.3 on page 29. Northern, Eastern, Western and Southern India have harvest from October to March for most states, with peak season from December to February. Central India has its main peak season in December to February, where Uttarakhand has an additional peak season in August and September. North-Eastern India has a bit earlier harvest season, where for instance Nagaland has harvest season from June to October with peak in July and August.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Haryana | Peak | Lean | Lean | | | | | | | Lean | Lean | Peak |
| Punjab | Lean | Lean | | | | | | | | Lean | Peak | Peak |
| Rajasthan | | | | | | | | | Lean | Peak | Lean | Lean |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | Peak | Peak | Lean | | | | | | | | Lean | Peak |
| Manipur | | | | | | | | Lean | Lean | Peak | Peak | Lean |
| Meghalaya | Lean | Lean | Peak | | | | | | | Lean | Peak | Peak |
| Mizoram | Peak | Lean | | | | | | | | | | Lean |
| Nagaland | | | | | | Lean | Peak | Peak | Lean | Lean | | |
| Sikkim | Lean | Lean | | | | | | | | Lean | Peak | Peak |
| **Central** | | | | | | | | | | | | |
| Chhattisgarh | Peak | Peak | Lean | | | | | | | | | Lean |
| Madhya Pradesh | Peak | Peak | Lean | | | | | | | | | Lean |
| Uttar Pradesh | Peak | Lean | | | | | | | Lean | Lean | Peak | Peak |
| Uttarakhand | Peak | Peak | Lean | | | | Lean | Peak | Peak | Lean | Lean | Peak |
| **Eastern** | | | | | | | | | | | | |
| Bihar | Peak | Peak | Lean | Lean | | | | | | Lean | Lean | Peak |
| Jharkand | Peak | Peak | Lean | Lean | | | | | | Lean | Lean | Peak |
| Odisha | Peak | Peak | Lean | | | | | | | Lean | Peak | Peak |
| West Bengal | Peak | Lean | Lean | | | | | | | Lean | Lean | Peak |
| **Western** | | | | | | | | | | | | |
| Gujarat | Peak | Peak | Lean | | | | | | | Lean | Lean | Peak |
| **Southern** | | | | | | | | | | | | |
| Karnataka | Peak | Peak | Lean | | | | | | | | | Lean |

Peak season   Lean season   Throughout year

**Table 3.4.3:** Harvest season of cauliflower (APEDA 2018, NCCD 2015).

Figure 3.4.2 on page 30 shows the average price each month at wholesale markets in India for the last four years. The seasons for cauliflowers are very similar to that of cabbages, with low price from about December to March. The average price is lowest in February before it increases with about 2.5 times until July, making storage economically feasible. However, cauliflower can not be stored for much more than about a month, making it difficult to profit from the increased price.

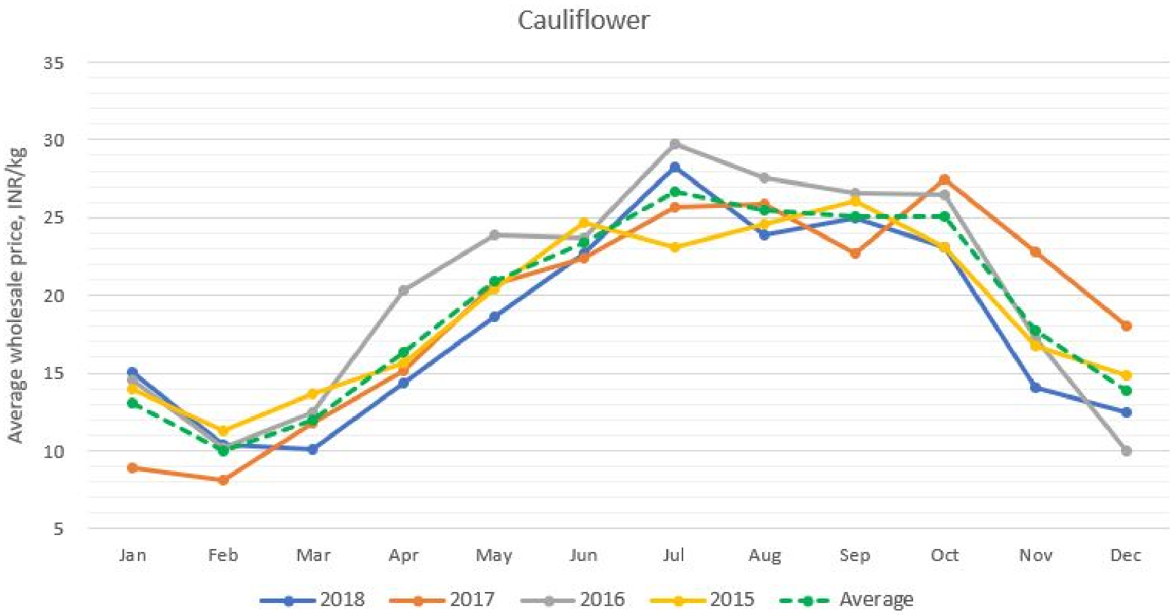



**Figure 3.4.2:** Monthly average wholesale price for cauliflowers (NHB 2019b).

### Okra

India is the world's largest producer of okra, with as much as 73% of the global market (NCCD 2015). There are no exact data for export of okra, but exports are increasing due to its nutritional value. As with cabbages and cauliflowers, Eastern India is the largest producer of okra with about 46% of the national production. West Bengal and Bihar are the most productive states here. Western India comes second with about 17% of the national production, where Gujarat accounts for most of the amount. Central India is third with roughly 16%.

The harvest season for okra varies through the country, as seen in Table 3.4.4 on page 31. Northern and North-Eastern India have harvest season mainly from April to September, with peak from May to August. In Eastern and Western India, Odisha, West Bengal and Gujarat produce throughout the year. Central India have production in different states the entire year, while Southern India produce all months except January and February.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Haryana | | | Lean | Peak | Lean | | | | | | | |
| Punjab | | | | Lean | Peak | Lean | | | | | | |
| Rajasthan | | | | Lean | Peak | Peak | Lean | Lean | Lean | Peak | Lean | |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | | | | Lean | Peak | Peak | Peak | Peak | Lean | | | |
| Manipur | | | | Lean | Lean | Peak | Peak | Lean | | | | |
| Mizoram | | | | | | Lean | Lean | Peak | Lean | | | |
| **Central** | | | | | | | | | | | | |
| Chhattisgarh | Peak | Peak | Lean | | | | | | | | | Lean |
| Madhya Pradesh | Peak | Peak | Lean | | | | | | | | | Lean |
| Uttar Pradesh | | | Lean | Peak | Peak | Lean | Lean | Lean | Peak | Peak | Lean | |
| Uttarakhand | | | | | | Lean | Peak | Peak | Lean | | | |
| **Eastern** | | | | | | | | | | | | |
| Bihar | | | Lean | Lean | Peak | Peak | Lean | Lean | Lean | Lean | | |
| Jharkand | | | Lean | Lean | Peak | Peak | Lean | Lean | Lean | Lean | | |
| Odisha | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| West Bengal | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| **Western** | | | | | | | | | | | | |
| Gujarat | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| Maharashtra | Lean | Lean | Peak | Peak | Peak | Lean | Lean | | | | | |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | | | Lean | Peak | Peak | Peak | Lean | Lean | Peak | Peak | Lean | Lean |
| Karnataka | | | | | | Lean | Peak | Peak | Lean | | | |
| Tamil Nadu | | | | | | Lean | Peak | Lean | | | | |

Peak season    Lean season    Throughout year

**Table 3.4.4:** Harvest season of okra (APEDA 2018, NCCD 2015).

Figure 3.4.3 on page 32 shows the average price each month at wholesale markets in India for the last four years. The average price of okra vary with about 14 INR/kg from high to low, despite being available throughout the entire year. During the production peak, from April to October, the price is low, before the average price peaks in January. These variations in price could make okra economically ideal for storage, were it not for its short storage life of only ten days.

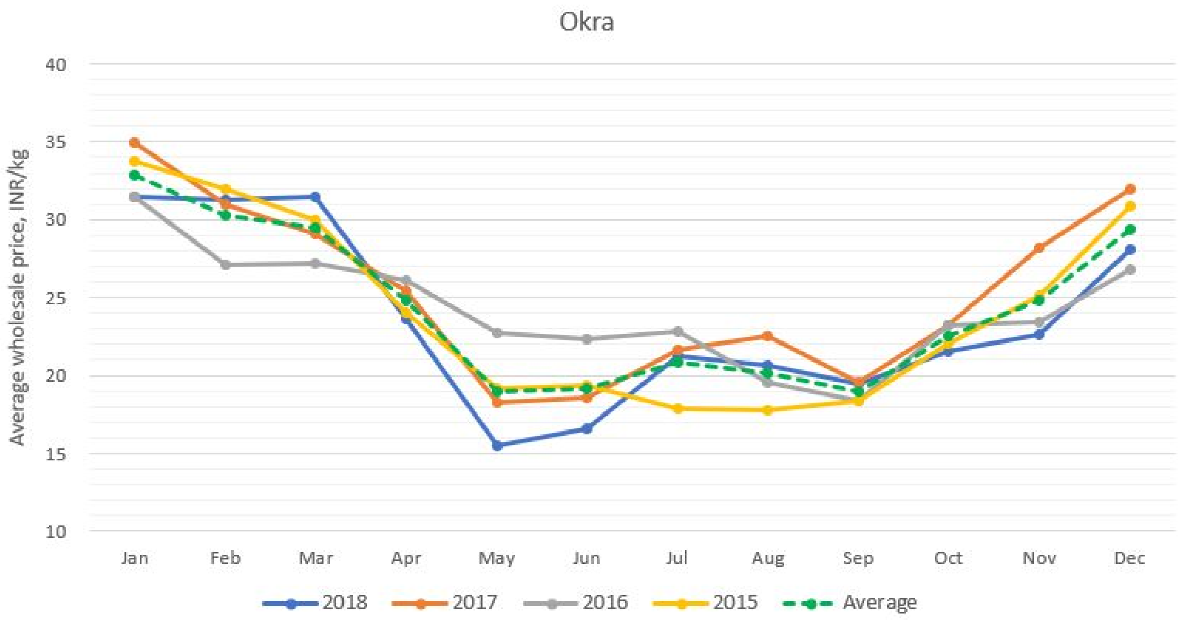



**Figure 3.4.3:** Monthly average wholesale price for okra (NHB 2019b).

### Onion

India is the world's second largest producer of onions, with 20% of the world share (NCCD 2015). There are many varieties of onions in India, and the statistics include both red and yellow onions. Indian onions are famous for their pungency and they are an extremely important crop, not only for national consumption, but also for international export (APEDA 2012c). Export values for onions are the highest of all fruits and vegetables, with 479.3 million US$ in 2017-2018. They are mainly exported to Bangladesh, Malaysia, Sri Lanka, United Arab Emirates and Nepal. Due to the high demand of Indian onions to the world, modern packhouses for sorting and grading are available at production zones (APEDA 2018). However, refrigerating facilities are lacking.

Onions are grown to large extents in the entire country, except North-Eastern India. Western India, primarily because of Maharashtra, produce most onions with about 38% of the national production. Southern India is second with about 21% of the production and Central India is third with about 18%. Maharashtra in Western India, Madhya Pradesh in Central India and Karnataka in Southern India account for the majority of the production in each region. The harvest pattern for the leading onion growing states are shown in Table 3.4.5 on page 33. Southern India have production of onions almost throughout the entire year, except January and February. Otherwise in India, onions are grown seasonal, with one season around March to May and another in November to December.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Haryana | | | Lean season | Peak season | Lean season | | | | | | | Peak season |
| Rajasthan | | | | | Peak season | Lean season | | | | | Peak season | Lean season |
| **Central** | | | | | | | | | | | | |
| Madhya Pradesh | | | Peak season | Peak season | Lean season | | | | | | | |
| Uttar Pradesh | | Lean season | Peak season | | | | | | | | | |
| **Eastern** | | | | | | | | | | | | |
| Bihar | | | Peak season | Peak season | Lean season | Lean season | | | | | | |
| **Western** | | | | | | | | | | | | |
| Gujarat | Lean season | Peak season | Lean season | | | | | | | | | |
| Maharashtra | | | Lean season | Peak season | Lean season | | | | | | | |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | | | Lean season | Peak season | | Peak season | Lean season | Lean season | Peak season | Peak season | Peak season | Lean season |
| Karnataka | | | | Peak season | Peak season | Peak season | Lean season | Lean season | Peak season | Peak season | Lean season | |

Peak season　Lean season　Throughout year

**Table 3.4.5:** Harvest season of onions (APEDA 2012c, NCCD 2015).

Figure 3.4.4 shows the average price each month at wholesale markets in India for the last four years. The average price of onions stays relatively constant, only varying with about 10 INR/kg. There are some variations between the different years and especially 2015 differs from the rest, with its peak price of 45 INR/kg in September. Despite this individual price peak, onions are not considered economically favourable for storage compared to some of the other crops.

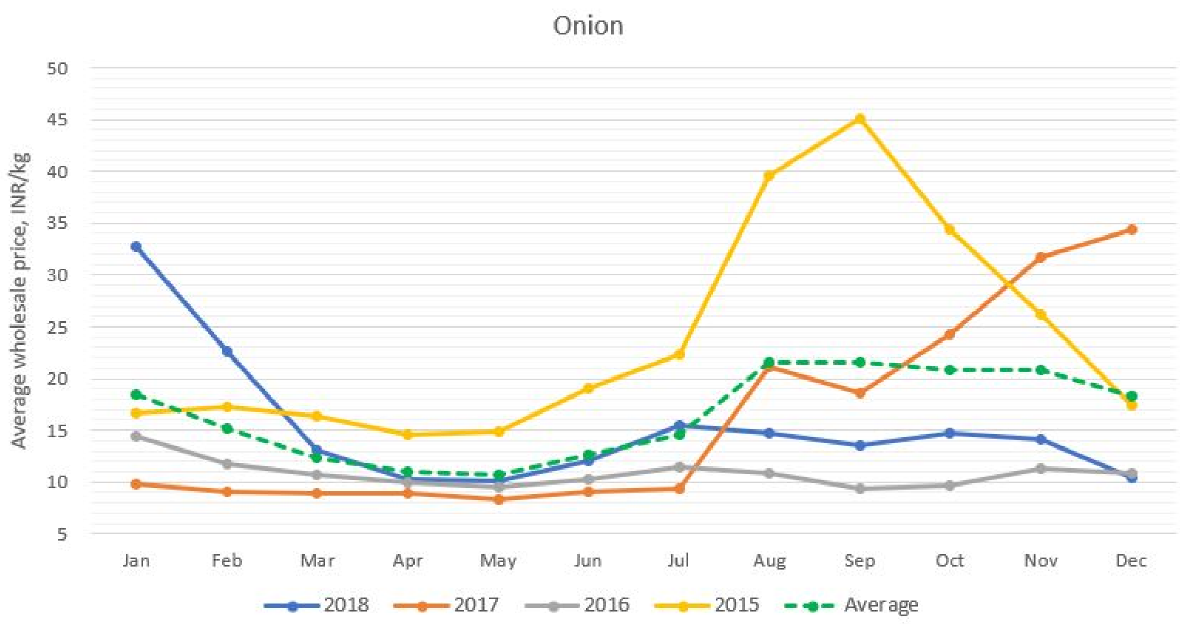



**Figure 3.4.4:** Monthly average wholesale price for onions (NHB 2019b).

### Potato

India is the world's second largest producer of potatoes, with 12% of the world share (NCCD 2015). Potatoes are the most produced vegetable and probably one of the most important crops in India. Export values were 63.9 million US$ in 2017-2018, primarily to Nepal, Sri Lanka and Oman (APEDA 2018). Central India is the largest producer of potatoes, because of Uttar Pradesh, with about 41% of the national production. Eastern India is second with about 36%, where West Bengal and Bihar are the most productive states. Western and Northern India produce about 8% each. Potatoes are among the few crops actually stored in cold storages. About 75% of cold storages in India are used to store potatoes (RX India 2013).

The harvest season for potatoes vary significantly throughout the country, as can be seen in Table 3.4.6 on page 35. Northern India has peak season around May and October, while North-Eastern India has peak season in June and July. Central India has several peaks and more or less some production throughout the entire year. Eastern and Western India have both full production the entire year. Southern India has season from March to December.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Haryana | | | Lean | Peak | Lean | | | | | | | |
| Punjab | | | | Lean | Peak | Lean | | | | | | |
| Rajasthan | | | | Lean | Peak | Peak | Lean | Lean | Lean | Peak | Lean | |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | | | | Lean | Lean | Peak | Peak | Lean | Lean | | | |
| Manipur | | | | Lean | Lean | Peak | Peak | Lean | | | | |
| Mizoram | | | | | | Lean | Lean | Peak | Lean | | | |
| **Central** | | | | | | | | | | | | |
| Chhattisgarh | Peak | Peak | Lean | | | | | | | | | Lean |
| Madhya Pradesh | Peak | Peak | Lean | | | | | | | | | Lean |
| Uttar Pradesh | | | Lean | Peak | Peak | Lean | Lean | Lean | Peak | Peak | Lean | |
| Uttarakhand | | | | | | Lean | Peak | Peak | Lean | | | |
| **Eastern** | | | | | | | | | | | | |
| Bihar | | | Lean | Lean | Peak | Peak | Lean | Lean | Lean | Lean | | |
| Jharkand | | | Lean | Lean | Peak | Peak | Lean | Lean | Lean | Lean | | |
| Odisha | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| West Bengal | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| **Western** | | | | | | | | | | | | |
| Gujarat | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout | Throughout |
| Maharashtra | Lean | Lean | Peak | Peak | Peak | Lean | Lean | | | | | |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | | | Lean | Peak | Peak | Peak | Lean | Lean | Peak | Peak | Lean | Lean |
| Karnataka | | | | | | Lean | Peak | Peak | Lean | | | |
| Tamil Nadu | | | | | | Lean | Peak | Lean | | | | |

Peak season  Lean season  Throughout year

**Table 3.4.6:** Harvest season of potatoes (APEDA 2018, NCCD 2015).

Figure 3.4.5 on page 36 shows the average price each month at wholesale markets in India for the last four years. Potatoes are stored in cold storages and due to this, the price stays more or less constant between 8 $^{\mathrm{INR}}/_{\mathrm{kg}}$ and 12 $^{\mathrm{INR}}/_{\mathrm{kg}}$. Potatoes are ideal for long time storage, but not economically favourable compared to the other crops discussed.

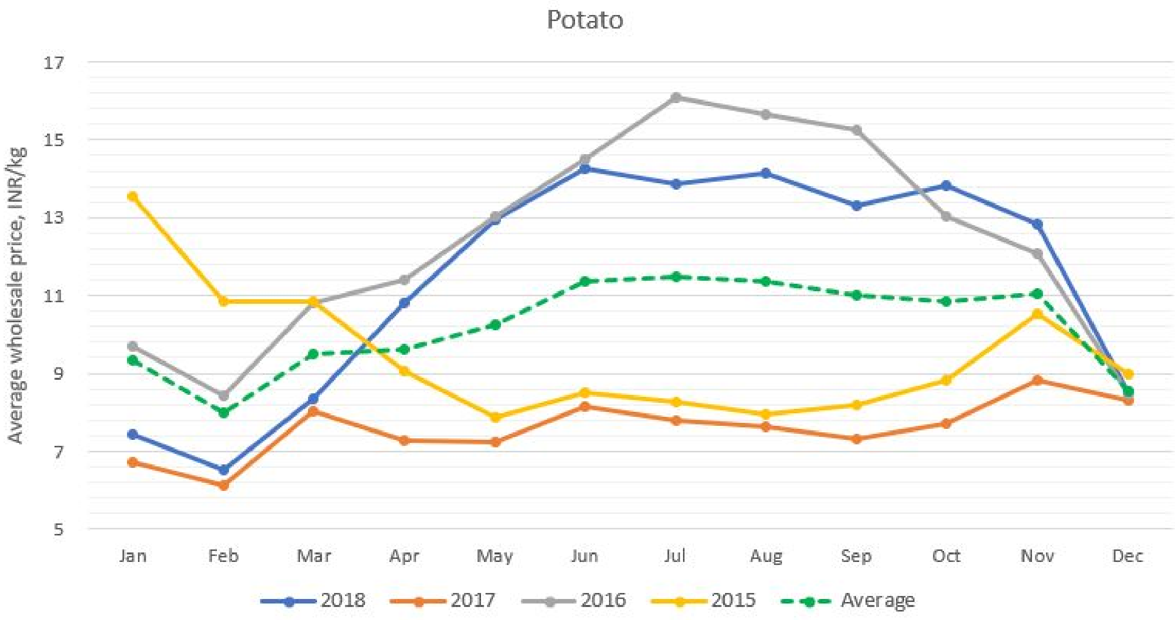



**Figure 3.4.5:** Monthly average wholesale price for potatoes (NHB 2019b).

### Tomato

India is the world's second largest producer of tomatoes, with 11% of the world share (NCCD 2015). It is the third most important vegetable in India, after potatoes and onions. Export values were 17.67 million US$ in 2017-2018, primarily to United Arab Emirates and Nepal (APEDA 2018). There is increased focus on enhancing the quality and productivity of tomatoes in India, to bring them to an international level in terms of packaging, presentation and quality (APEDA 2012d).

Tomatoes are grown somewhat evenly over the entire country, except for the northern areas. Southern India is the largest producer of tomatoes, with about 34% of the national production. Central India is second largest with about 22% and Eastern India is third with about 15%. Madhya Pradesh in Central India and Andhra Pradesh and Karnataka in Southern India are the most productive states. The harvest season is varying through the country, as can be seen in Table 3.4.7 on page 37. The main season for Northern, North-Eastern, Central and Eastern India is around November to February. Central India, together with Western and Southern India, have production throughout the entire year in some states.

| Region/State | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern** | | | | | | | | | | | | |
| Haryana | Peak season | Lean season | Lean season | | | | | | | Lean season | Lean season | Peak season |
| Punjab | Lean season | Lean season | | | | | | | | Lean season | Peak season | Peak season |
| Rajasthan | | | | | | | | | Lean season | Peak season | Lean season | Lean season |
| **North-Eastern** | | | | | | | | | | | | |
| Assam | Peak season | Peak season | Lean season | | | | | | | | Lean season | Peak season |
| Manipur | | | | | | | | Lean season | Lean season | Peak season | Peak season | Lean season |
| Meghalaya | Lean season | Lean season | Peak season | | | | | | | Lean season | Peak season | Peak season |
| Mizoram | Peak season | Lean season | | | | | | | | | | Lean season |
| Nagaland | | | | | | Lean season | Peak season | Peak season | Lean season | Lean season | | |
| Sikkim | Lean season | Lean season | | | | | | | | Lean season | Peak season | Peak season |
| **Central** | | | | | | | | | | | | |
| Chhattisgarh | Peak season | Peak season | Lean season | | | | | | | | | Lean season |
| Madhya Pradesh | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year |
| Uttar Pradesh | Peak season | Lean season | | | | | | | Lean season | Lean season | Peak season | Peak season |
| Uttarakhand | Peak season | Peak season | Lean season | | | | Lean season | Peak season | Peak season | Lean season | Lean season | Peak season |
| **Eastern** | | | | | | | | | | | | |
| Bihar | Peak season | Peak season | Lean season | Lean season | | | | | | Lean season | Peak season | Peak season |
| Jharkand | Peak season | Peak season | Lean season | Lean season | | | | | | Lean season | Lean season | Peak season |
| Odisha | Peak season | Peak season | Peak season | Lean season | | Lean season | Lean season | Lean season | Lean season | Lean season | | Lean season |
| West Bengal | Peak season | Lean season | Lean season | | | | | | | | Lean season | Peak season |
| **Western** | | | | | | | | | | | | |
| Gujarat | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year |
| **Southern** | | | | | | | | | | | | |
| Andhra Pradesh | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year | Throughout year |
| Karnataka | | | | | Peak season | Peak season | Peak season | Lean season | Lean season | | | |

Peak season  Lean season  Throughout year

**Table 3.4.7:** Harvest season of tomatoes (APEDA 2018, NCCD 2015).

Figure 3.4.6 on page 38 shows the average price each month at wholesale markets in India for the last four years. During season the price is relatively low, but out of season, in June to September, the price fluctuates. In 2017 it peaks twice, first in July and second in November. The average price shows some variations as well, from a low point of 12 INR/kg in February to 30 INR/kg in July. This makes tomatoes somewhat economically feasible for storage, were it not for the relatively short storage life.

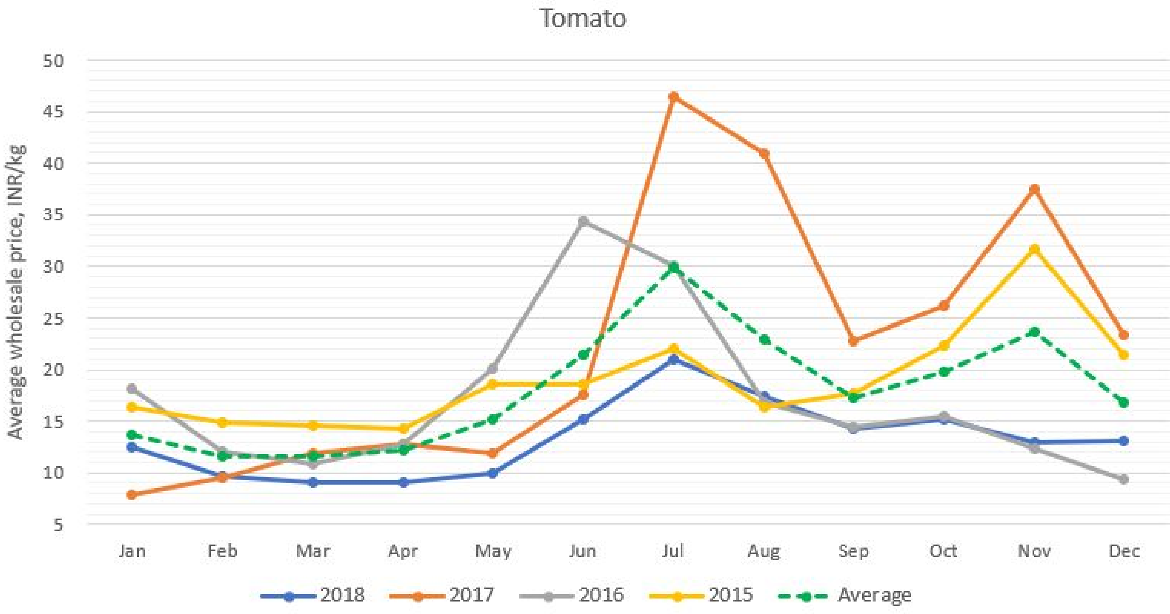



**Figure 3.4.6:** Monthly average wholesale price for tomatoes (NHB 2019b).

## 3.5 Storage conditions

Ideal storage conditions and storage life, for selected fruits and vegetables, are shown in Table 3.5.1 on page 39. Recommendations for controlled atmosphere are included, among with ethylene sensitivity and production. Many of these products can be stored together, if they are compatible. Important properties to consider when deciding compatible fruits and vegetables are temperature, relative humidity, production of ethylene, sensitivity to ethylene, production of odours and absorption of odours. Thompson et al. (1996) suggest six different groups for storing compatible fresh fruits and vegetables. Some compromises are made for temperature and humidity and short storage time is assumed. Ethylene concentrations should be kept low for all groups, particularly for longer storage. One should also be aware that odours might transfer from one product to another.

| Food item | Storage temperature °C | Relative Humidity % | Storage life | Ethylene production | Ethylene sensitivity | $O_2$ % | $CO_2$ % |
|---|---|---|---|---|---|---|---|
| **Fruits** | | | | | | | |
| Apple | -1 | 90-95 | 3-6 months | Very high | High | 2-3 | 1-2 |
| Banana | 13 to 15 | 90-95 | 1-4 weeks | Moderate | High | 2-5 | 2-5 |
| Grapes | -0.5 to 0 | 90-95 | 1-6 months | Very low | Low | 2-5 | 1-3 |
| Mango | 13 | 85-90 | 2-3 weeks | Moderate | Moderate | 3-5 | 5-10 |
| Orange | 0 to 9 | 85-90 | 3-12 weeks | Very low | Moderate | 5-10 | 0-5 |
| **Vegetables** | | | | | | | |
| Cabbage | 0 | 95-100 | 5-6 months | Very low | High | 3-5 | 3-7 |
| Cauliflower | 0 | 95-98 | 3-4 weeks | Very low | High | 2-5 | 2-5 |
| Okra | 7 to 10 | 90-95 | 7-10 days | Low | Moderate | Air | 4-10 |
| Onion | 0 | 65-70 | 1-8 months | Very low | Low | 1-3 | 5-10 |
| Potato | 4 to 12 | 95-98 | 5-10 months | Very low | Moderate | - | - |
| Tomato | 10 to 13 | 90-95 | 2-5 weeks | Very low | High | 3-5 | 2-3 |

**Table 3.5.1:** Storage requirements for selected fresh fruits and vegetables (ASHRAE 2018).

### Group 1: Fruits, 0-2°C, 85-95% relative humidity

This group contains the majority of temperate-origin fruits and berries and most importantly, apples, grapes and Florida oranges. Many crops in this group produce ethylene.

| | | | | |
|---|---|---|---|---|
| **Apple** | Cantaloupe | Elderberry | Loquat | Plum |
| Apricot | Cashew apple | Fig | Lychee | Plumcot |
| Avocado, ripe | Cherry | Gooseberry | Nectarine | Pomegranate |
| Barbados cherry | Coconut | **Grape** | **Orange*** | Prune |
| Blackberry | Currant | Kiwifruit | Peach | Quince |
| Blueberry | Cut fruits | Longan | Pear** | Raspberry |
| Boysenberry | Date | Loganberry | Persimmon | Strawberry |
| Caimito | Dewberry | | | |

*Florida orange **Asian and European

### Group 2: Vegetables, 0-2°C, 90-98% relative humidity

This group contains most leafy vegetables and most importantly, cabbages and cauliflowers. Many crops in this group are ethylene sensitive. It is worth noting that garlic is moisture sensitive, so extended storage at this relative humidity will deteriorate the product.

| | | | | |
|---|---|---|---|---|
| Alfalfa Sprouts | Broccoflower | Cut vegetables | Kohlrabi | Salsify |
| Amaranth | Brussels sprouts | Daikon | Leek | Scorzonera |
| Anise | **Cabbage** | Endive-Chickory | Lettuce | Shallot |
| Artichoke | Carrot | Escarole | Mint | Snow Pea |
| Arugula | **Cauliflower** | Fennel | Mushroom | Spinach |
| Asparagus | Celeriac | Garlic | Mustard greens | Sweet Pea |
| Beans* | Celery | Green onion | Parsley | Swiss chard |
| Bean sprouts | Chard | Herbs (not basil) | Parsnip | Turnip |
| Beet | Chinese cabbage | Horseradish | Radicchio | Turnip greens |
| Belgian endive | Chinese turnip | Jerusalem artichoke | Radish | Water chestnut |
| Bok choy | Collard | Kailon | Rutabaga | Watercress |
| Broccoli | Corn** | Kale | Rhubard | |

*Fava and Lima **Sweet and baby

### Group 3: Fruits, 7-10°C, 85-95% relative humidity

This group contains citrus and subtropical fruits and most importantly California and Valencia oranges.

| | | | | |
|---|---|---|---|---|
| Avocado, unripe | Durian | Kumquat | **Orange*** | Tamarillo |
| Babaco | Feijoa | Lemon | Passion fruit | Tamarind |
| Cactus pear | Granadilla | Lime | Pepino | Tangelo |
| Calamondin | Grapefruit | Limequat | Pineapple | Tangerine |
| Carambola | Guava | Mandarin | Pummelo | Ugli fruit |
| Cranberry | Juan canary melon | Olive | Sugar apple | Watermelon |
| Custard apple | | | | |

*California and Valencia orange

### Group 4: Vegetables, 7-10°C, 85-95% relative humidity

This group contains many fruit-type vegetables and most importantly okra.

| | | | |
|---|---|---|---|
| Basil | Chayote | Kiwano | Pepper** |
| Beans* | Cowpea | Long bean | Squash*** |
| Cactus leaves | Cucumber | Malanga | Tomatillo |
| Calabasa | Eggplant | **Okra** | Winged bean |

*Span, green and wax **Bell and chili ***Summer, soft rind

#### Group 5: Fruits 13-18°C, 85-95% relative humidity

This group contains most tropical fruits and melons and most importantly bananas and mangoes.

| | | | | |
|---|---|---|---|---|
| Atemoya | Casaba Melon | Jabolicaba | Mangosteen | Rambutan |
| **Banana** | Cherimoya | Jackfruit | Papaya | Sapodilla |
| Breadfruit | Crenshaw melon | Mamey sapote | Persian melon | Sapote |
| Canistel | Honeydew melon | **Mango** | Plantain | Soursop |

#### Group 6: Vegetables, 13-18°C, 85-95% relative humidity

This group contains common root-type vegetables and most importantly onions, potatoes and tomatoes. It is worth noting that onions are moisture sensitive and should ideally be stored at 0°C, so extended storage at these conditions will deteriorate the product. In tropical climates like India, it is not common to store onions refrigerated. They are rather stored at 25-30°C with proper ventilation to avoid condensation on the onions when they are taken out of storage, which would destroy the product. Storage life at 25-30°C with proper ventilation can still be up to 9 months (MFI group 2018).

| | | | | |
|---|---|---|---|---|
| Bitter melon | **Dry onion** | **Potato** | Sweet potato | **Tomato**** |
| Boniato | Ginger | Pumpkin | Taro | Yam |
| Cassava | Jicama | Squash* | | |

*Winter, hard rind **Ripe, partially ripe and mature green

# Chapter 4

# The Indian scenario

## 4.1 Highlights

In this chapter the export and domestic cold chains are investigated. The cold chain and commodity flow through the Indian mandis, the fruit and vegetable wholesale markets throughout the country, are also investigated. Important weak links and challenges in the chains are identified. The findings are then compared to the results of a field investigation performed at IIT Kharagpur in India, before a specific problem and solution are discussed. At last, the technical layout, revenue and assumptions for the discussed solution are presented.

#### Cold chains

A typical cold chain for export of fresh horticultural produce is presented in Figure 4.2.1 on page 45. Lack of refrigerated transport and pre-cooling were found to be major weak links in the export cold chain. Grapes are the only crop pre-cooled and transported in refrigerated containers. None of the other crops are pre-cooled before export and most are transported to neighbouring countries by road, without refrigeration. To increase the revenue from export of fresh horticultural produce, one solution proposed is to use the experience they have from exporting grapes, to adapt technologies to pre-cool and export other crops. Mangoes are highlighted as a very potential export product. A typical cold chain for domestic horticultural produce is presented in Figure 4.3.1 on page 47. The domestic cold chain is not as well developed as the export cold chain, but, similar to the export chain, lack of pre-cooling and refrigerated transport are identified as major inhibitors. Additionally, there is a need for cold storages. Cold storages are present in India, but 75% are used for potatoes and 16% are out of operation.

### The Indian mandis

One problem highlighted in both cold chains are the very large number of intermediates. This was found to especially inhibit the cold chain and commodity flow through the Indian mandis. A typical cold chain for the product flow through the mandis is presented in Figure 4.4.1 on page 48. The mandis is associated with low quality, poor remuneration and very high wastes due to lack of cold chain facilities. Products are displayed at ambient temperatures, which may reach above 40°C, often forcing the seller to discard the unsold produce at the end of each day due to deterioration. The mandis is identified as an important link in both the export and domestic flow chain, as seen in Figure 4.4.2 on page 49.

### Field investigation

The field investigation at IIT Kharagpur confirmed many of the previously discussed conditions. In total, 66 people answered the survey, all from professors to fruit and vegetable vendors and grocery shop owners. Most people answered that they do refrigerate their food, except for the fruit and vegetable vendors. None of them used refrigeration. Despite this, they answered that the product quality is most important to them, but that they don't see the need for refrigeration to maintain the quality. In terms of wasting food, there is little correlation between education and amount of food waste. Most people actually reported less waste than what is presented in literature.

When asked how important they believe refrigeration is for food quality and shelf life, those higher educated think it is more important. Controversially, the majority of fruit and vegetable vendors answered that refrigeration is very important. However, when asked how important it is for them that their food or product is refrigerated the answers are different. Even though most people are aware of the importance of refrigeration, they do not really care if their food is refrigerated or not. Almost all fruit and vegetable vendors answered that refrigeration is unimportant to them. The majority of people agreed that there should be more use of refrigeration in Indian homes and that the lack of domestic refrigeration is due to economical reasons. However, when asked about the current use of refrigeration between production and consumption, more people find the current system sufficient. Generally, only those with higher education see the need for a better cold chain. Poor infrastructure is highlighted as the main reason for the lack here. Some people elaborated further on their answers and some elaborations can be seen in section 4.5.

### Cold storage at Indian mandis

It was decided to approach the problem of lacking cold chain facilities at the mandis. Some approaches and considerations revolving the problem are discussed, like design, configuration, energy sources, refrigeration system and costs. A small, movable cold storage, the size of a 20ft shipping container, was considered an appropriate solution. The layout can be seen in Figure 4.6.1 on page 58. Two configurations of the refrigeration system are compared, a single stage $NH_3$ refrigeration system with and without $CO_2$ in a NCL. The refrigeration systems are illustrated in Figure 4.6.2 on page 59 and the assumptions taken when designing the storage are presented in subsection 4.6.3.

To decide which products to store, the wholesale price variations from chapter 3 are investigated. To operate the storage through the entire year, the products regarded as most economically feasible for storage are apples, grapes and mangoes. The monthly average wholesale prices for apples, grapes and mangoes are presented in Figure 4.6.3 on page 60. Apples can be bought in January for 66 INR/kg, stored until June and sold for 106 INR/kg. Mangoes can be bought for 84 INR/kg in July and stored for as long as possible to be sold for 125 INR/kg in August. Then, grapes can be bought for 39 INR/kg in September, stored until December and sold for 83 INR/kg. To ensure that there is available product when storage starts, the monthly supply of each product for the last four years are investigated. A summary of the logistics is presented in Table 4.6.2 on page 63.

## 4.2 Export cold chain

The importance of a proper cold chain was discussed in chapter 1 and 2. For fruits and vegetables, the cold chain is all about extending the shelf life and maintaining the desired food quality, so that the product is in a consumable state for a longer period of time. A cold chain for fruits and vegetables, is often very similar to the general cold chain portrayed in Figure 1.1.1 on page 3, with refrigeration all the way from producers to consumers. A typical flow diagram for fresh horticultural produce should consist of pre-cooling, reefer transport, cold storage, refrigerated distribution and retail.

A typical cold chain flow diagram for export of fresh horticulture is illustrated in Figure 4.2.1 on page 45. This is similar to the cold chain recommended by NHB (2019a) for export of apples, bananas, citrus, grapes and mango. To maintain the high quality they emphasise the importance of refrigerated transport during export. However, many fruits and vegetables are transported without refrigeration in India. Several problems are highlighted in section 2.2, and the main inhibitors are economy, poor infrastructure, absence of national focus, social norms and lack of knowledge. Another major issue is the presence of a large number of intermediates. Each of the separate steps in the flow diagram may often include several different agents. This decreases the reliability and increases the cost of the exported produce. However, the lack of refrigerated transport and reefer trucks are possibly the biggest challenge.

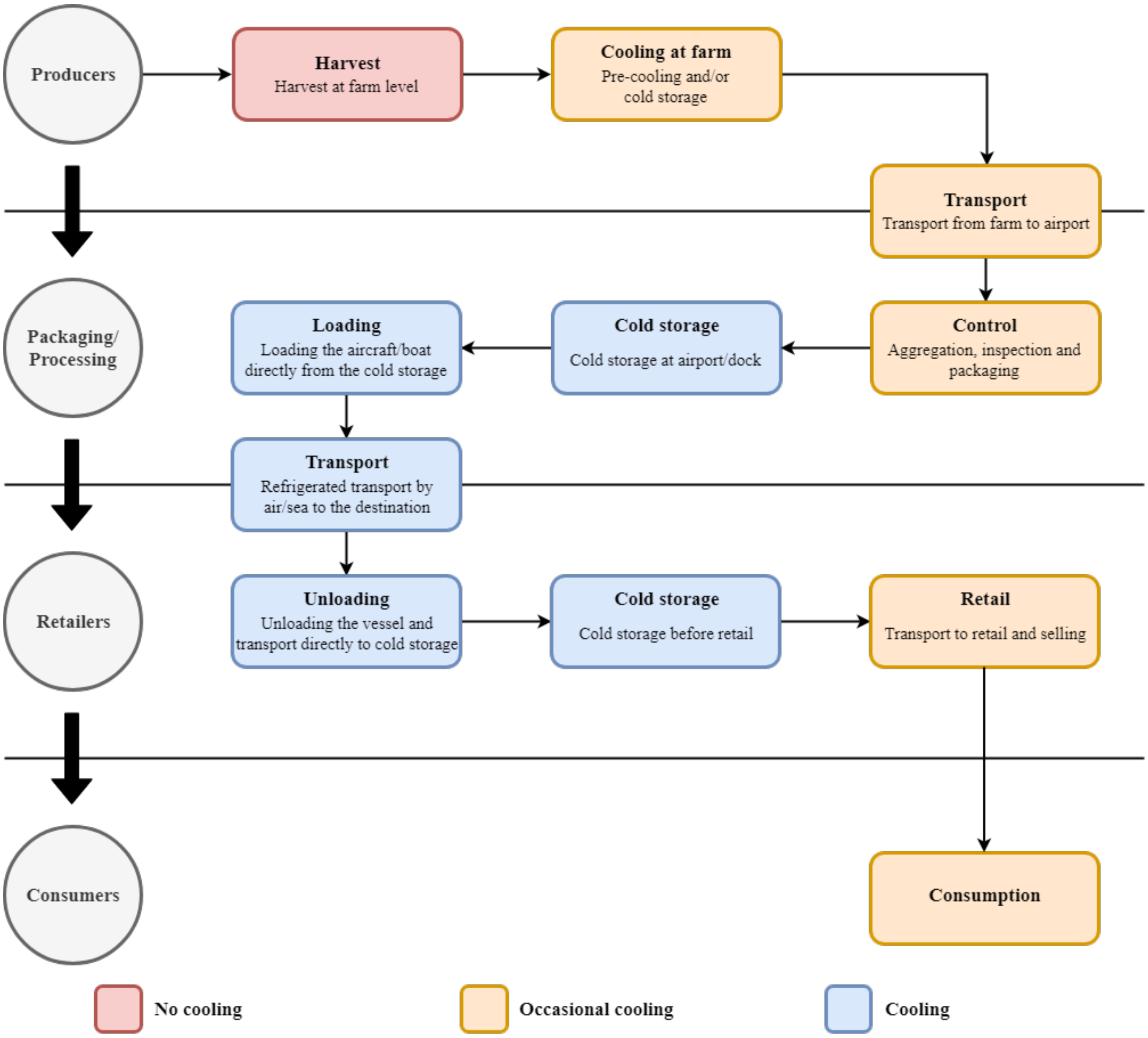



**Figure 4.2.1:** Typical cold chain for export of fresh horticultural produce.

Pre-cooling or cold storage at farm level is another important part of the cold chain often not performed. The need for pre-cooling is not felt in India, as people are used to buying or selling their product fresh on a daily basis. This will, however, vary depending on which crop they export. Grapes are one of the most exported fruits in India and consequently, they have the most complete cold chain. Grapes are pre-cooled, before they are transported in refrigerated containers to Europe, Asia and Middle East. The transport by sea to England might take three weeks and grapes are expected to maintain farm fresh for up to six weeks. Due to this, Indian exporters quickly realised that the only way they could meet this need is by having a proper cold chain (Aswaney 2007).

Another high value export product are mangoes. The mango flow chain lacks pre-cooling, cold storages and cold chain facilities, inhibiting the export and increasing the post-harvest losses. Similar to grapes, mangoes have the potential to be a high value export product, but they need appropriate cold chain facilities to fulfil this potential. The situation is similar for oranges and onions too, as they are also transported to the neighbouring countries by road, without refrigeration.

The obvious weak links in the export cold chain are the lack of pre-cooling and refrigerated transport (excluding grapes). The potential for exporting other crops is huge, but they need to increase the quality and shelf life of the other fresh horticultural produces to reach their full potential. One way of doing this is by using the experience they have gained from exporting grapes. For several years, India have successfully pre-cooled grapes and transported them with refrigeration to the international market. The easiest way to improve the export cold chain would probably be to use this experience and knowledge to adapt the technology to pre-cool and transport other horticultural crops.

## 4.3 Domestic cold chain

A typical cold chain flow diagram for perishable crops produced and sold domestically is illustrated in Figure 4.3.1 on page 47. This is similar to that suggested by NCCD (2015). The domestic cold chain is not as developed as the export cold chain. There is less money to be made on domestic sale compared to exports. The reasons are many, but the main reason is the average economical level. From section 2.2, it is known that the cost of storing food refrigerated is very high, often making it too expensive for both farmers and customers. In general, fruits and vegetables are not cooled at all, as it is not considered necessary (Aswaney 2007).

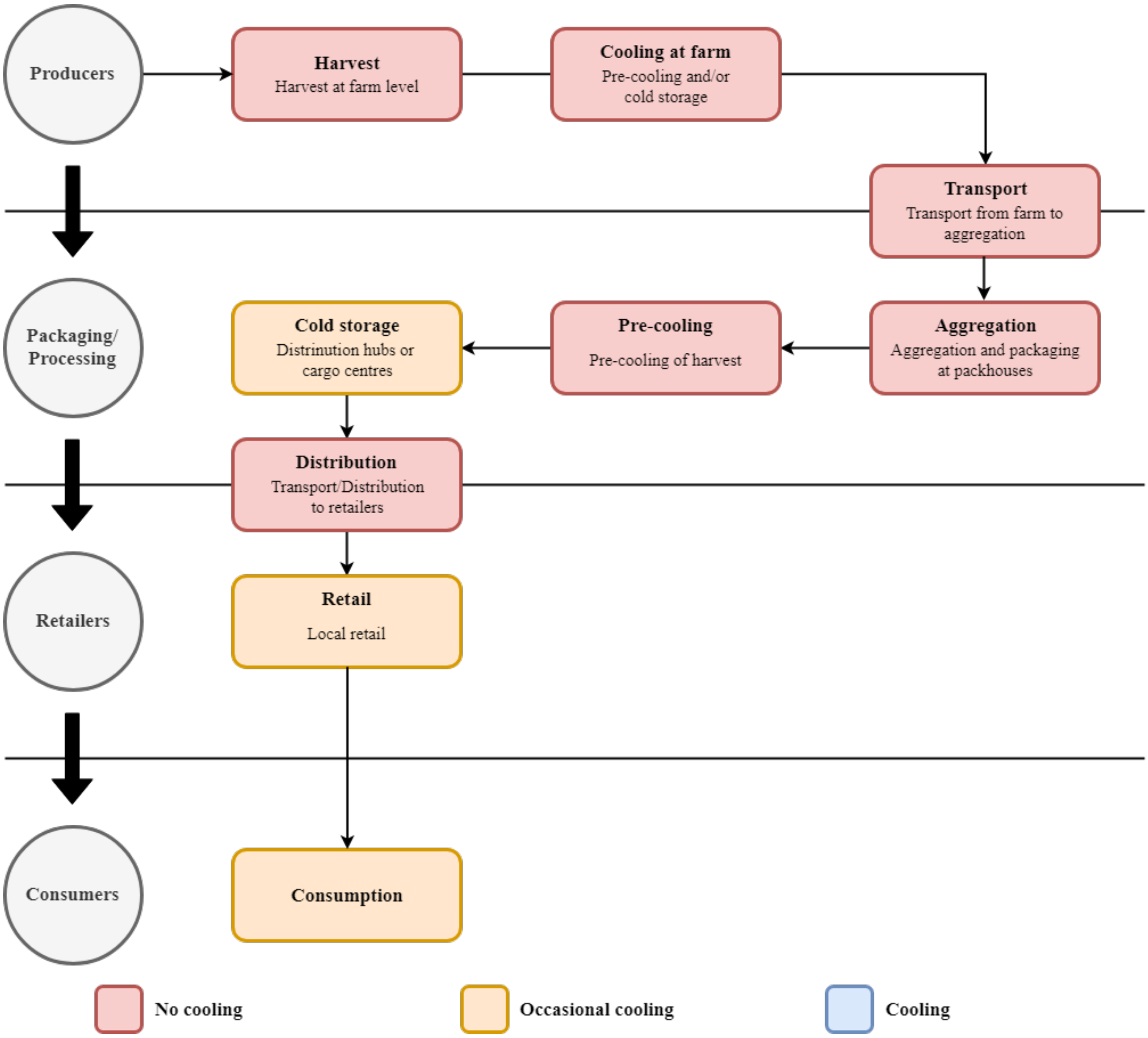



**Figure 4.3.1:** Typical cold chain for domestic horticultural produce.

There is a major need for pre-cooling in the domestic cold chain. The few crops actually cooled, are usually just put directly into the cold storage from ambient temperature. The need for cold storages is also huge. From section 2.2, it is known that they need double the current cold storage capacity. Potatoes are more or less the only horticultural produce stored in cold storages. About 75% of cold storages in India are used to store potatoes (RX India 2013). Considering that almost 16% of the cold storage capacity is out of operation, there is only about 10% capacity left for other crops. In addition, India has negligible reefer transportation of perishable horticultural produce. Almost all crops are transported by road at ambient conditions (NCCD 2015).

## 4.4 The Indian mandis

One of the problems highlighted in section 2.2 is the large number of intermediates in the Indian food chain. Each step in Figure 4.3.1 can include several other independent agents, like the producer, customer, village, itinerary merchant, pre-harvest contractors, commissioning agents, transport agents etc. (Krishnan 2008). This is a major problem in the all food chains and it is especially inhibiting the Indian mandis. The agricultural mandis' are the fruit and vegetable wholesale markets throughout the country. There are about 7 500 mandis' all over India and they are among the most common place to both buy and sell fruits and vegetables. A more realistic cold chain flow diagram for horticultural produce sold through the mandis, is illustrated in Figure 4.4.1.

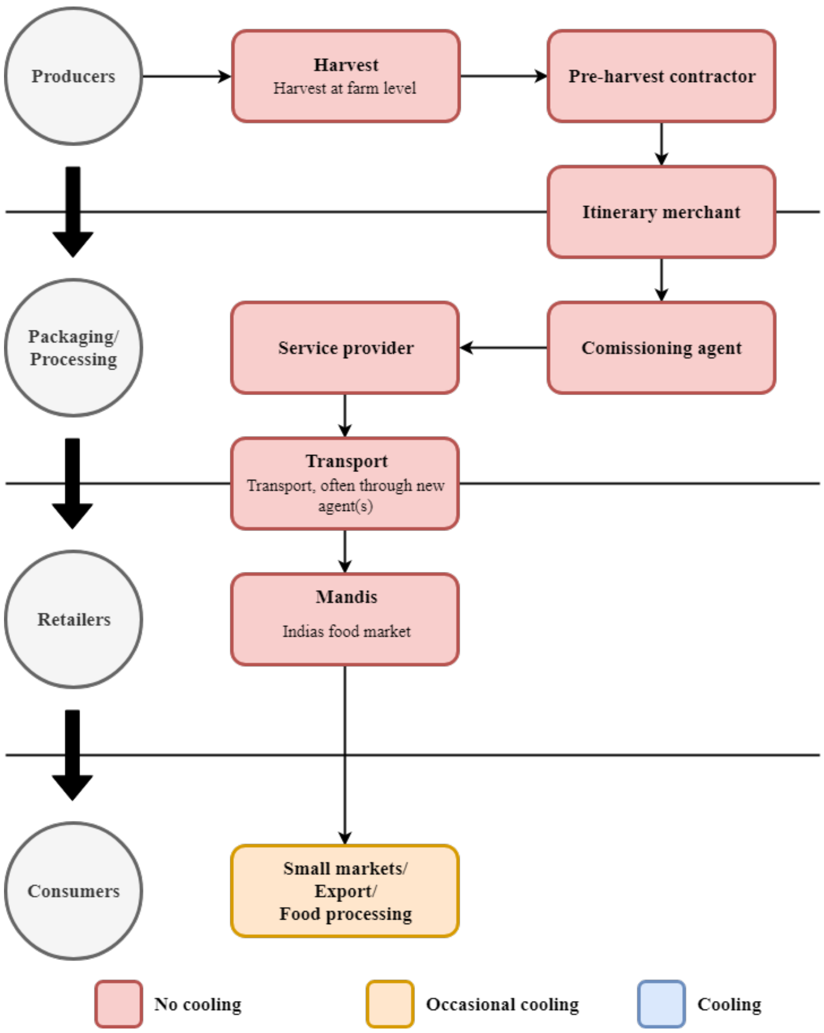



**Figure 4.4.1:** Typical cold chain for the Indian mandis.

The large number of intermediates are inhibiting the efficiency of the food chain and economy of all agents, resulting in high wastes, lower quality and poor remuneration to the growers (Krishnan 2008). The lack of appropriate cold storages is the main reason for the high waste and post-harvest losses through the mandis. People usually display their products in ambient conditions, which may reach above 40°C. Due to this, they often have to discard the produce they have not sold at the end of the day, as it has deteriorated in the high ambient temperatures. The Indian mandis is in great need of modernisation. One of the main objectives in the modernisation is to provide efficient cold storages for the perishable produce. Providing cold storage facilities to the mandis is probably the easiest and most important step to improve the cold chains in India. This would allow sellers to store the unsold crop, instead of having to discard it at the end of each day. Post-harvest losses would decrease, the quality of the horticultural produce would increase and, in turn, the profit of the different agents would improve.

In the investigated cold chains, the weakest links are the lack of pre-cooling, reefer trucks and cold storages. If India aim to increase its profit from export, it needs to improve its domestic cold chain. In addition to being a crucial link in the domestic food flow chain, the mandis form an important link in the overall flow chain, including export, which is illustrated in Figure 4.4.2.

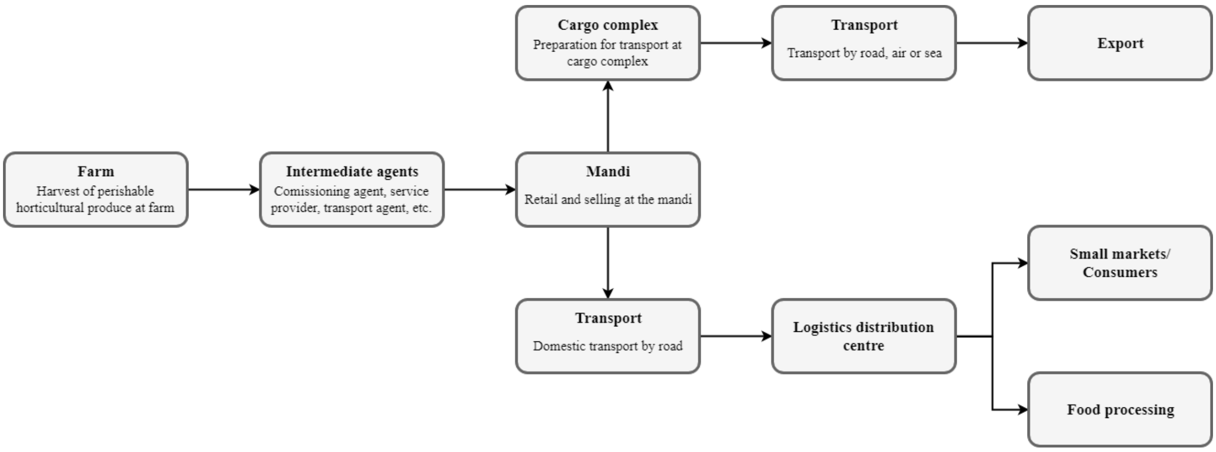



**Figure 4.4.2:** Commodity flow through a mandis.

## 4.5 Field investigation at IIT Kharagpur

In relation to writing the Master Thesis, a stay at IIT Kharagpur in India was carried out from 22.01.2019 to 05.04.2019. The purpose of this stay was to investigate and experience the conditions, culture and mindset of the country and its people, in addition to understanding why they face certain challenges. One of the challenges experienced was India's growing population and their mindset. A large amount of the population are uneducated and unaware of what's best for the environment and the world around them. Another challenge is the average economy. Many people do not have the economy to neither buy or use the appropriate tools, equipment or technologies to, for example, cool, store or process food the right way. The majority of the lesser educated people in India did not know how, or why, to store food the correct way. They live on a day-to-day basis, i.e. they buy the food they eat each day. By the end of the day, they have consumed whatever they have bought. However, this is not only due to the mindset, it is also a consequence of economy and poverty. Domestic refrigerators are making their way into Indian homes, but many people still don't see the need for it. This lack of knowledge is one of the many reasons why the high post-harvest wastes in India. The people producing, transporting and selling the food are usually uneducated and unaware of how the food should be treated.

To map peoples perspective on food and refrigeration, a survey was conducted, where students, professors, shop owners, fruit and vegetable vendors, fish vendors and other people answered. In total, 66 people answered, and their occupations are presented in Figure 4.5.1. Asking agents at the local market at IIT Kharagpur proved to be more difficult than expected. Even though the survey was given in both an English version and a Bengali version, the language spoken in the state of West Bengal, many people could not answer as they did not know how to read. To overcome this problem, the survey was conducted orally with an interpreter. However, some people still refused to answer, as they felt they might give a "wrong" answer, even though it was thoroughly explained that there are no right or wrong answers. The easiest source of proper answers was other students at IIT Kharagpur, which is the reason most answers are from students. However, the main targets of the survey were agents at the market and other people in the same line of trade.

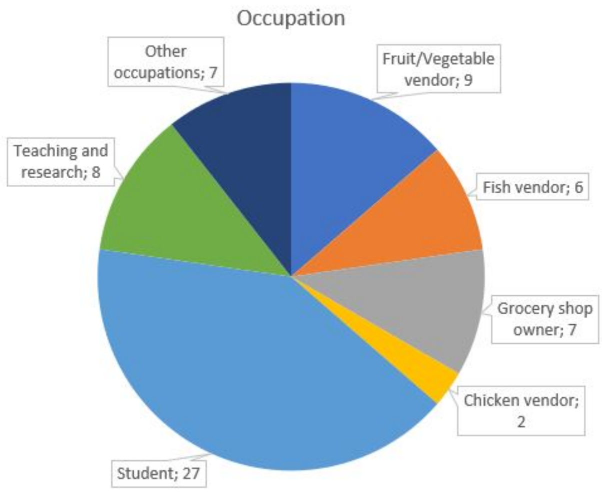



**Figure 4.5.1:** Investigation: Occupation.

In Figure 4.5.2 on page 51, the results from the question "Do you refrigerate your food?" are presented, sorted by occupation. As shown, both fish vendors and grocery shop owners generally refrigerate their food which is crucial, especially when dealing with fresh fish.

People with higher education also tend to refrigerate their food. However, none of the fruit or vegetable vendors answered that they refrigerate their food. Refrigerating fruits or vegetables is not something considered important among market agents in India, as they just don't see the need for cooling. This confirms the conditions for the previously discussed cold chains. What is very controversial is that most fruit and vegetable vendors answer that quality is the most important aspect for them when buying food, in Figure 4.5.3, yet none of them refrigerate their product to maintain the quality. The second most important aspect is the season and since cold storage of fruits and vegetables can extend the shelf life with months, depending on the product, is it interesting that none of them use it. People in general prefer quality when buying food.

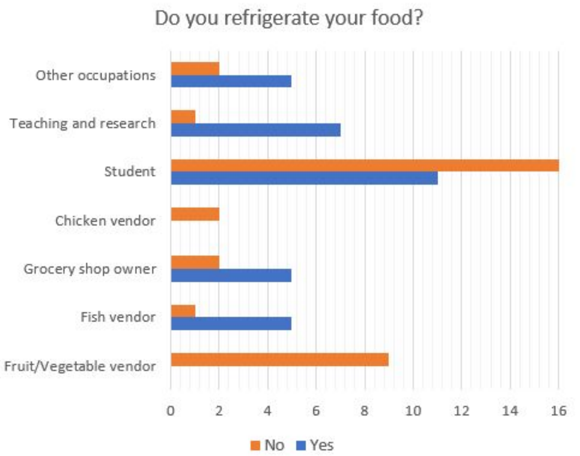



**Figure 4.5.2:** Investigation: Do you refrigerate your food?

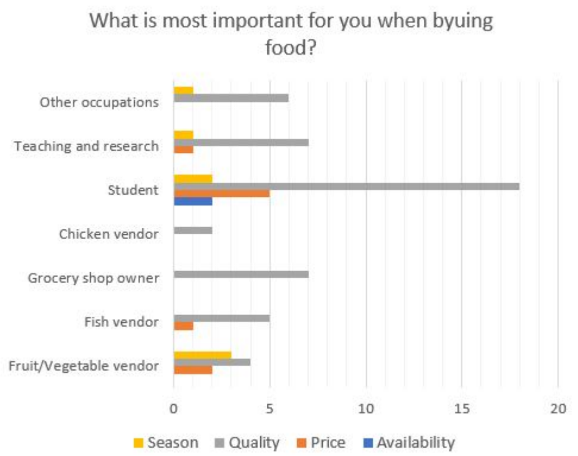



**Figure 4.5.3:** Investigation: What is most important for you when buying food?

Knowing whether people refrigerate their food or not and what they consider most important when buying food, the question "Approximately how much of your fruits and vegetables do you throw away due to deterioration or poor quality?" was asked. The results are presented, sorted by occupation, in Figure 4.5.4 on page 52. There is no clear correlation between education and reported waste. In fact, most people answer that they waste less food than what was investigated in the literature in section 2.2. Surprisingly, only two fruit/vegetable vendors reported losses of above 31%. Despite this, they are, together with students, those with the highest wastes.

Most people buy their food at small vendors or the, previously investigated, mandis, as seen in Figure 4.5.5 on page 52. In addition, many students buy their food at food stalls, canteens or restaurants. This might be a source of inaccuracy for the question "Do you refrigerate your food?", as they are not in the need of refrigerating food if they eat at canteens, food stalls or restaurants. Both fish, fruit and vegetable vendors buy their products from local distribution markets instead of directly from the farmer, which confirms the high number of intermediates in the food chain discussed in section 4.4. The local market at IIT Kharagpur is where they sell their product to most of the other people asked in the survey.

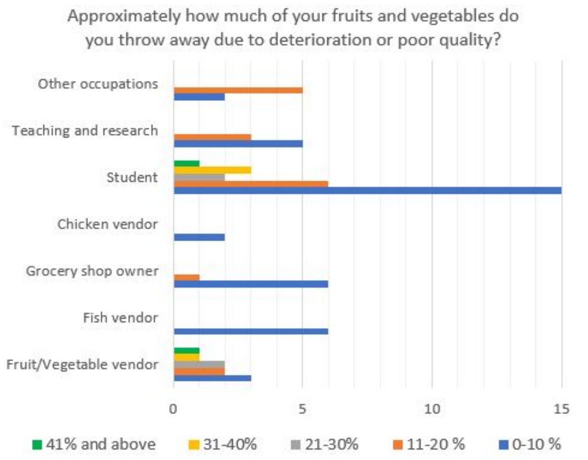



**Figure 4.5.4:** Investigation: Approximately how much of your fruits and vegetables do you throw away due to deterioration or poor quality?

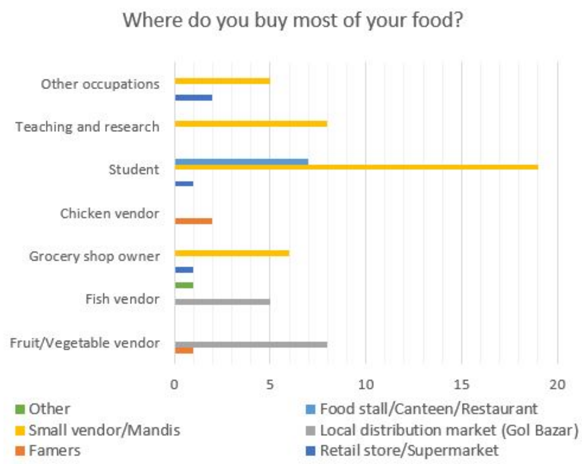
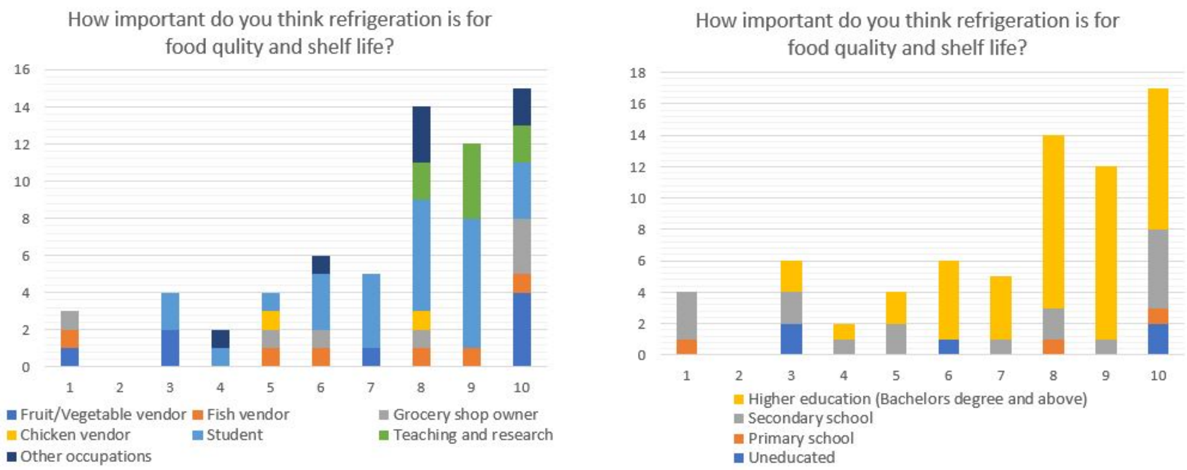



**Figure 4.5.5:** Investigation: Where do you buy most of your food?

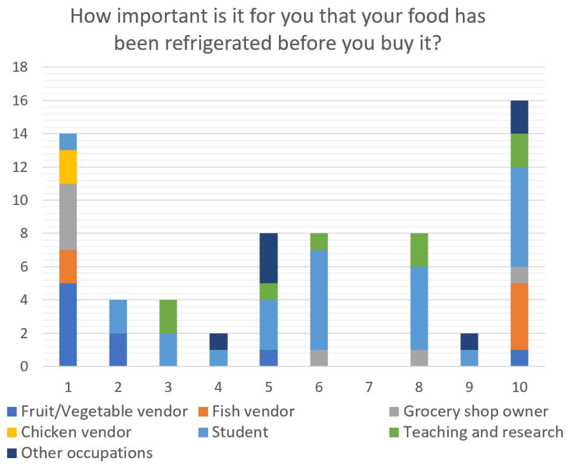
To further investigate their mindset, they were asked to, on a scale from one (not important) to ten (very important), say how important they think refrigeration is for food quality and shelf life. The results are presented in Figure 4.5.6, sorted by occupation and level of education. Those with higher education tend to understand the importance of refrigeration, while those with only secondary school or lower are more unaware. Five of the people asked were uneducated, however, two of them answered that refrigeration is very important. Out of the nine fruit and vegetable vendors asked, four answered a value of ten, while three answered an importance of three or lower.



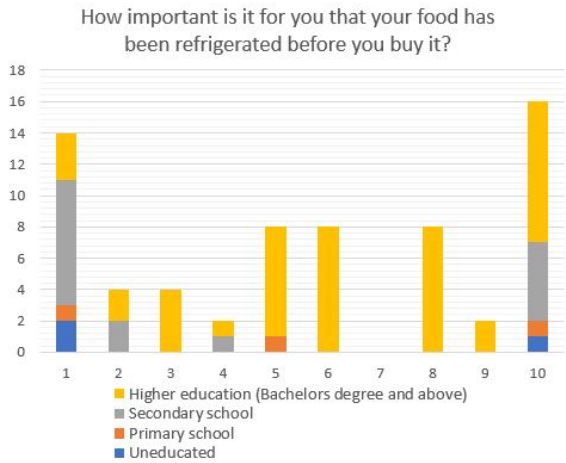

(a) Sorted by occupation. (b) Sorted by education level.

**Figure 4.5.6:** Investigation: How important do you think refrigeration is for food quality and shelf life?

On the same scale from one to ten, they were asked “How important is it for you that your food has been refrigerated before you buy it?”. The results are presented in Figure 4.5.7. The results clearly state that even though people might be aware of the importance of refrigeration, it may not be that important for them that it is refrigerated. Almost all fruit and vegetable vendors, grocery owners and chicken vendors answered that they don’t care whether the food is refrigerated before they buy it, or not. This might be one of the reasons why fruit and vegetable vendors don’t refrigerate their products. The chicken vendors are a source of inaccuracy as they buy live chickens, which are kept alive until they are sold, so they do not require refrigeration. On the other side, most fish vendors say that cooling the fish is very important for them, which is good. It is more difficult to see a relation between level of education and care for refrigeration.




(a) Sorted by occupation




(b) Sorted by education level

**Figure 4.5.7:** Investigation: How important is it for you that your food has been refrigerated before you buy it?

When asked “Do you think there should be more use of refrigeration in Indian homes?” the results, in Figure 4.5.8 on page 54, are clear. The majority of those asked agree that there should be more use of refrigeration in Indian homes. As discussed in section 2.2, domestic refrigerators are coming, but obviously, people see the need for more. This is a very good sign, as the results state that people are aware of the benefits of domestic refrigeration. However, it is interesting that most fruit and vegetable vendors think there should be more use of domestic refrigeration, when the previous results state that they neither refrigerate the food themselves, or find it important for the food they buy. When asked “If yes, what do you think is the main reason for lack of refrigeration in Indian homes?”, the results, in Figure 4.5.9 on page 54, are also evident, economy is the main reason. This confirms the problems discussed in section 2.2 and the investigated cold chains. Economical reasons might be the reason why fruit and vegetable vendors don’t use refrigeration.

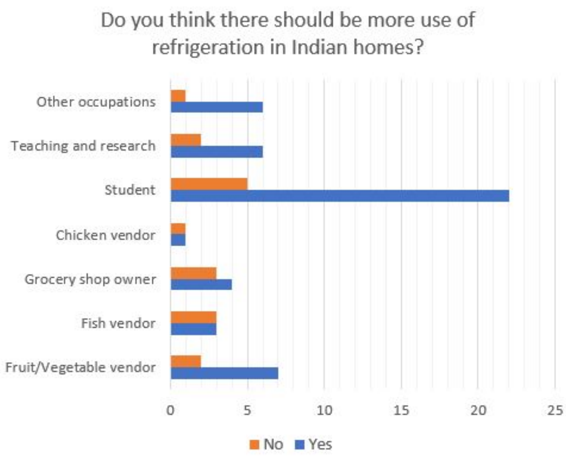



**Figure 4.5.8:** Investigation: Do you think there should be more use of refrigeration in Indian homes?

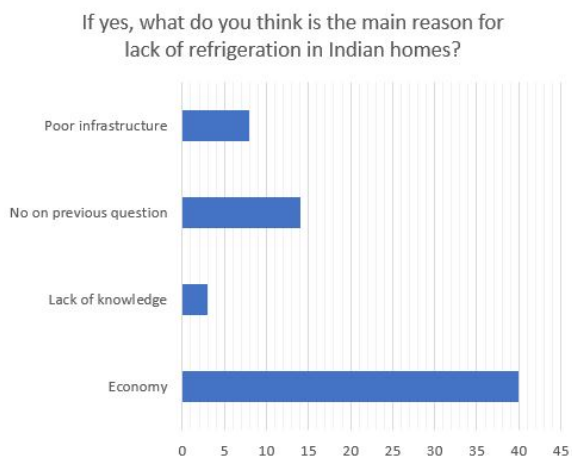



**Figure 4.5.9:** Investigation: If yes, what do you think is the main reason for lack of refrigeration in Indian homes?

People were allowed to elaborate on the answer in Figure 4.5.9 and some of the elaborations are given below. Many people highlight the economy as the main problem, as domestic refrigerators still might be too expensive for many people. However, what is interesting is that people don't consider the food as fresh if it is stored refrigerated. The last person even confirms that many people don't see the need for refrigeration, while also highlighting the costs. All this just confirms the general mindset that refrigeration is not needed.

- "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."
- "Fresh food should be preferred instead of consuming refrigerated food."
- "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."

The results above are for domestic refrigeration needs. From section 2.2, it is known that most post-harvest losses occur between production and sale. Due to this, the question "Do you think there should be more use of refrigeration between where your food is produced and to your home?" was asked and the results are presented in Figure 4.5.10 on page 55. Surprisingly, more people answer "No" here. All chicken and fish vendors, and the majority of the grocery shop owners, think the current situation is good. As mentioned, the chicken vendors operate with live animals and must be considered accordingly. Fish vendors, selling fresh fish, surprisingly don't see the need for more cooling of their product. Four out of nine fruit and vegetable vendors also answer "No" on this question.

Most students and people working within teaching and research, i.e. those with higher education, see the need for more refrigeration in the supply chain. When asked "If yes, what do you think is the main reason for the lack of refrigeration between producers and homes in India?", the results, in Figure 4.5.11, deviates from the above. Poor infrastructure is the main reason for this lack of refrigeration, although both economy and lack of knowledge score high. In other words, people are aware that the agents in the food chain just don't know why they should use refrigeration.

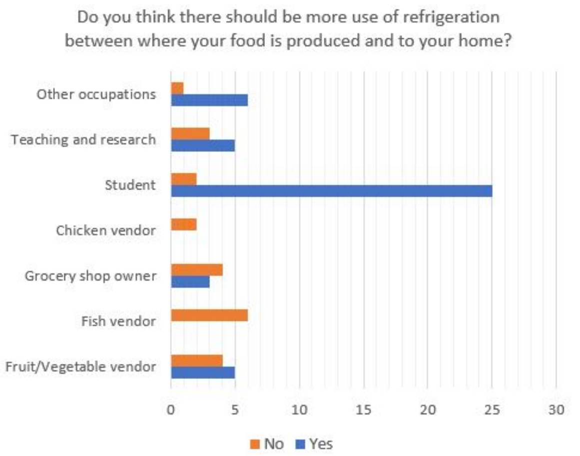



**Figure 4.5.10:** Investigation: Do you think there should be more use of refrigeration between where your food is produced and to your home?

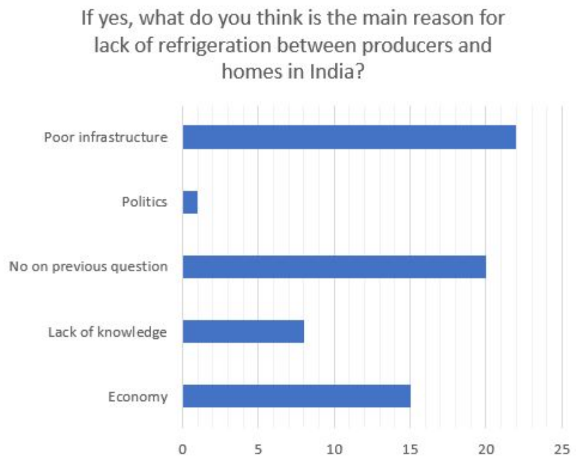



**Figure 4.5.11:** Investigation: If yes, what do you think is the main reason for lack of refrigeration between producers and homes in India?

People were also allowed to elaborate on the answer in Figure 4.5.11 and some of the elaborations are given below. Many people answered that they find the existing system and capacity sufficient, which contradicts most literature presented section 2.2. However, some are aware of the problems and highlight the lack of cold chain facilities and refrigerated trucks and minimum support from the government, which confirms the discussed problems. One person even highlights the ignorance of agents working in the food chains and the fact that they only care for profit. Many answers also focus on the costs of refrigeration and how it is too expensive for some people. The last two answers are both from fruit and vegetable vendors. Their view on the situation is very different. One of them state that he only buys the amount of goods he can sell so that he won't need to store the product refrigerated. However, the other person explicitly says that he often finds deteriorated food and that he wants, and would use, a cold storage, if it was available.

- "The demand for cooling is met in the market. Demand and supply is equal."
- "The existing system is sufficient."
- "Lack of proper cold chain facilities and availability of electricity."

- "Refrigerated trucks are scarce. Economy is a major factor."
- "In my locality from where I belong, no cold storage facility is available nearby 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 organisations in increasing the awareness and developing the infrastructure."
- "Since the producers and the sellers only care of profits, they don't care of what should be done in between."
- "The cost of using refrigeration adds to the price of vegetables and fruits which might turn away people from purchasing it."
- "Many times i find deteriorated food at the place i am buying it. There is no refrigeration which makes a lot of food go bad. If a cold storage would be made available to me I would use it, I want it."
- "I buy the capacity for the day and sell that amount."

## 4.6 Cold storage at Indian mandis

Based on the investigation of the different cold chains and the answers in the survey at IIT Kharagpur, improving the food quality and shelf life by introducing a cold storage at the mandis, seems like a good solution to a much needed problem. The mandis is in great need for modernisation and cold chain facilities are among the most needed improvements. Such a system could be beneficial for smaller markets as well. One problem with cold storage facilities at mandis' is the costs. They might be to expensive for the agents at the mandis or the market. It is therefore important that the cold storage is cost-effective, easy to maintain and operate and energy efficient.

A cold storage that is movable would be very flexible, as it could come to the seller, instead of having the seller come to the storage. By designing a cold storage the size of a container, it could either be moved by a large truck or it could be designed as a trailer to be attached to a vehicle and moved around. A problem that might arise when it is movable is the energy source. Should it rely on an external electrical input or should it produce its own power through a solar panel? The power supply in India is very unstable and varying, and a renewable power source would be beneficial for both the environment and the flexibility of the storage. However, the costs would increase and power would become a problem at nighttime with a solar panel. Therefore, the most cost-effective alternative would be to make it dependent on an external electrical input and skip the solar panels. The storage should not be in operation during transport, it should only be powered when stationary.

From section 2.3, it is known that India is going through a comprehensive plan to phase out HCFCs and HFCs, so use of natural refrigerants should be in focus. Ammonia is a refrigerant used for a long time in India, but there are uncertainties around its safety. By using ammonia as primary refrigerant in combination with a secondary refrigerant, it is possible to contain the ammonia to the machine room. Hence, ammonia pipes would never be in contact with food or the food storage room. It would still require proper training for service and maintenance personnel to operate the ammonia refrigeration system. A potential secondary, natural refrigerant is $CO_2$. $CO_2$ has many advantages when used as secondary refrigerant, highlighted in section 2.5. It is not toxic, nor flammable, it is environmental friendly and considered among the safest refrigerants. In addition $CO_2$ can be used in both natural and forced circulation loops.

The refrigeration system should be cost-effective, efficient and easy to control and maintain. Using a single stage ammonia refrigeration system is a cost-effective and efficient solution. The possibility of having $CO_2$ in a NCL should be further investigated, to avoid distributing ammonia to the storage space. Having a multi-commodity storage will increase the flexibility and allow storage of multiple groups investigated in section 3.5. However, it is uncertain whether or not the people at the market would use this correctly. The different agents using the storage are probably not educated in correct use of the storage and would store whatever food they have wherever it is available space, without taking concern to the products storage requirements. The results from the survey at IIT Kharagpur also indicate that knowledge about proper storage might be scarce. In addition, having separate storage spaces would decrease the capacity and increase the complexity of the refrigeration system and consequently increase the costs. Hence, the storage will be designed with one large storage space.

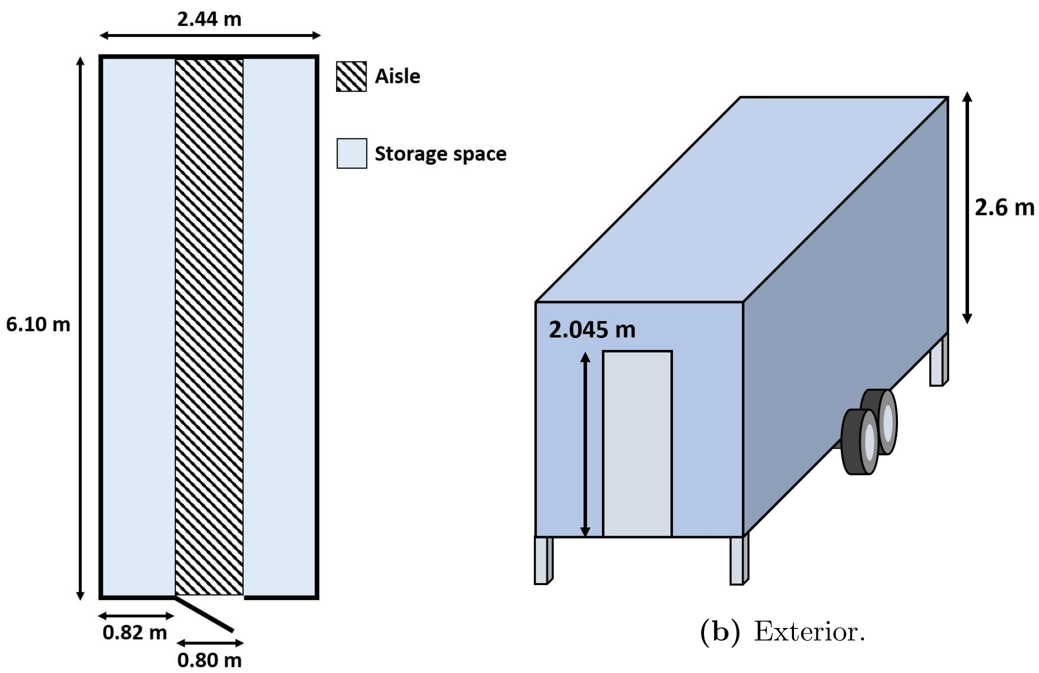
### 4.6.1 Layout

The cold storage is designed as a trailer, on wheels, to make it movable. This will eliminate the need for a crane when placing the storage at the desired location. The size will be according to the ISO shipping container sizes, respectively the standard 20ft shipping container. Anything larger will be difficult to transport by road in India. The specific sizes can be found in Table 4.6.1 on page 58. The given measures are without insulation.

| | Length | Width | Height |
|---|---|---|---|
| **Exterior** | 6.10 m | 2.44 m | 2.60 m |
| **Interior** | 5.87 m | 2.34 m | 2.38 m |

**Table 4.6.1:** ISO 20ft shipping container standards (Container Solutions 2019).

The cold storage layout is illustrated in Figure 4.6.1. Measures are given for the exterior size. The aisle spans the entire length of the cold storage and is the same width as the door. This is to ensure access to all commodities. Storage space is alongside each wall, from floor to roof. The machine room, with required equipment, is assumed to be placed on top of the storage to maximise the available storage space. This will shield the storage from some sunlight, though refrigeration load calculations are performed with sun exposure on the entire roof. The door is assumed to be facing north. Loading of the storage is assumed to happen evenly during the first week. The storage is then assumed to be fully loaded until the last day of the month the products are sold.

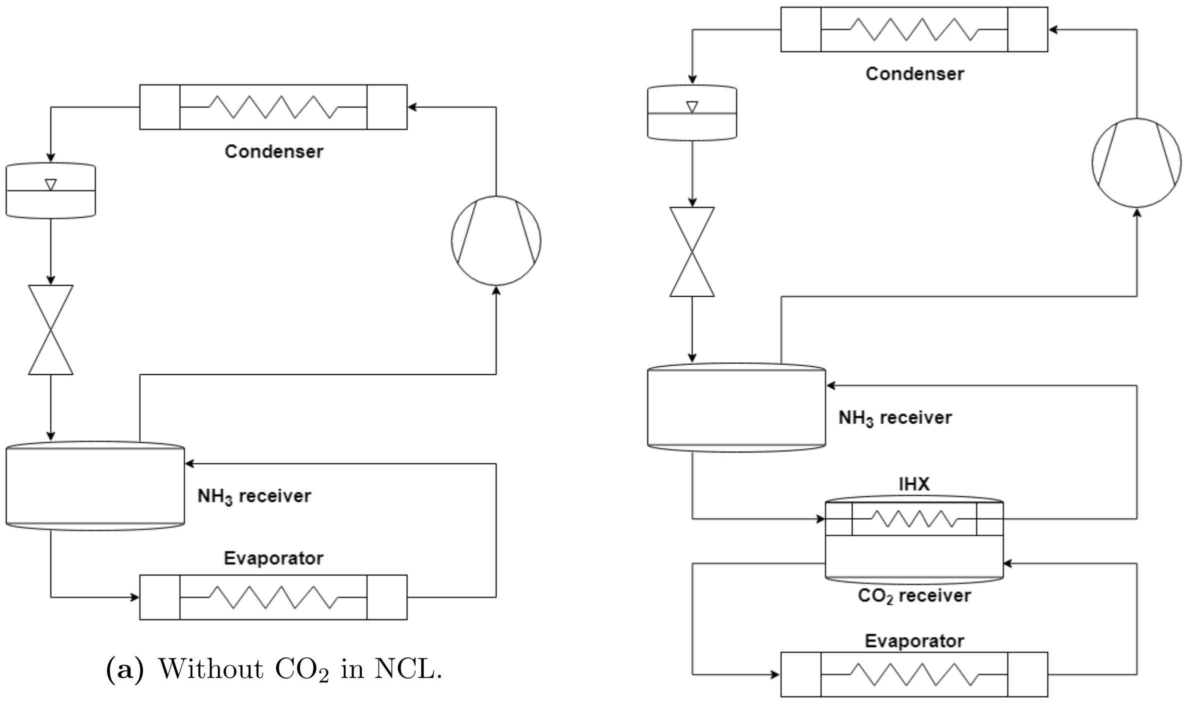



**(a)** Interior.

**(b)** Exterior.

**Figure 4.6.1:** Cold storage layout.

The refrigeration systems investigated in this thesis are a single stage vapour compression cycle, using ammonia as working fluid, with and without $CO_2$ in a Natural Circulation Loop (NCL). The two configurations investigated are illustrated in Figure 4.6.2 on page 59.




**(a)** Without $CO_2$ in NCL.

**(b)** With $CO_2$ in NCL.

**Figure 4.6.2:** Single stage ammonia refrigeration system.

Since the machine room is assumed to be on top of the storage, the NCL should have sufficient height to function. Heat is transferred from the refrigerated space to the NCL. The $CO_2$ will then partly or fully evaporate and its density will decrease. The resulting buoyancy force will drive the $CO_2$ from the evaporator and up to the $CO_2$ receiver in the machine room, which also acts as the IHX. Here, the $CO_2$ transfer the heat to the ammonia refrigeration system and condenses. This denser, liquid $CO_2$, flows down to the evaporator due to gravity. This way, heat can be transferred from the refrigerated space, to the machine room, without any need for pumping power. It is important that the evaporator is located below the $CO_2$ receiver/IHX for this to work.

Changing the evaporation temperature of $CO_2$ in the NCL requires changing the pressure in the loop, which is impossible without adding another compressor. Consequently, the NCL must be designed to keep a constant pressure and temperature level regardless of the room temperature. Matching this level to apples and grapes, which have similar storage conditions, is possible, but problems will arise when storing mangoes at 13°C. When mangoes are in storage, the evaporator will operate with a temperature difference much larger than what is necessary and the efficiency of the system will decrease. Using natural circulation loops can be beneficial for conditions requiring a constant temperature, but in this case, where the room temperature varies, it is more difficult. Despite the inhibitors, performance of the system with the NCL will be investigated.

### 4.6.2 Revenue

One challenge is justifying the increased price because the products are stored chilled. Many fruits and vegetables are available for large periods of the year, so why should someone buy the refrigerated product, when they can buy it farm fresh at a cheaper price somewhere else? The obvious reason is the increased food quality and safety as the deterioration rate is decreased. However, this might not be enough to justify the higher cost. For people to understand the importance of storing food properly, there is a need for change at a deeper level. People need to understand that this helps reduce the post-harvest waste, feeds more people, helps the environment, and is a step in the right direction for India as the world's second largest fruit and vegetable producer. The agriculture is a backbone in India's economy and India is a backbone in the world's horticulture production, but most of the population are unaware of the importance of cold storages and cold chains. For people to change their mindset, it will probably require changes on a political level. However, India is a low-income country with great diversity and many different opinions, so this might be very difficult.

One reason for storing fruits and vegetables is to provide supply of the product off-season. Considering the average wholesale prices for the selected crops discussed in chapter 3, in addition to the storage life and conditions in Table 3.5.1, apples, grapes and mangoes are regarded as most ideal for storage. The average wholesale price for the last four years for apples, grapes and mangoes are presented in the same diagram, Figure 4.6.3. The solid part of each graph illustrates where storage would be economically ideal.

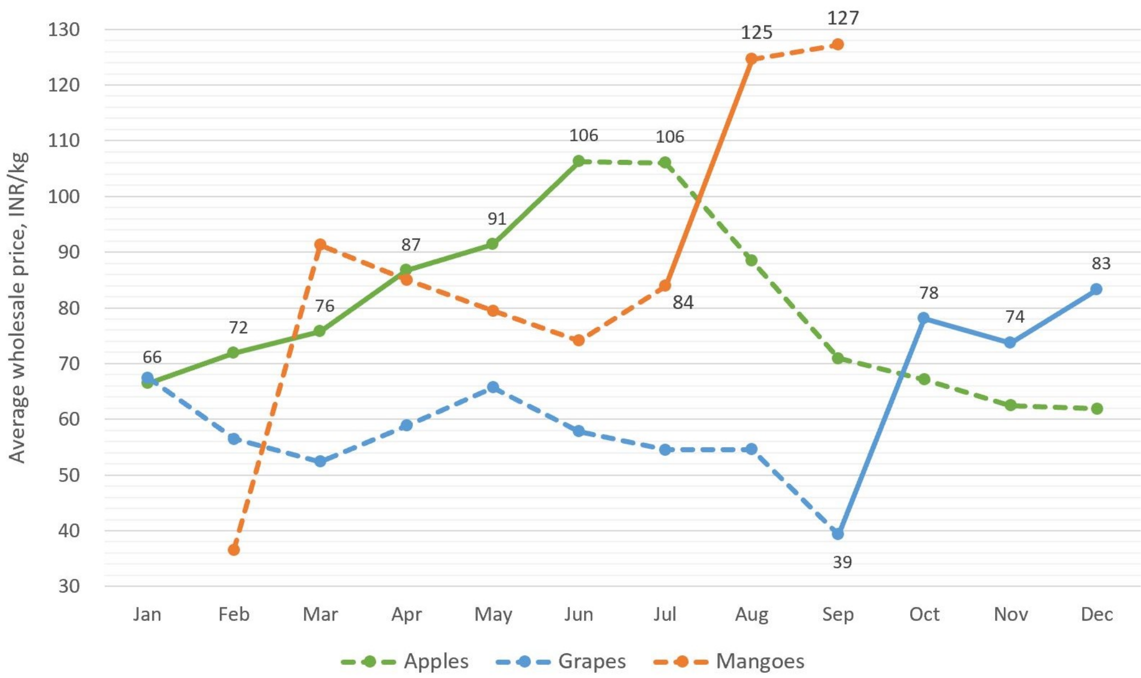



**Figure 4.6.3:** Monthly average wholesale price for apples, grapes and mangoes (NHB 2019b).

Apples are 66 INR/kg in January, can be stored for up to 6 months and sold for 106 INR/kg in June. Mangoes are 84 INR/kg in July, can be stored for up to 3 weeks and sold for 125 INR/kg in August. Grapes are 39 INR/kg in September, have a storage life of up to 6 months and can be sold for 83 INR/kg in December. Storing apples from January to June, mangoes from July to August and grapes from September to December could be economically feasible and would provide supply of the products to the market when the availability is low. Though it might be impossible to store mangoes from July to August, considering their storage life of three weeks, the storage should be loaded consecutively if possible while the price is low.

The season for apples end in November and sufficient supply to load the storage in January might be difficult. Figure 4.6.4 shows the monthly supply of apples from Jammu and Kashmir for the last four years. During the harvest season, the monthly supply is very high. The average supply of apples in January is above 70 000 tonnes and it should not be a problem to load a small cold storage.

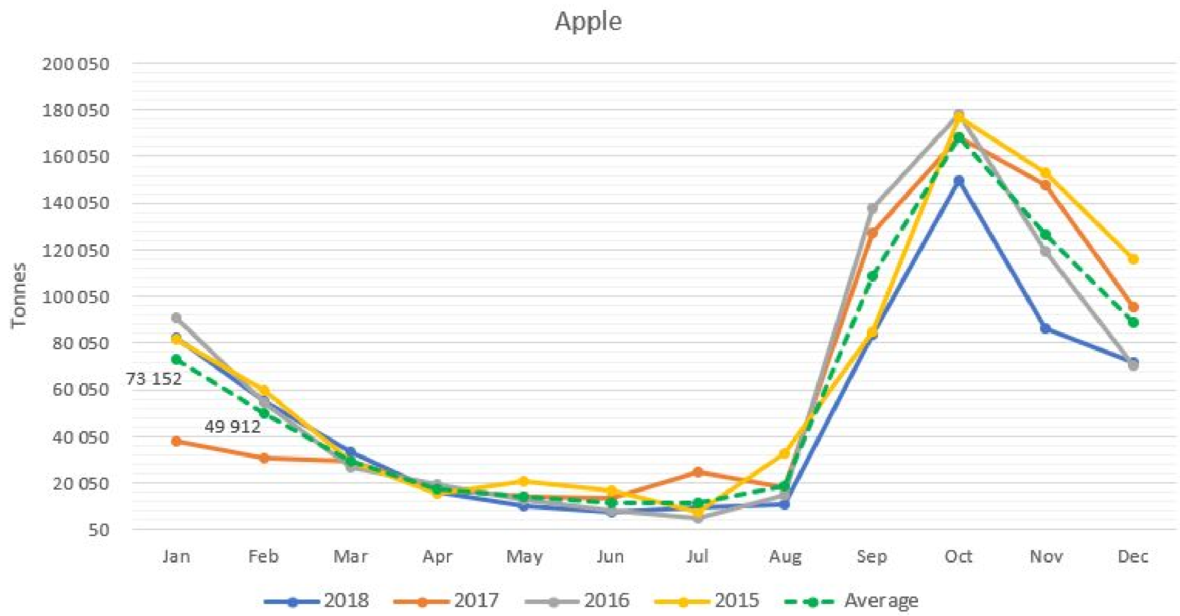



**Figure 4.6.4:** Monthly supply of apples (NHB 2019b).

The season for grapes end in July and sufficient supply to load the storage in September might be difficult. Figure 4.6.5 on page 62 shows the monthly supply of grapes for the last four years. Most of the supply is during the harvest season in Maharashtra and Karnataka, in December to May, as they produce 98% of all grapes in India. The supply in the remaining months are relatively low. The average supply in August, September and October is 259, 189 and 579 tonnes, respectively. Seasonal variations might make it impossible to load the storage with grapes in September, which again might be a reason for the unusually low average price. Still, the average supply in September is 189 tonnes and loading of the storage this month is assumed possible.

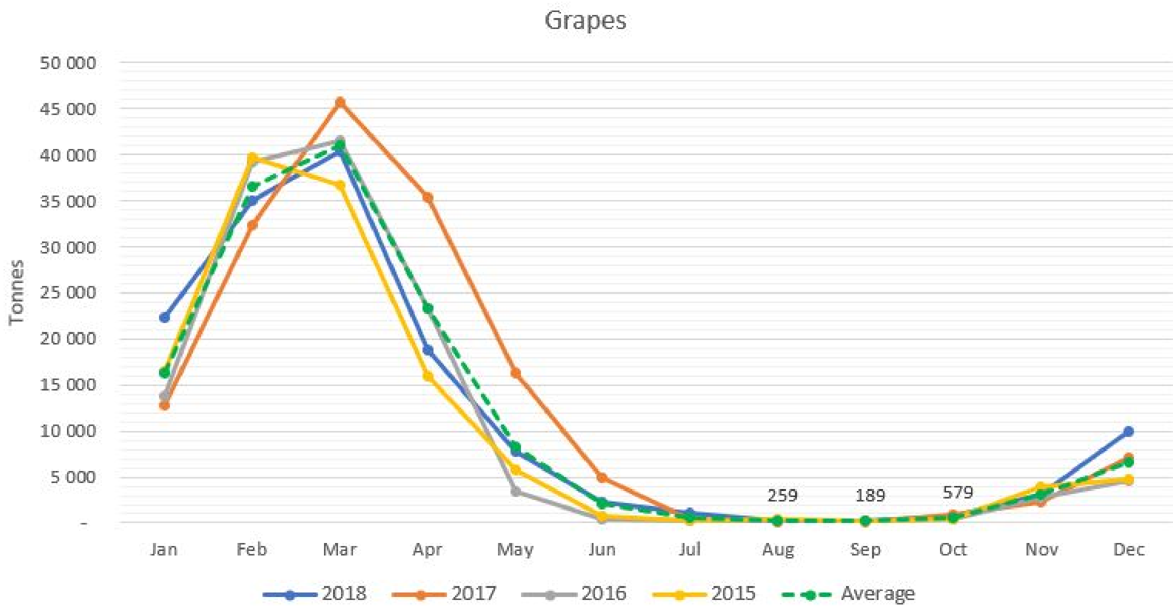



**Figure 4.6.5:** Monthly supply of grapes (NHB 2019b).

The season for mangoes end in July and sufficient supply to load the storage should be available. Figure 4.6.6 on page 63 shows the monthly supply of alphonso mangoes for the last four years. Early in the harvest season, especially in 2016, the monthly supply is high. There is no supply of mangoes from October to January and supply of mangoes in August and September only happened in 2018, which explains the increase in price these months. It seems to be a steady supply of mangoes in July, with an average of above 20 000 tonnes and loading the storage should not be a problem. In addition, the longer the mango is stored with acceptable quality after July, the higher price it can be sold for.

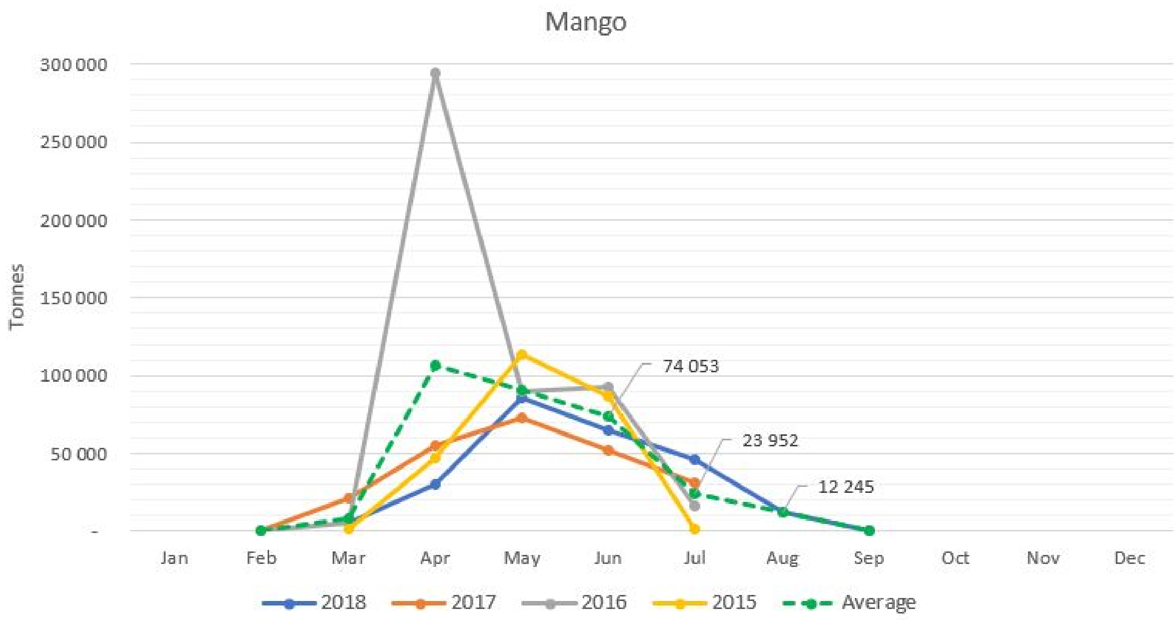



**Figure 4.6.6:** Monthly supply of mangoes (NHB 2019b).

If the average supply of apples, grapes and mangoes stays relatively constant the coming years, it should be possible to operate a cold storage with these three commodities through the entire year. Table 4.6.2 shows a summary of the logistics and revenue for storing these fruits.

| Commodity | Loading | Cost | Storage time | Selling | Income | Profit |
|---|---|---|---|---|---|---|
| Apples | January | 66 INR/kg | 6 months | June | 106 INR/kg | 40 INR/kg |
| Mangoes | July | 84 INR/kg | 2 months | August | 125 INR/kg | 41 INR/kg |
| Grapes | September | 39 INR/kg | 4 months | December | 83 INR/kg | 44 INR/kg |

**Table 4.6.2:** Cold storage logistics and revenue.

Loading is assumed to happen during the first week of the month or as soon as sufficient supply of the respective commodity is available. Sale of the product will happen consecutively through the respective month or in earlier months if the product degrades sooner. Mangoes might be impossible to store for two months, so the storage should be refilled when possible, if the price is low. Calculations are performed for full storage until the last day of the month for all products. The profit is calculated as the difference between the wholesale price when loading and when selling. This is a conservative approach considering that agents at wholesale markets buys the product from distribution markets, merchants or other agents at a lower price than the wholesale price that given month. The profit might, in reality, be larger than listed here. The revenue is relatively equal for the commodities, where grapes have the highest price increase, with 44 INR/kg from September to December. Investigating the monthly profit reveals that mangoes increase with 20.5 INR/kg per month, making it the most valuable product. Apples have about 6.7 INR/kg and grapes 11 INR/kg increase per month.

### 4.6.3 Assumptions

**Ambient temperatures:**

Ambient temperatures are used according to the daily temperatures provided in Figure 4.6.7. Product loading temperatures are equal to the ambient conditions at the day of loading.

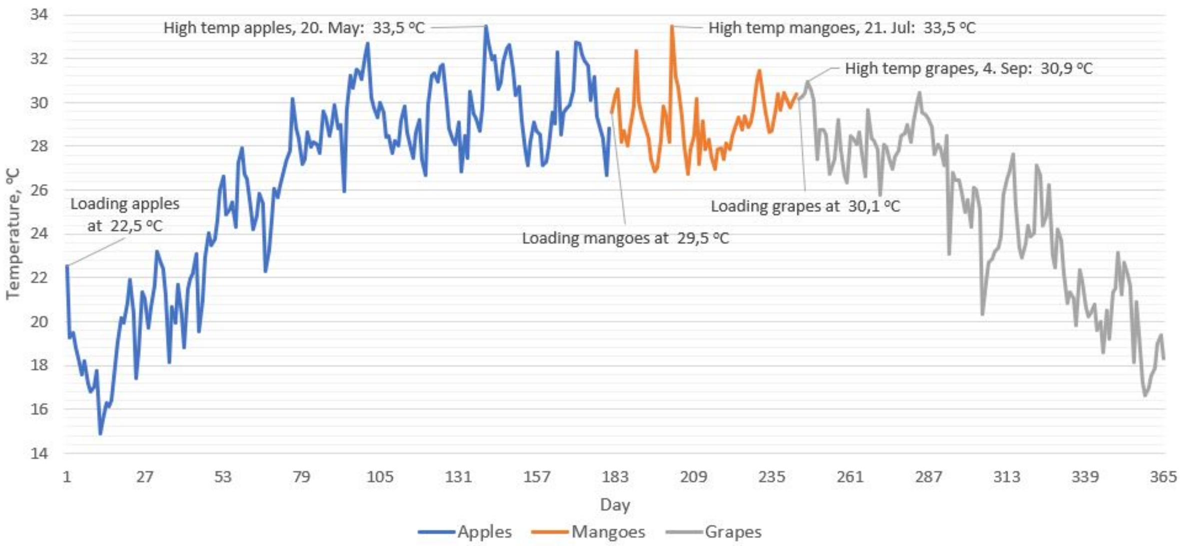



**Figure 4.6.7:** Daily average temperatures in Kolkata year 2005 (Meteotest Genossenschaft 2005).

**Products and temperatures:**

- Apples are stored at -0.5°C room temperature.
- Grapes are stored at -0.5°C room temperature.
- Mangoes are stored at 13°C room temperature.
- All products are loaded at the ambient temperature the respective day.

**Storage density:**

Compact storage with 200 $kg/m^3$ density (IIR 1993).

**Loading rate and pull down time:**

The storage is loaded with with 1/7 of the total capacity each day, over a period of 7 days, to reduce the pull down load. The storage should reach optimal temperature within 24 hours after each loading.

**Door:**

Size is chosen for pressed steel doors according to manual by CPWD (2006), where width and height are 0.8 m and 2.045 m, respectively. Insulation is equal to the wall insulation. The door is opened once a day to check on the stored product. Open-close time is set to 30 seconds. It is assumed to stand open for 5 minutes when checking the product, and for 1 hour when loading. Strip curtains are installed to inhibit air flow through open door, with effectiveness of E=0.9 (ASHRAE 2018).

**Ventilation:**

The storage should be properly ventilated to remove excess ethylene. The heat gain from ventilation is, however, negligible in such a small cold storage and ventilation is not regarded any further.

**Equipment:**

Equipment loads are set to contribute 10% of the holding load.

**Heat exchangers:**

- Evaporator: Forced air finned coil evaporator. A fin spacing of 3 mm is used (Grundfos 2019). Fin thickness is neglected in further calculations. A tube spacing of 25 mm is used.
- Intermediate Heat Exchanger (IHX): Cascade heat exchanger with the $NH_3$ evaporator inside the $CO_2$ receiver.
- Condenser: Geometry and area are not considered in this thesis. Temperature difference is set constant to 5°C.

**Compressors:**

Compressor efficiency will vary with the pressure ratio over the compressor, which again is dependent on evaporator and condenser temperature. Studying varying compressor efficiency is not considered as a relevant goal in this thesis and efficiency is therefore set constant as $\eta = 0.8$, according to the isentropic efficiency chart, Figure A.3.1 in Appendix A.

**Insulation:**

Expanded polystyrene (R-142b) is used. Thermal conductivity, $k_{ins} = 0.037\ ^{W}/_{mK}$. Thickness, $\delta_{ins} = 75$ mm (ASHRAE 2018).

**Walls, roof, floor:**

Exterior and interior walls, roof and floor are (corrugated) sheet metal. Thickness and thermal conductivity are negligible. Exterior walls and roof are painted in a light colour.

**Sun allowance:**

Heat gain due to sun radiation is included according to Table 5.2.1 on page 68 for light-coloured surfaces.

**Safety factor:**

A safety factor of 10% is included in refrigeration loads.

# Chapter 5

# Method

## 5.1 Highlights

In this chapter, methods for the different calculations made when designing the cold storage and refrigeration system are discussed. First the relevant equations and information to calculate the refrigeration loads are presented. Then the method used to design both refrigeration systems are discussed, before the method for heat exchanger calculations are investigated and presented. At last, pressure losses through the NCL are discussed.

## 5.2 Refrigeration load calculation

### 5.2.1 Transmission loads

This is the heat loss related heat transmission through the walls, roof and floor of the refrigerated space. The transmission load is usually the largest load and can be calculated as:

$$\dot{Q}_T = UA(T_{amb} - T_R) \tag{5.2.1}$$

where $A$ is the surface area, $T_{amb}$ is ambient temperature and $T_R$ is the cold storage room temperature. $U$ is the heat transfer coefficient, defined as:

$$U = \frac{k_{ins}}{\delta_{ins}} \tag{5.2.2}$$

where $k_{ins}$ and $\delta_{ins}$ are the thermal conductivity and thickness of the insulation, respectively. The solar irradiation will influence the transmission through the wall. To compensate for the solar irradiation, a sun-air temperature difference, $\Delta \mathrm{T}_{\mathrm{sun}}$, is added, depending on the direction the wall is facing and the type of surface. The sun-air temperature differences are shown in Table 5.2.1.

| Typical surface types | East/West wall, K | South wall, K | Flat roof, K |
|---|---|---|---|
| Dark-coloured surfaces: Slate or tar roofing, black paint | 5 | 3 | 11 |
| Medium-coloured surfaces: Unpainted wood, brick, red tile, dark cement, red, gray, green paint | 4 | 3 | 9 |
| Light-coloured surfaces: White stone, light coloured cement, white paint | 3 | 2 | 5 |

**Table 5.2.1:** Allowance for sun effect (ASHRAE 2018).

Instead of using the ambient temperature in Equation 5.2.1, the wall temperature, $T_{\mathrm{wall}}$, must be used:

$$T_{wall} = T_{amb} + \Delta T_{sun} \tag{5.2.3}$$

### 5.2.2 Infiltration loads

Infiltration loads are the heat gains from infiltrating air. When opening the door, there will be air flow between the refrigerated room and the ambient. Heat load through doorways from air exchange is as follows (ASHRAE 2018):

$$\dot{Q}_D = \dot{Q}_S D_t D_f (1 - E) \tag{5.2.4}$$

where $\dot{Q}_S$ is the sensible and latent refrigeration load due to air exchange. For fully established flow, it is:

$$\dot{Q}_S = 0.221 A_D (h_{amb} - h_R) \rho_R \left(1 - \frac{\rho_{amb}}{\rho_R}\right)^{0.5} (g H_D)^{0.5} F_m \tag{5.2.5}$$

where $g$ is the gravitational constant, $A_D$ and $H_D$ are the doorway area and height, $h_{amb}$ and $\rho_{amb}$ are the ambient air enthalpy and density and $h_R$ and $\rho_R$ are the cold storage room air enthalpy and density, respectively. $F_m$ is the density factor, defined as:

$$F_m = \left( \frac{2}{1 + \left(\frac{\rho_R}{\rho_{amb}}\right)^{\frac{1}{3}}} \right)^{1.5} \tag{5.2.6}$$

For a cyclical, irregular, and constant door usage, alone or in combination, the doorway open-time factor, $D_t$, can be calculated as:

$$D_t = \frac{N\Theta_p + 60\Theta_o}{3600\Theta_d} \tag{5.2.7}$$

where $\Theta_d$ is the daily time period, $\Theta_o$ is the time the door simply stands open, $\Theta_d$ is the door open-close time and $N$ is the number of doorway passages. Typical time, $\Theta_p$, for conventional pull-cord-operated doors are from 15-25 seconds per passage (ASHRAE 2018). $\Theta_o$ and $\Theta_d$ varies with the usage.

The doorway flow factor, $D_f$, is the ratio of actual air exchange for fully established flow. This is dependent on the temperature difference between the refrigerated room and the ambient. The respective values are presented in Table 5.2.2.

| $\mathbf{T_{amb}}$ **-** $\mathbf{T_R}$ | $\mathbf{D_f}$ |
|---|---|
| $< 11$ | 1.1 |
| $> 11$ | 0.8 |

**Table 5.2.2:** Doorway flow factor (ASHRAE 2018).

The effectiveness of doorway protective device, $E$, is 0.95 or higher for newly installed strip, fast-fold, and other non-tight-closing doors (ASHRAE 2018).

### 5.2.3 Product loads

Product loads are the heat loads related to the products kept in storage. This may either be due to the product entering the cold storage at a higher temperature than the storage, or due to respiration heat generated by the stored products. The load required to cool the product from the initial temperature, to a room temperature above the freezing point is (ASHRAE 2018):

$$Q_P = \frac{mC_P(T_i - T_R)}{3600t} \tag{5.2.8}$$

where $m$ and $C_P$ are the mass and specific heat capacity of the product, respectively. $T_i$ is the initial loading temperature and $T_R$ is the cold storage room temperature. $t$ is the time, in hours, required for the product to reach the room temperature. The specific heat capacity for the investigated products are listed in Table 5.2.3. The values apply to mature products shortly after harvest.

| Product | $C_P$, $^{kJ}/_{kgK}$ |
|---|---|
| Apple | 3.81 |
| Grape | 3.70 |
| Mango | 3.74 |

**Table 5.2.3:** Specific heat capacity above freezing for selected fresh fruits (ASHRAE 2018).

The heat of respiration for the selected fruits, at selected temperatures, are shown in Table 5.2.4. The respiration close to the freezing point is unavailable due to the temperature being borderline to damaging the food. The listed heat of respiration is not constant and, as some values indicate, it might vary over a given range for the same temperature. Foods are living things and properties will vary between each single fruit or vegetable. Young, actively growing tissues or fast-developing fruits have a high heat of respiration. Slow developing crops however, have lower heat of respiration. Additionally, the first one or two days after harvest, the heat of respiration will be high, but within a few days it will stabilise at a lower equilibrium value. Crops that ripen in storage function the opposite way, they will increase in respiration rate as they ripen.

| Product | Temperature, °C | Heat of respiration, $^{mW}/_{kg}$ |
|---|---|---|
| Apple, Delicious | 0 | 10.2 |
| | 5 | 15.0 |
| Grape, Thompson seedless | 0 | 5.8 |
| | 5 | 14.1 |
| Mango | 15 | 133.4 |
| | 20 | 222.6-449.1 |

**Table 5.2.4:** Heat of respiration for selected fresh fruits (ASHRAE 2018).

### 5.2.4 Equipment loads

There might be other refrigeration equipment contributing to the total refrigeration load, like:

- Fan motors when forced-air circulation is used.
- Heat from defrosting of evaporators. This can be done by hot-gas defrost, electricity

defrost or water defrost. Water defrost produces the least amount of load, while electricity defrost contributes most to the refrigeration load.

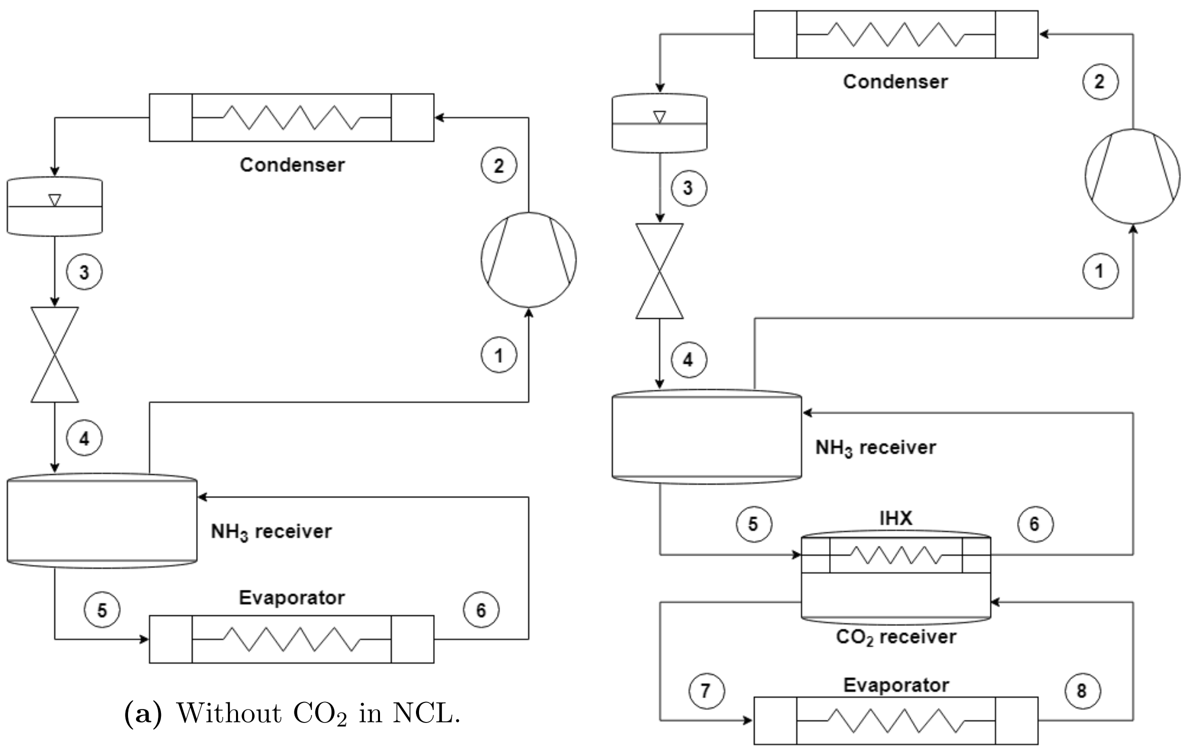
At refrigeration temperatures above -1°C, equipment loads usually contribute about 5% of the total refrigeration load. At lower refrigeration temperatures, like -30°C, this part can become as high as 15%, or more, of the total refrigeration load (ASHRAE 2018).

### 5.2.5 Safety factor

When calculating the total refrigeration load, it is very common to add a safety factor to allow for possible discrepancies between the design and the actual operation. This factor will vary depending on the quality of the cold storage, but generally, a safety factor of 10% of the total refrigeration load is used (ASHRAE 2018).

## 5.3 Refrigeration cycle calculations

The refrigeration systems investigated in this thesis are a single stage vapour compression cycle, using ammonia as working fluid, either combined with $CO_2$ in a NCL or without. The two configurations, with state points, are illustrated in Figure 5.3.1.




**(a)** Without $CO_2$ in NCL.

**(b)** With $CO_2$ in NCL.

**Figure 5.3.1:** Single stage ammonia refrigeration system.

Looking at the ammonia system in Figure 5.3.1a, the heat absorbed in the evaporator is given as:

$$\dot{Q}_e = \dot{m}_e \cdot (h_6 - h_5) \tag{5.3.1}$$

where $\dot{m}_e$ is the mass flow through the evaporator and $h$ is the enthalpy. $\dot{Q}_e$ is equal to the total refrigeration load, $\dot{Q}_L$. Adding the NCL in Figure 5.3.1b, the heat absorbed by the $CO_2$ in the evaporator is given as:

$$\dot{Q}_e = \dot{m}_e \cdot (h_8 - h_7) \tag{5.3.2}$$

The heat transferred from the $CO_2$ NCL to the ammonia system in in the IHX is given as:

$$\dot{Q}_{IHX} = \dot{m}_{NH_3} \cdot (h_6 - h_5) = \dot{m}_{CO_2} \cdot (h_8 - h_7) \tag{5.3.3}$$

where $\dot{m}_{NH_3}$ and $\dot{m}_{CO_2}$ are the mass flows of $NH_3$ and $CO_2$ through the IHX, respectively. The energy balance over the $NH_3$ receiver can be expressed as:

$$\begin{gathered} \dot{Q}_{in} = \dot{Q}_{out} \\ \dot{m}_4 h_4 + \dot{m}_6 h_6 = \dot{m}_1 h_1 + \dot{m}_5 h_5 \end{gathered} \tag{5.3.4}$$

The relations between the real compressor work, $\dot{W}$, the isentropic compressor work, $\dot{W}_{is}$, and the isentropic compressor efficiency, $\eta_{is}$, is given as:

$$\dot{W}_{is} = \dot{m}_c \cdot (h_{2s} - h_1) \tag{5.3.5}$$

$$\dot{W} = \dot{m}_c \cdot (h_2 - h_1) \tag{5.3.6}$$

$$\eta_{is} = \frac{\dot{W}_{is}}{\dot{W}} = \frac{\dot{m}_c \cdot (h_{2s} - h_1)}{\dot{m}_c \cdot (h_2 - h_1)} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{5.3.7}$$

where $\dot{m}_c$ is the mass flow through the compressor and condenser. The isentropic compressor efficiency can often be found in tables or graphs, if the compressor pressure ratio, $\pi$, is known

$$\pi = \frac{P_2}{P_1} \tag{5.3.8}$$

Further, the heat rejected in the condenser, $\dot{Q}_c$ is given as:

$$\dot{Q}_c = \dot{m}_c \cdot (h_2 - h_3) \tag{5.3.9}$$

Finally, the COP can be calculated:

$$COP = \frac{\dot{Q}_e}{\dot{W}} \tag{5.3.10}$$

where $\dot{W}$ is given in Equation 5.3.6 and $\dot{Q}_e$ is given in Equation 5.3.1 or Equation 5.3.2, depending on the system configuration. The maximum theoretical efficiency, the Carnot Coefficient of Performance ($\mathrm{COP_{Ca}}$), is given as:

$$COP_{Ca} = \frac{T_R}{T_{amb} - T_R} \tag{5.3.11}$$

where $T_R$ is the storage room air temperature and $T_{amb}$ is the ambient air temperature.

## 5.4 Heat exchanger calculations

The heat exchanger design equation is given as (Eikevik 2018):

$$\dot{Q} = UA\Delta T \tag{5.4.1}$$

where $U$ is the heat transfer coefficient, $A$ is the heat transfer area and $\Delta T$ is the temperature difference between the hot and cold fluid in the heat exchanger. Equation 5.4.1 can be modified in order to calculate the required heat exchanger are as:

$$A = \frac{\dot{Q}}{U\Delta T} \tag{5.4.2}$$

If the temperature of one, or both, fluids change between inlet and outlet of the heat exchanger, the Logarithmic Mean Temperature Difference (LMTD) have to be used:

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{5.4.3}$$

where $\Delta T_1$ is the temperature difference between the two fluids at end 1 of the heat exchanger and $\Delta T_2$ is the temperature difference between the two fluids at end 2 of the heat exchanger.

The overall heat transfer coefficient, U, for a given heat exchanger is often determined empirically, but typical ranges of U-values for various heat exchangers and fluid combinations are available in literature. Typical U-values for selected heat exchangers are given in Table 5.4.1.

| Heat exchanger | U, $W/m^2K$ | Note |
|---|---|---|
| Forced air finned coils | 12-25 | Air velocity 2-4 $m/s$ |
| Cascade, $NH_3$ evaporator inside $CO_2$ receiver | 2 500 | |

**Table 5.4.1:** Typical heat transfer coefficients for selected heat exchangers (Eikevik 2018).

## 5.5 Natural circulation loop pressure loss

The driving force in a NCL is the difference between the pressure in the downcomer and the riser. This driving force will be influenced by the sum of the pressure losses through the downcomer, evaporator and riser. An illustration of the NCL is presented in Figure 5.5.1. There will be two major losses through the pipes, the static pressure losses and the head losses. The static loss is the pressure loss (or increase in the downcomer) when the fluid changes relative height. The head loss can be separated into the major head loss and the minor head loss.

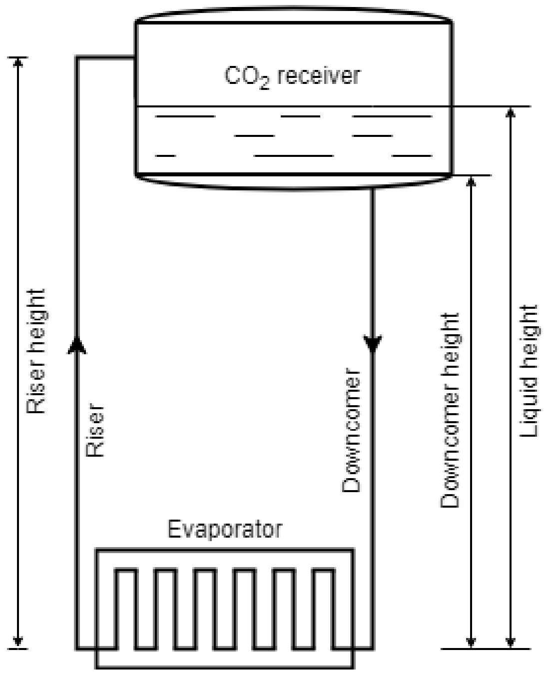



**Figure 5.5.1:** NCL illustration.

### 5.5.1 Static pressure loss

The inlet and outlet of the evaporator is assumed to be at the same height, so that static pressure losses only will be relevant in the riser and downcomer. Assuming that the

$CO_2$ through the downcomer and riser is incompressible, ideal and moving with constant velocity, Bernoulli's equation can be simplified to give the pressure difference caused by changing relative height through the pipe as (The Engineering ToolBox 2019a):

$$\Delta P_{static} = \rho g \Delta H \tag{5.5.1}$$

where $\rho$ is the fluid density, $g$ is the gravitational constant and $\Delta H$ is the change in height.

## 5.5.2 Head loss

The head losses can be separated into major head losses, the frictional pressure drops through the pipe, and the minor head losses, the pressure losses through valves, bends and fittings.

### Major head loss

The major head loss will be dependent on whether the fluid is in single-phase or two-phase. The fluid in the downcomer will be in single, liquid phase, while the fluid in the evaporator and riser will be two-phased. The frictional pressure drop for a steady flow through a pipe with constant cross-section area can be expressed through the Darcy-Weisbach equation as (Singal et al. 2015):

$$\Delta P_{major} = f \frac{l}{d} \frac{\rho v^2}{2} \tag{5.5.2}$$

Using that the fluid velocity, $v = \dot{V}/A$, and that the volume flow, $\dot{V} = \dot{m}/\rho$, Equation 5.5.2 can be expressed as

$$\Delta P_{major} = f \frac{l}{d} \frac{\rho \left(\frac{\dot{V}}{A}\right)^2}{2} = f \frac{l}{d} \frac{\rho \left(\frac{(\dot{m}/\rho)}{A}\right)^2}{2} = f \frac{l}{d} \frac{\dot{m}^2}{2\rho A^2} \tag{5.5.3}$$

The cross-section area, $A = \pi d^2/4$, is constant, which gives:

$$\Delta P_{major} = f \frac{l}{d} \frac{\dot{m}^2}{2\rho \left(\pi d^2/4\right)^2} = f \frac{2}{\pi} \frac{l}{d^3} \frac{\dot{m}^2}{\rho} \tag{5.5.4}$$

where $l$ is the length of the pipe, $d$ is the diameter of the pipe, $\rho$ is the fluid density and $\dot{m}$ is the mass flow. The friction factor, $f$, is dependent on whether the fluid is in single-phase or two-phase. For laminar flow, $Re$ <2 000, the single-phase friction factor, $f_{1ph}$, is given as:

$$f_{1ph} = \frac{64}{Re_{1ph}} \tag{5.5.5}$$

where $Re_{1ph}$ is the single-phase Reynolds number, given as:

$$Re_{1ph} = \frac{\rho v d}{\mu} = \frac{\dot{m} d}{A\mu} = \frac{4}{\pi}\frac{\dot{m}}{d\mu_{1ph}} \tag{5.5.6}$$

where $\mu_{1ph}$ is the single-phase dynamic viscosity. If the flow is turbulent, $Re_{1ph}$ >4 000, the single-phase friction factor can be implicitly estimated using the Colebrook-White formula. However, a good explicit approximation of the Colebrook-White formula is the Swamee and Jain formula, given as (Zeghadnia et al. 2019):

$$f_{1ph} = \left[-2log\left(\frac{\epsilon/d}{3.7} + \frac{5.74}{Re_{1ph}^{0.9}}\right)\right]^{-2} \tag{5.5.7}$$

where $\epsilon$ is the absolute surface roughness of the pipe. Absolute roughness, $\epsilon$, for new copper, lead, brass and aluminium pipes are 0.001-0.002 mm (The Engineering ToolBox 2019b).

The two-phase friction factor, $f_{2ph}$ is defined through the following equation (Shannak 2008):

$$\frac{1}{\sqrt{f_{2ph}}} = -2log\left[269.7963\frac{\epsilon}{d} - \frac{5.0452}{Re_{2ph}}log\left(\frac{1}{2.8257}\left(\frac{1000\epsilon}{d}\right)^{1.1098} + \frac{5.8506}{Re_{2ph}^{0.8981}}\right)\right] \tag{5.5.8}$$

where the Reynolds number for two-phase flow, $Re_{2ph}$, is expressed as (Shannak 2008):

$$Re_{2ph} = \frac{4000\dot{m}}{\pi d} \cdot \frac{x^2 + (1-x)^2\left(\frac{\rho_g}{\rho_l}\right)}{\mu_g x + \mu_l(1-x)\left(\frac{\rho_g}{\rho_l}\right)} \tag{5.5.9}$$

where $\mu_g$ and $\mu_l$ are the dynamic viscosities of gas and liquid face, respectively, and $\rho_g$ and $\rho_l$ are the densities of the gas and liquid face, respectively. $x$ is the vapour quality, here assumed to be constant for the given pipe length. The vapour quality through the evaporator will change, making this model invalid. To deal with the changing vapour quality, the total length of the evaporator will be divided into several smaller sections where the vapour quality is assumed to be constant.

### Minor head loss

There are several bends in the pipes going from the receiver through the evaporator and back. These minor head losses can be modelled with the equivalent length in the Darcy-

Weisbach equation as (Singal et al. 2015):

$$\Delta P_{minor} = f\frac{l_{eq}}{d}\frac{\rho v^2}{2} = f\frac{2}{\pi}\frac{l_{eq}}{d^3}\frac{\dot{m}^2}{\rho} \tag{5.5.10}$$

where $f$ is the friction factor given in Equation 5.5.5 or Equation 5.5.8, depending on whether the flow is single-phased or two-phased. $l_{eq}$ is the equivalent length for the fitting. Relevant fittings are tabulated in Table 5.5.1.

| **Outer pipe diameter, mm** | **6** | **9** | **12** | **18** |
|---|---|---|---|---|
| $l_{eq}$ for regular 90° bend, m | 0.7 | 0.9 | 1.1 | 1.3 |
| $l_{eq}$ for regular 180° bend, m | 0.7 | 0.9 | 1.1 | 1.3 |

**Table 5.5.1:** Equivalent straight length for relevant pipe fittings (Singal et al. 2015).

# Chapter 6

# Results and discussion

## 6.1 Highlights

In this chapter, the results of all all cold storage calculations are presented. First, the refrigeration loads during the entire year and during the loading week of each product are presented. Then, heat exchangers are investigated, where temperature differences and surface areas are calculated. When the size of the evaporator is known, the natural circulation loop is designed. First, the results of changing gas quality are investigated, before the optimal height and circulation rate are decided, based on the pressure drop through the system. More specifics around the evaporator and $CO_2$ receiver are given. When height and circulation rate are chosen, the performance of the NCL at different loads are investigated. Once all parameters are set, the SCOPs for the investigated refrigeration systems are presented. Knowing the performance of the entire system, the required compressor works are used to give an estimate about the operating profits for the cold storage.

### Refrigeration load

The refrigeration load variations, based on the daily average ambient temperatures in Kolkata in 2005 (Figure 4.6.7 on page 64), are presented in Figure 6.2.1 on page 81. The peak loads naturally occur during the loading weeks, when the pull down loads are occurring. The highest refrigeration load, when loading grapes, is 2.43 kW. The lowest refrigeration load is 0.84 kW, in January. When the load variations are investigated using the hourly temperatures during the loading week, the resulting loads are smaller. When storing apples, the load peak the first day with 1.81 kW. Loads when storing mangoes peak the seventh day with 1.77 kW and grapes the fourth day with 2.30 kW. They are presented in Figure 6.2.2, 6.2.3 and 6.2.4 on page 82 and 83.

### Heat exchangers

When deciding the temperature differences in the heat exchangers, an I,x-diagram for moist air was used to set the evaporator temperature difference. A relative humidity of 90% in the cold storage resulted in a temperature difference of about 1.5°C in the evaporator, to avoid condensation and frost when apples and grapes are stored. A disadvantage with the NCL, is that it has to keep a constant temperature regardless of what is stored. This temperature is consequently set to -2°C. The standard system, without the NCL, will change its evaporation temperature when storing mangoes. Using a heat transfer coefficient of 25 $^{W}/_{m^2K}$, the resulting heat transfer area for the evaporator is 64.8 $m^2$ for a load of 2.43 kW. Design, size and placement of the evaporator can be found in Figure 6.3.2 and Table 6.3.2 on page 85 and 86. To design the IHX, effects of changing temperature difference were first investigated. Considering the effects, the temperature difference was chosen to be 1°C, due to a very high heat transfer coefficient of 2 500 $^{W}/_{m^2K}$ and the resulting area is 0.97 $m^2$. The condenser is not investigated in this thesis and the temperature difference is set to 5°C.

### Natural circulation loop

To model the NCL, effects of changing gas quality out of the $CO_2$ heat source, Figure 6.4.1 on page 88, was first investigated to decide which range of circulation rates to further investigate. A schematic of the NCL is presented in Figure 6.4.2 on page 89, where the maximum and minimum possible heights were calculated to be 2.5 m and 1.0 m, respectively. The downcomer liquid height includes the amount of liquid $CO_2$ inside the receiver, so both the receiver size and the pipe length through the evaporator were calculated, with three different pipe sizes. The specifics for the receiver are presented in Figure 6.4.3 on page 90. It was calculated that a total pipe length of 128.8 m, goes through the evaporator. The specifics for the evaporator are presented in Figure 6.4.4 on page 91 and the resulting liquid height, dependent on the circulation rate, can be found in Table 6.4.2 on page 91. At last, the driving force in the NCL could be calculated for the three chosen pipe sizes. The results are presented in Figure 6.4.5, 6.4.6 and 6.4.7 on page 92. A height of 1 m, to ensure good air distribution, and a circulation rate of 2 was chosen. This was designed at maximum load and the performance at varying refrigeration loads had to be estimated. The NCL has a relatively constant driving force, regardless of the load, which can be seen in Figure 6.4.8 on page 93.

### Performance

With all relevant parts of the refrigeration system and cold storage designed, the performance was estimated, based on the presented load variations. The SCOP was calculated to be between about 4.5 and 10, for both systems through the year, as seen in Figure 6.5.1 on page 95. When storing apples and grapes, the COP for the NCL system is just slightly below the COP for the standard system, but the difference is almost negligible. The standard system has an average COP through the year of about 6.5, while the NCL system has about 5.6. This is due to relatively poor performance of the NCL system, compared to the standard configuration, when storing mangoes. During this period, the standard system operates with a COP of between 8 and 10, while the NCL system, due to the unnecessary low evaporation temperature, operates with a COP of around 5. The COPs during the loading weeks are also presented, in Figure 6.5.2, 6.5.3 and 6.5.4 on page 96 and 97. As expected, when using hourly temperatures, the calculated COPs vary more. They are both higher and lower, than the COP calculated with the average daily temperature.

### Revenue

The final part of the results is the estimated revenue of the system. Using two average electrical rates in India, Table 6.6.1 on page 98, and the expected profit from changing market price, Table 4.6.2 on page 63, the operating profits are estimated. When a domestic consumer rate is used, the estimated operating profit for one year is about 479 000 INR for the standard system and about 478 000 for the NCL system. If a commercial consumer rate is used, the estimated operating profit is about 476 000 INR for the standard system and about 474 000 for the NCL system. The electricity rates in India vary from state to state, but on average, they are low and almost negligible to the income. The power costs for one year is calculated to be only between 9 000 INR and 16 000 INR, depending on the system configuration and electricity rate. Detailed results can be found in Table 6.6.3 to 6.6.6 on page 99 and 100. Investment costs are not considered.

## 6.2 Refrigeration load

The refrigeration loads are calculated using Engineering Equations Solver (EES) and the respective codes used can be seen in section B.2, B.3 and B.4 in Appendix B. The refrigeration load will change depending on the product stored and the ambient temperature. Figure 6.2.1 on page 81 shows how the total refrigeration load changes throughout the year, based on the temperatures in Kolkata in 2005, Figure 4.6.7 on page 64. Generally, the loads change more or less similar to how the ambient temperature changes. The highest loads naturally occur during the loading week for the three products, where the absolute peak is 2.43 kW when grapes are loaded. The total loading capacity of the storage is 3 914 kg, when using the storage density assumed in subsection 4.6.3.

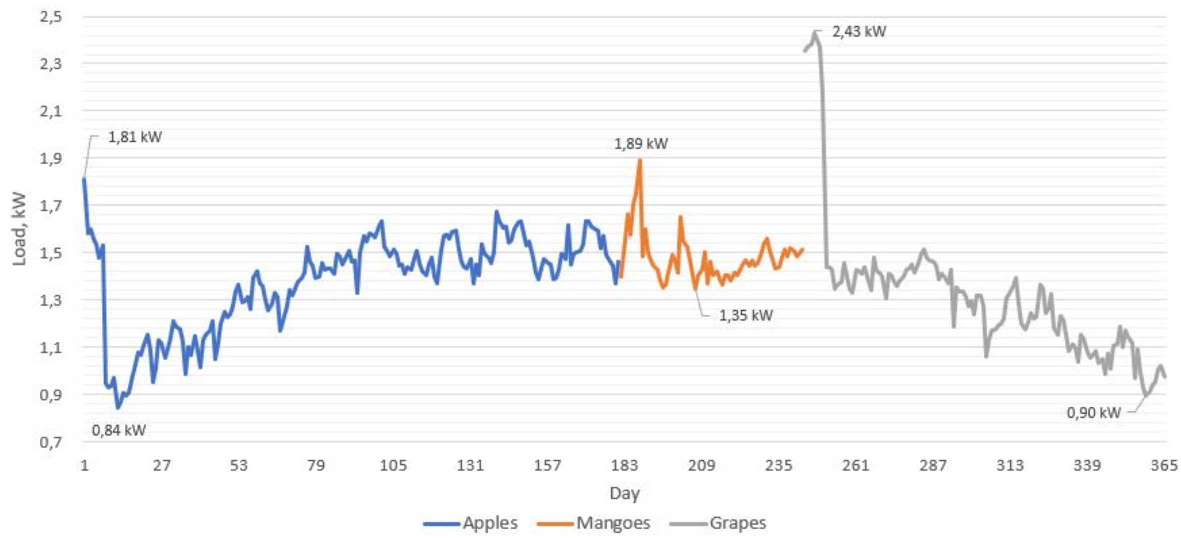



**Figure 6.2.1:** Annual total refrigeration load.

The refrigeration system should be designed to handle the maximum load. Ideally, the fruits should be pre-cooled rapidly to the desired storage temperature with a suited pre-cooling system, to avoid the large pull down loads. The master thesis written by Espedalen (2019) investigates the possibility of a pre-cooling system, which would be a great addition to the cold storage investigated in this thesis. However, as discussed in section 3.3 and chapter 4, pre-cooling is only performed when exporting grapes. It is therefore reasonable to believe that the product will be loaded at ambient temperatures and pull down loads have to be regarded. The system will be in need of a compressor covering a range from about 0.8 kW to 2.5 kW and from about 15°C to about 34°C ambient temperature. From section 2.4, it is known that Frigopol produce separating hood compressors with an operating range from -30°C to 50°C, which is sufficient for Indian conditions. In addition, it can provide a cooling capacity of 1 kW, up to 95 kW, with capacity control down to 20% of the chosen capacity. Using this compressor for a maximum capacity of 2.5 kW is a good solution. It can be regulated down to 0.5 kW, which covers the entire range of refrigeration loads.

The total loads in Figure 6.2.1 are calculated with the average daily temperature. Real temperatures will become higher than this, often close to 40°C for a few hours during the day. Hourly loads are therefore investigated to determine whether or not the average daily temperatures provide a decent representation. Since the highest loads occur during the loading week, the hourly loads during the loading week for each of the products are further investigated. The temperatures each hour during the week, when loading apples, mangoes and grapes, can be seen in Figure A.4.1, Figure A.5.1 and Figure A.6.1 in Appendix A.

### Apples

The different loads during the loading week for apples are presented in Figure 6.2.2. The dominating load is the transmission load, reaching above 1.1 kW the first day. The pull down load is the second largest load, also highest during the first day. The remaining loads are relatively small. The highest total load, occurring at the middle of the first day, is 1.81 kW. This is equal to the peak load for calculations using the average daily temperature. Hence, using the average daily temperatures provides a good estimation of refrigeration loads when storing apples.

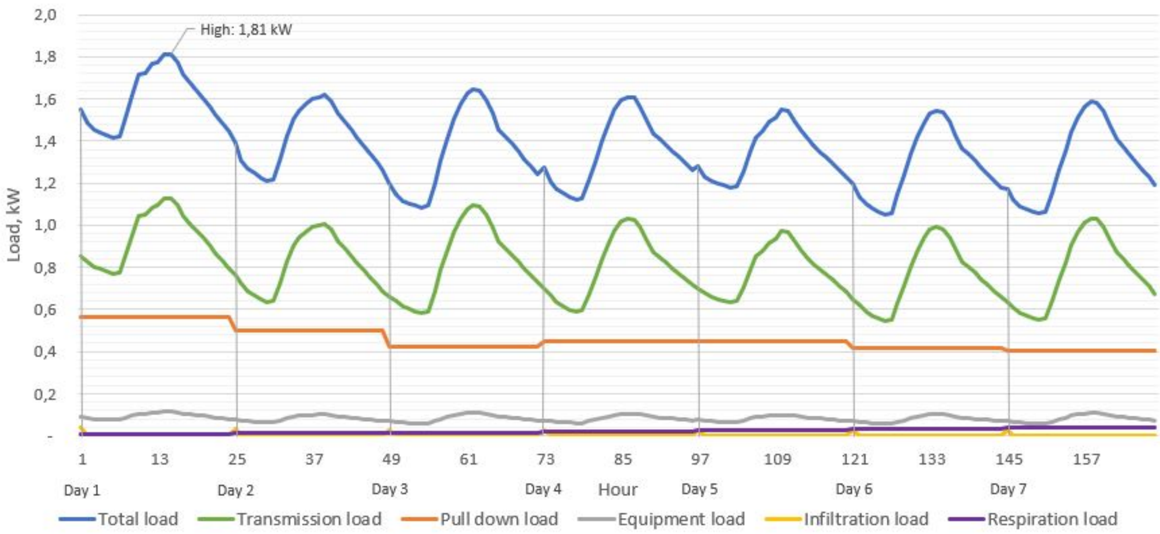



**Figure 6.2.2:** Refrigeration loads during loading week for apples.

### Mangoes

The different loads during the loading week for mangoes are presented in Figure 6.2.3 on page 83. The dominating load is the transmission load, reaching about 0.9 kW the first three days. From day four and out, the temperatures vary less between day and night, making the load variations less predictable. The pull down load is the second largest load, the first four days. The respiration heat for mangoes, however, is much larger than the respiration heat of apples and grapes. When loading more mangoes each day, the respiration load eventually exceed the pull down load, reaching a value of above 0.5 kW. The equipment and infiltration loads are relatively small. The highest total load occur at the middle of day seven, reaching 1.71 kW. This is actually smaller than the load calculated with the average daily temperature, 1.89 kW in Figure 6.2.1. Hence, using the average daily temperature is a conservative approach when storing mangoes.

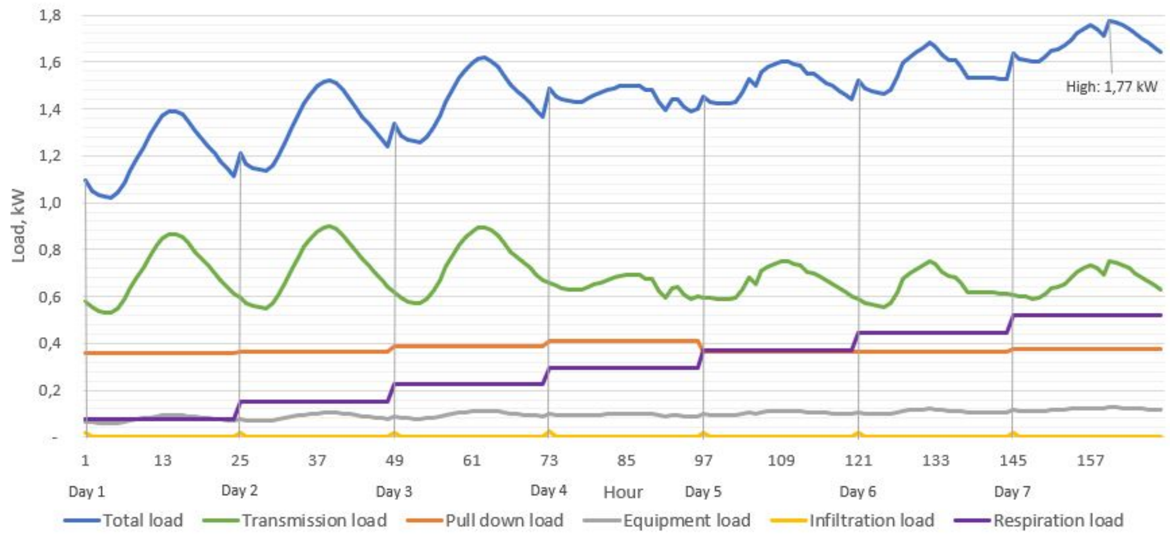



**Figure 6.2.3:** Refrigeration loads during loading week for mangoes.

### Grapes

The different loads during the loading week for grapes are presented in Figure 6.2.4. The dominating load is the transmission load, reaching above 1.4 kW several days. Grapes are loaded when ambient temperatures are high and they are stored below 0°C, so the pull down load is the second largest load, staying relatively constant around 0.75 kW. The remaining loads are relatively small. The total load reach its peak value on day four, with 2.3 kW. As with mangoes, this load is smaller than the load calculated with the average daily temperature, 2.43 kW. Using the average daily temperature will therefore be a conservative approach when storing grapes.

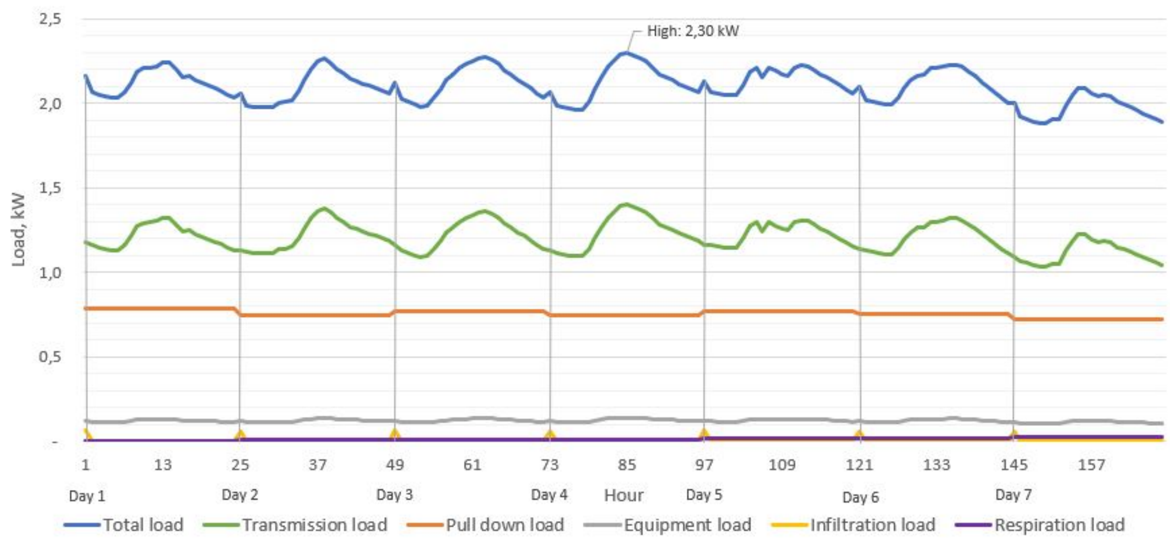



**Figure 6.2.4:** Refrigeration loads during loading week for grapes.

# 6.3 Heat exchangers

## 6.3.1 Evaporator

### Temperature difference

The room temperature should be kept at -0.5°C for apples and grapes, and 13°C for mangoes. The relative humidity, from Table 3.5.1 on page 39, should ideally be kept at 90-95% for apples and grapes, and 85-90% for mangoes. A relative humidity of 90% is therefore a decent compromise for all three products. Looking at Figure 6.3.1, for a storage temperature of -0.5°C and relative humidity of 90%, the temperature difference between the evaporator and storage air should be no more than 1.5°C to avoid moisture to condense on the evaporator. Hence, the evaporator, when using the NCL will operate at a temperature of -2°C. Since the evaporation temperature must be kept constant when using the NCL, problems will arise when storing mangoes. From the I,x-diagram, we see that an evaporator temperature of -2°C will be far into the condensing area for moist air when the room temperature is 13°C with relative humidity of 90%. Water will condense on equipment below about 11°C. Consequently, condensation and frost will form on the evaporator when storing mangoes.

This problem will only occur when using the NCL, which must be kept at a constant temperature. The standard system configuration can change its evaporation temperature. When storing apples and grapes, the evaporator will still operate at -2°C to avoid condensation, but when storing mangoes, the evaporator will be kept at 11.5°C to avoid condensation. In both cases, with or without the NCL, the temperature difference between the evaporator and storage air should stay low enough to avoid condensation.

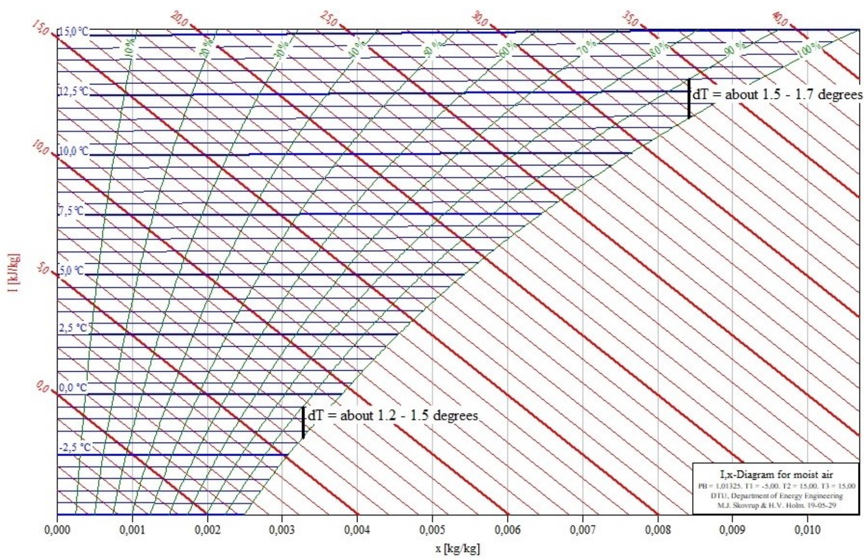



**Figure 6.3.1:** I,x-diagram for moist air.

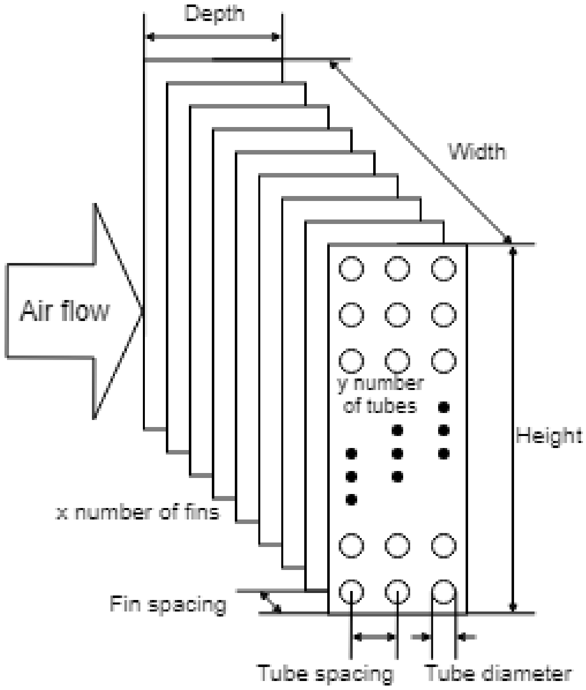
### Evaporator surface area

The evaporator area must be designed at the maximum load, which is during the fourth day of loading grapes. The peak load was calculated to be 2.43 kW and the evaporator temperature difference has already been set to 1.5°C. From Table 5.4.1 on page 74, the heat transfer coefficient, U, is set to 25 $^{W}/_{m^2K}$. Using Equation 5.4.2, the required evaporator surface area can be calculated. The results are presented in Table 6.3.1.

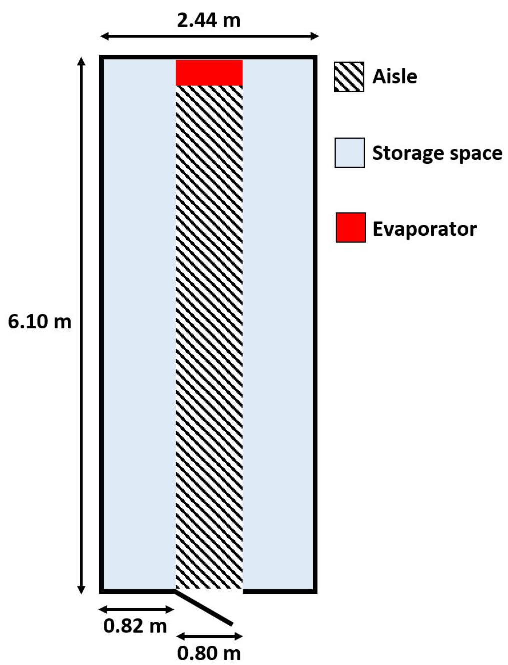
| Parameter | Value | Unit |
|---|---|---|
| $\dot{Q}$ | 2 430 | W |
| U | 25 | $^{W}/_{m^2K}$ |
| ΔT | 1.5 | °C |
| **A** | **64.8** | $\mathbf{m^2}$ |

**Table 6.3.1:** Required evaporator area.

The required evaporator surface area is calculated to be 64.8 $m^2$. The width of the evaporator is set equal to the aisle width, 80 cm, so it can be placed on the wall opposite of the door, see Figure 6.3.2b. Using a fin spacing of 3 mm and neglecting fin thickness, see subsection 4.6.3, results in a maximum of 266 plates. The depth is set to 20 cm, to avoid a large pressure loss in the air through the evaporator, resulting in a fin height of about 61 cm. Size specifics are summarised in Table 6.3.2 on page 86.




(a) Schematic.




(b) Placement.

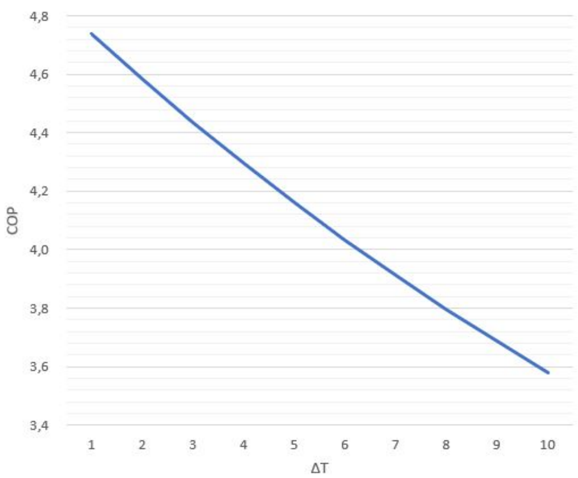
**Figure 6.3.2:** Evaporator design.

| Total area | Width | Depth | Height | Number of fins | Fin area | Fin spacing |
|---|---|---|---|---|---|---|
| 64.800 $m^2$ | 0.800 m | 0.200 m | 0.609 m | 266 | 0.244 $m^2$ | 0.003 m |

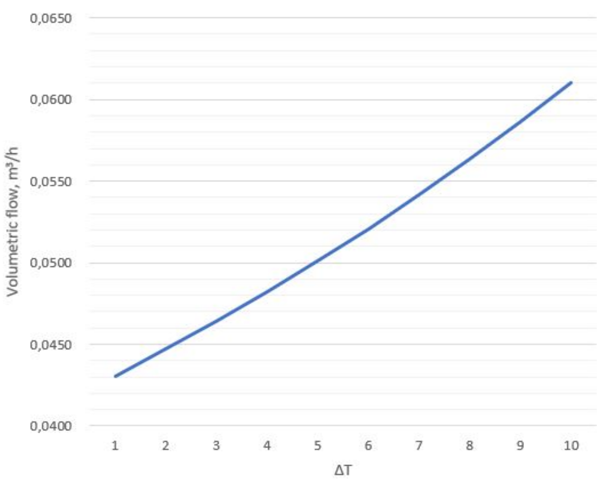
**Table 6.3.2:** Evaporator size specifics.

### 6.3.2 Intermediate Heat Exchanger (IHX)

The effects of changing the temperature difference in the IHX are investigated using EES, when the load is highest. Changing the temperature difference in the IHX will change the $NH_3$ receiver pressure which will change the low pressure side of the compressor. From subsection 4.6.3, the condenser temperature difference is set constant to 5°C, which will determine the high pressure side of the compressor. The changes in the IHX will mainly influence three parameters; COP, volumetric flow into the compressor and heat exchanger area. Investigating how the COP changes with temperature difference should be sufficient to determine the expected performance change of the system. Investigating the change of volumetric flow into the compressor will give an estimation about the required compressor size. The heat exchanger area will give an indication about the size of the IHX. From Table 5.4.1, the heat transfer coefficient is set to 2 500 $\mathrm{W/m^2K}$. Condenser area will not be further considered. The effects of changing temperature difference are presented in Figure 6.3.3.

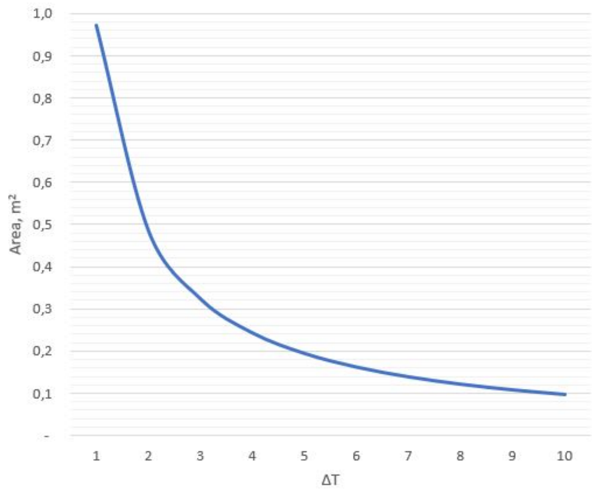



**(a)** COP.




**(b)** Volumetric flow into compressor.

**Figure 6.3.3:** Effects of changing temperature differences in heat exchangers.




**(c)** IHX area.

**Figure 6.3.3:** Effects of changing temperature differences in heat exchangers.

In Figure 6.3.3a, increasing the temperature difference in the IHX, will reduce the COP with about $^{0.13}/_{°C}$. However, even with a temperature difference of $\Delta$T=10, the COP is above 3.5. Looking at the volumetric flow into the compressor in Figure 6.3.3b, an increase in temperature difference will increase the flow with about $^{4\%}/_{°C}$. In other words, keeping a low temperature difference allows for a smaller compressor. In Figure 6.3.3c, for a temperature difference of $\Delta$T=1, the required heat transfer area is below 1 $m^2$. The required area change somewhat exponentially, so increasing the temperature difference to $\Delta$T=4 reduce the required area to about 0,25 $m^2$. For temperature differences above $\Delta$T=4, the decrease in area is relatively small. When calculating the IHX area, the NCL is assumed to be an ideal loop, meaning no loss in energy, so that there is 2.43 kW heat flow through the IHX. This heat exchanger is designed as a cascade heat exchanger, which is very efficient as both fluids go through a phase change. Considering all the effects of changing the temperature difference in the IHX, a temperature difference of $\Delta$T=1 seems possible due to the high efficiency, resulting in the best performance of the system. $\Delta$T is therefore set equal to 1 for the IHX and the specifics are given in Table 6.3.3.

| Parameter | Value | Unit |
|---|---|---|
| $\dot{Q}$ | 2 430 | W |
| U | 2 500 | $^{W}/_{m^2K}$ |
| $\Delta$T | 1 | °C |
| **A** | **0.97** | $\mathbf{m^2}$ |

**Table 6.3.3:** IHX size specifics.

## 6.4 Natural circulation loop

The NCL is modelled using EES and the respective pressure losses discussed in section 5.5. The EES code can be seen in section B.1 in Appendix B.

### 6.4.1 Gas quality out of $CO_2$ heat source

Effects of changing gas quality out of the $CO_2$ heat source are investigated when the refrigeration load is highest. Since the NCL in the refrigeration system in Figure 5.3.1b is designed with the IHX inside the $CO_2$ receiver, changing the gas quality out of the evaporator will mainly change the required $CO_2$ mass flow through the evaporator to remove the desired amount of heat. Effects of changing gas quality out of $CO_2$ evaporator are presented in Figure 6.4.1.

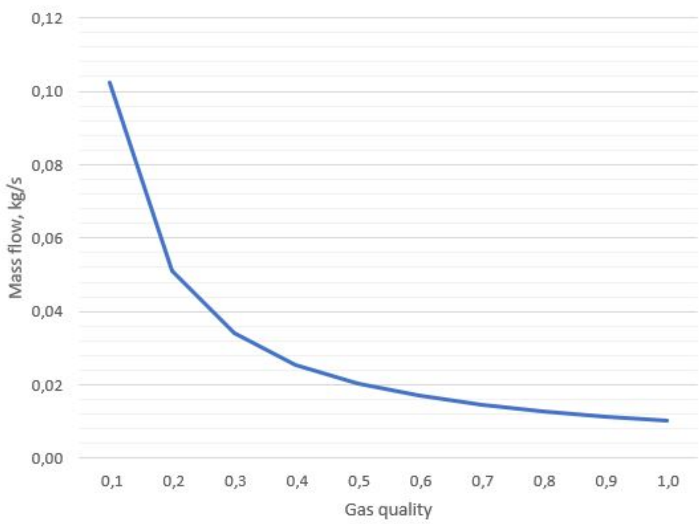
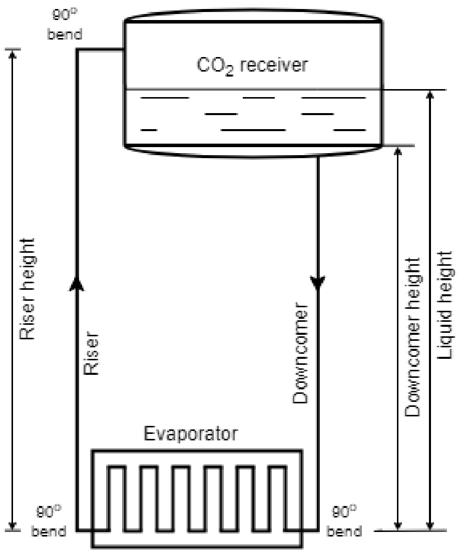



**Figure 6.4.1:** Effects of changing gas quality out of $CO_2$ evaporator.

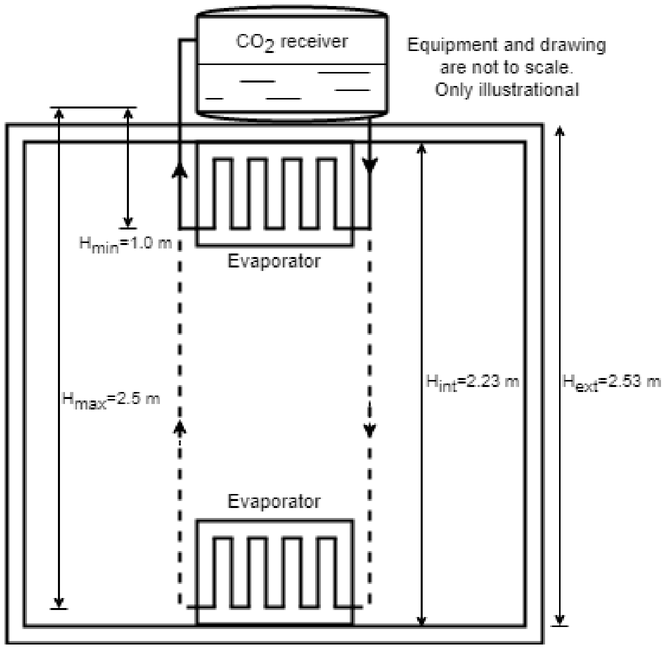
If the gas quality decrease from 1, down to 0.5, the mass flow through the evaporator must double to provide the required cooling capacity. This change is, however, small compared to the increase in mass flow when the gas quality is below about 0.3 to 0.4. For low gas qualities, the required mass flow has an exponential increase, reaching values about 10 times the mass flow for gas quality equal to 1. Typical recommended circulation rates through heat exchangers are between 2 and 4, which corresponds to a gas quality between 0.5 and 0.25, but circulation rates from 1 to 5 will be investigated during modelling of the NCL.

### 6.4.2 Optimal height and circulation rate

The system is modelled from the $CO_2$ receiver and down, including downcomer, riser and evaporator. A schematic of the loop, showing piping and liquid height, is illustrated in Figure 6.4.2a. Figure 6.4.2b shows the minimum and maximum height possible for the placement of the evaporator inside the cold storage. Note that neither of the drawings are to scale, they are only illustrational. The riser is designed with two 90°bends, while the downcomer only have one. The optimum height of the evaporator will be investigated between 1.0 m and 2.5 m. Heights above 2.5 m are possible if the receiver are raised above the roof, but 2.5 m is assumed to be the maximum height in this model.



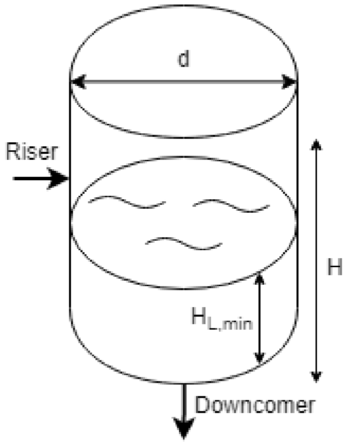

**(a)** NCL schematic.




**(b)** NCL placement.

**Figure 6.4.2:** Design of NCL.

When calculating the liquid height, a minimum liquid level in the receiver have to be decided. When the system is in operation, the liquid height will change depending on the circulation rate and pipe length. The receiver is modelled as a standing cylinder with a diameter of 30 cm. The minimum liquid height, when the downcomer, evaporator and riser, are filled with liquid, is set to 10 cm, see Figure 6.4.3 on page 90. The receiver height is set to 20 cm above the maximum liquid height.




| Parameter | Value | Unit |
|---|---|---|
| Diameter, d | 0.3 | m |
| Minimum liquid height, $H_{L,min}$ | 0.1 | m |
| Receiver height, H | Liquid hgt. + 0.2 | m |

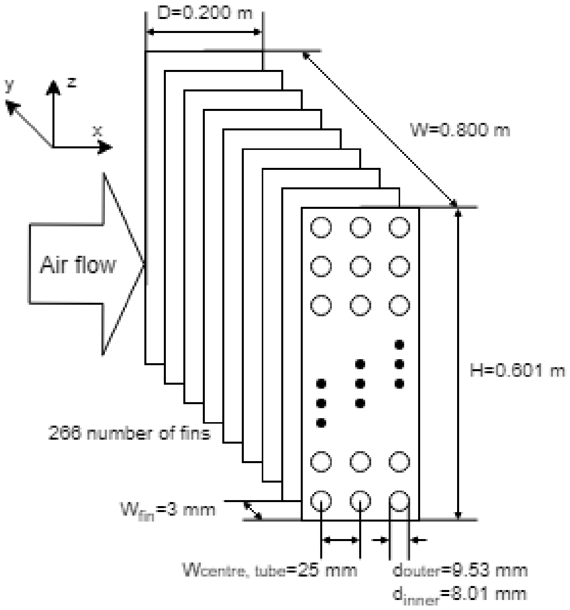
**Figure 6.4.3:** $CO_2$ receiver.

To estimate the liquid standing in the evaporator during system standstill, the pipe length through the evaporator have to be calculated. Using Figure 6.3.2a, with the calculated sizes, the number of pipes can be decided. Three different pipe sizes will be investigated, 3/8", 1/2" and 5/8". Specific pipe sizes are provided in Table 6.4.1. The pipe size is assumed to be equal in all parts of the NCL.

| Size | Outer diameter | Wall thickness | Maximum pressure |
|---|---|---|---|
| 3/8" | 9.53 mm | 0.76 mm | 48 bars |
| 1/2" | 12.70 mm | 0.89 mm | 48 bars |
| 5/8" | 15.88 mm | 1.02 mm | 48 bars |

**Table 6.4.1:** Selected pipe sizes.

The resulting pipe lengths are presented in Figure 6.4.4 on page 91. The bends on the sides of the evaporator, connecting each pipe, are neglected in total length.




| Parameter | Value | Unit |
|---|---|---|
| $N_{pipes,x}$ | 7 | pcs |
| $N_{pipes,z}$ | 23 | pcs |
| $N_{pipes,tot}$ | 161 | pcs |
| $L_{pipe,y}$ | 0.8 | m |
| $\mathbf{L_{pipes,tot}}$ | **128.8** | **m** |

**Figure 6.4.4:** Pipe length through evaporator.

Knowing the total pipe length below the receiver, the change in liquid height when the system is running can be calculated. The resulting receiver liquid heights are presented in Table 6.4.2. The length of the downcomer and riser are negligible compared to the pipe length trough the evaporator. Due to this, the liquid height in the receiver will be approximately only dependent on the circulation rate. Changes in pipe length in the downcomer and riser influence the liquid height in the receiver with a maximum of about 5 mm. Hence, liquid height is set constant for all heights, varying only with circulation rate. The inlet of the riser is set to 10 cm above the highest liquid height.

| Circulation rate | Liquid height 3/8" pipe | Liquid height 1/2" pipe | Liquid height 5/8" pipe |
|---|---|---|---|
| 1 | 0.18 m | 0.26 m | 0.35 m |
| 2 | 0.14 m | 0.18 m | 0.23 m |
| 3 | 0.13 m | 0.15 m | 0.18 m |
| 4 | 0.12 m | 0.14 m | 0.16 m |
| 5 | 0.12 m | 0.13 m | 0.15 m |

**Table 6.4.2:** Liquid height in the $CO_2$ receiver.

The liquid height will influence the static pressure increase through the downcomer and the length of the riser. When the pipe size is set, the operation conditions of the NCL will be dependent on the riser and downcomer height and the circulation rate. Plotting the circulation rate against the height to visualise the pressure difference in the downcomer versus the riser, will give an indication about the optimal height and circulation rate.

The driving force for the NCL for the different pipe sizes are presented in Figure 6.4.5 to Figure 6.4.7.

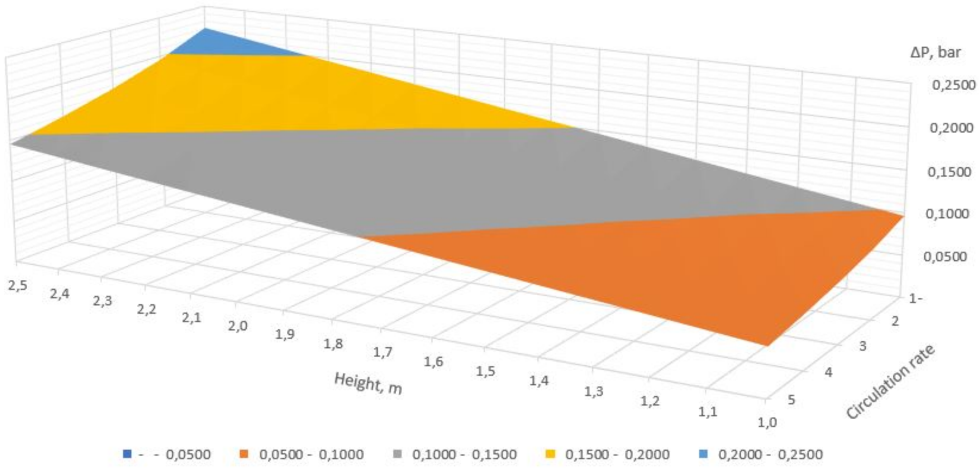



**Figure 6.4.5:** NCL driving force for 3/8" pipes.

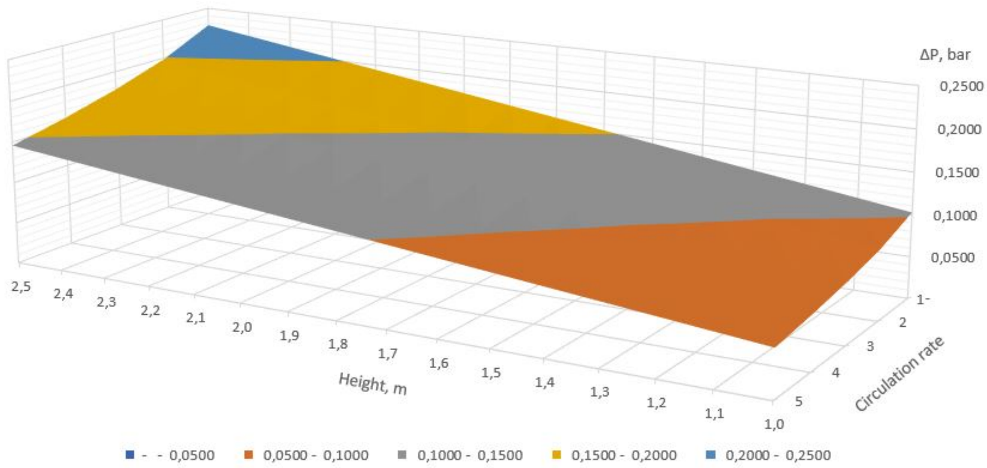



**Figure 6.4.6:** NCL driving force for 1/2" pipes.

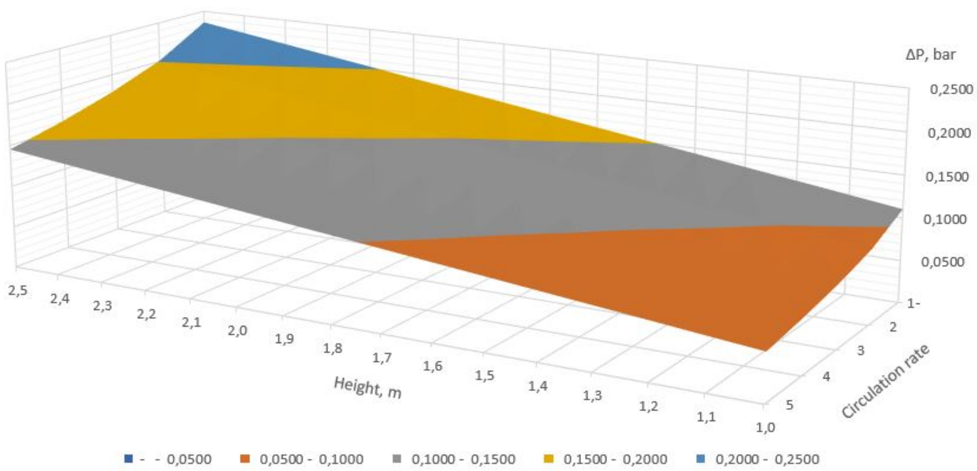
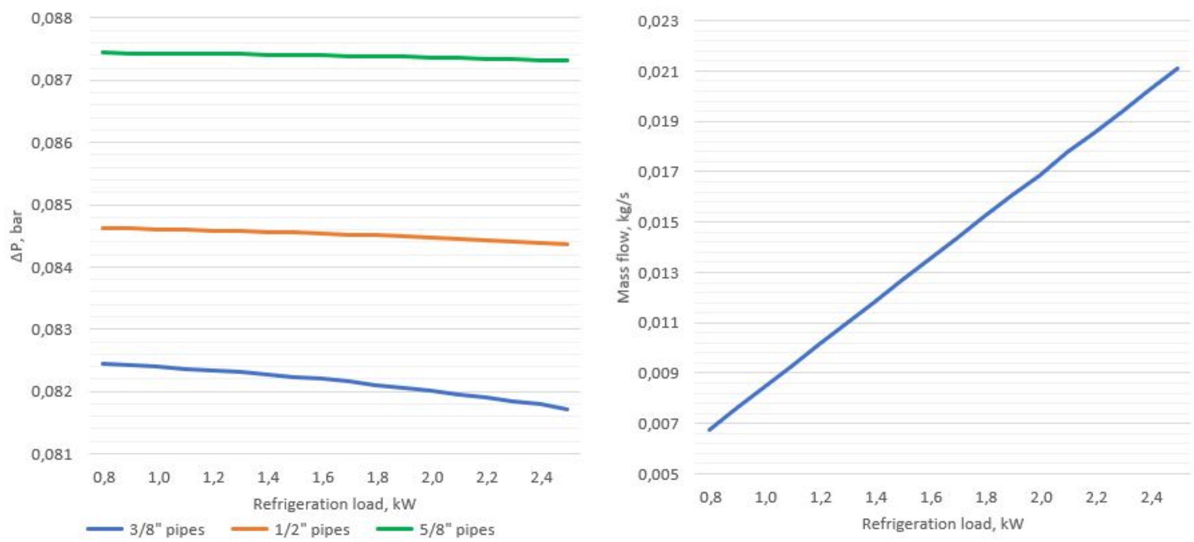



**Figure 6.4.7:** NCL driving force for 5/8" pipes.

The NCL will have enough driving force to work for all heights and circulation rates investigated, regardless of pipe size. The friction losses through the evaporator are very small and the driving force is most dependent on the height and circulation rate. There is a slightly larger pressure loss through the system, and consequently lower driving force, when using the smallest, 3/8", pipes, but this is negligible. As expected, the largest driving force will occur at the largest height and circulation rate of 1, due to the increased amount of gas in the system and liquid height in the receiver. However, placing the evaporator on the floor in the storage room will result in a bad distribution of the cold air in the room. The evaporator should be placed high up and since this is possible in terms of driving force, the evaporator will be placed at a height of 1 m. A circulation rate of 1 might also cause trouble with the heat transfer in the evaporator. Since the recommended circulation rate is between 2 and 4, the circulation rate in further calculations will be set to 2.

### 6.4.3 NCL performance

A height of 1 m and circulation rate of 2 are values chosen when designing the NCL for a maximum load of 2.43 kW. Most days of the year, the refrigeration system will operate with a lower refrigeration load, down to 0.84 kW. The NCL performance should be investigated at varying loads, using the design conditions. To estimate the performance, the driving force and $CO_2$ mass flow will be investigated at loads between 0.80 kW and 2.50 kW. This is presented in Figure 6.4.8.




(a) Driving force. (b) Mass flow.

**Figure 6.4.8:** NCL performance at varying refrigeration load.

The driving force will actually increase when the load decrease, especially when using

3/8" pipes, as seen in Figure 6.4.8a. At high loads, the mass flow will increase and the smallest pipe might restrict the flow, causing the drop in driving force. However, for the investigated loads, this change is very small and negligible, so the driving force can be considered constant for this range. The slightly larger driving force when using larger pipes can be seen here. The variations in mass flow for varying refrigeration loads are presented in Figure 6.4.8b. The mass flow will be linearly dependent on the load, and will consequently be low at low loads. When modelling, the mass flow is decided using the given refrigeration load and enthalpy difference over the evaporator, causing this relation. Increasing the circulation rate will increase the mass flow, if it becomes to low, but when estimating COP, the circulation rate will still be set to 2.

One problem with NCLs not investigated in this thesis are the challenges related to instability. Here, it is modelled under ideal conditions, without unsuspected variations in operating conditions. Due to the lack of a pump controlling the flow, it will be very unpredictable in real applications. This is a difficult problem to address, as most solutions would include the addition of equipment governing the flow, like a pump, which in turn makes the flow forced. A constant circulation rate is also decided, which will not be constant in real applications. Misale (2014) discuss the problem in more detail. They highlight the nonlinear nature and low driving force as the main source for the instability. The buoyancy and friction forces are not in phase, so small disturbances can heavily affect the driving force and cause oscillations when the system should be in steady state. This instability is a problem not yet considered solved for industrial applications.

## 6.5 Refrigeration system performance

Based on the previous calculations, designs and loads, the expected performance of the system can be calculated. SCOP and COP during the loading weeks are investigated using EES and the codes can be seen in section B.2, B.3 and B.4 in Appendix B. A comparison of the SCOP for both system configurations are presented in Figure 6.5.1 on page 95.

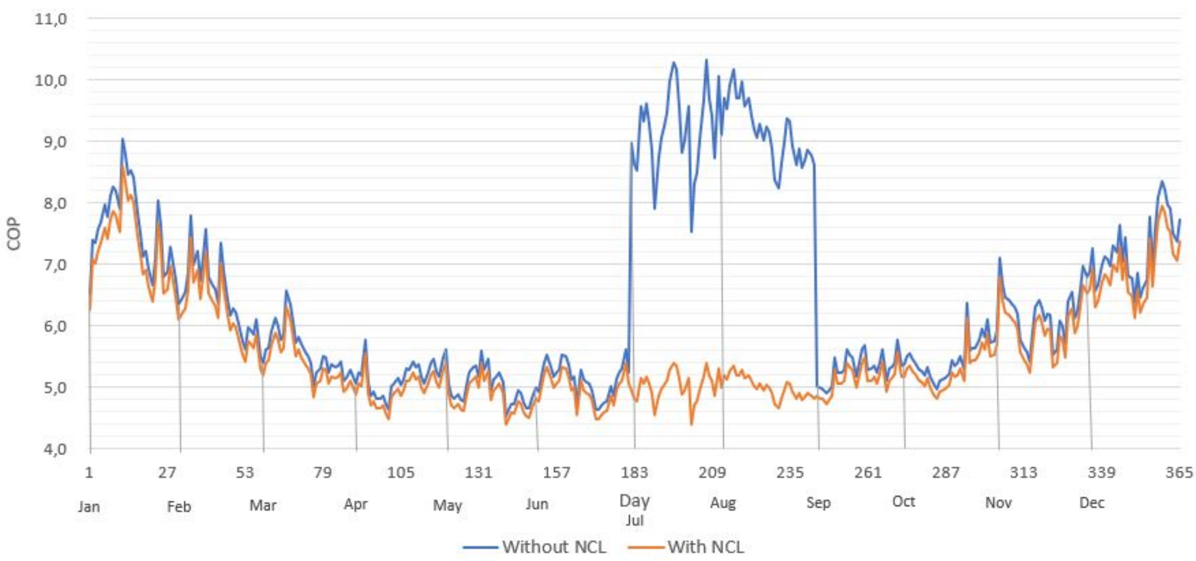



**Figure 6.5.1:** Refrigeration system SCOP, with and without NCL.

The COP for the standard system is slightly better than the COP when using the NCL. However, the difference is relatively small and the NCL system is competitive. The average SCOP for the standard system during the entire year is 6.47, while the NCL system operates with an average SCOP of 5.57. Compared to the $COP_{Ca}$, which is an average of 11.92, they are inferior. However, comparing the performance with the systems described in section 2.4, the performance of both systems are considered to be good. Both systems have a COP in the higher range of COPs discussed in Table 2.4.1.

One of the major weaknesses of the NCL is obvious here, the issue with evaporator temperature. When storing mangoes, from July to September, at a room temperature of 13°C, the standard ammonia system can change its evaporator temperature up to 11.5°C and the COP is consequently excellent, with values of around 8 to 10. However, when using the NCL, the evaporation must continue at -2°C, and the COP is around 5. It is obvious that the addition of a NCL is ineffective when the system operates with a varying room temperature. On the other hand, if the room temperature is kept constant, using a NCL can be a good alternative to avoid distributing ammonia into the storage room.

In section 6.2, refrigeration loads every hour during the loading weeks were investigated to validate the use of average daily temperatures. Based on this, the COPs during loading weeks for all three products will be presented.

### Apples

The COPs during the loading week of apples are presented in Figure 6.5.2. The COP vary from about 5 to above 10, with peaks higher than the calculated COP using the average daily temperature. Hence, the performance can actually be better than what is estimated in Figure 6.5.1. The COP is highly dependent on the ambient temperature and the variation is therefore similar to how the ambient temperature change in Figure A.4.1 in Appendix A. The NCL system has a COP of about 0.2 to 0.5 lower than the standard ammonia system.

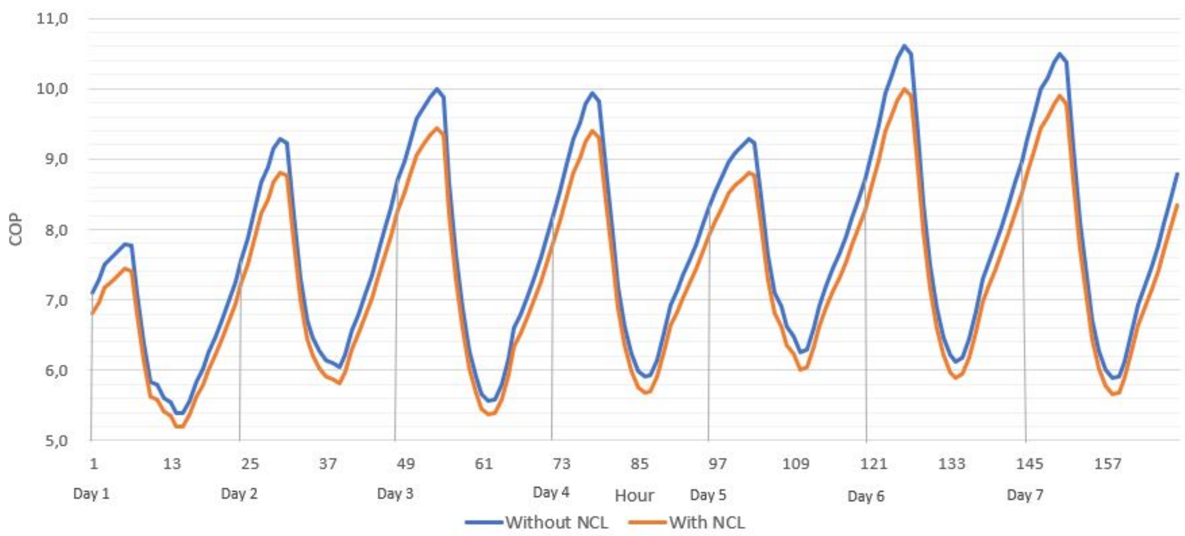



**Figure 6.5.2:** COP during loading week of apples.

### Mangoes

The COPs during the loading week of mangoes are presented in Figure 6.5.3 on page 97. It is obvious that the addition of the NCL makes the performance inferior. The standard system operates with an excellent COP of about 7 to 11.5, depending on the ambient temperature. The NCL system only operates at a COP of about 4 to 6. However, the variations in COP during the day is smaller for the NCL system, compared to the standard system. Just as for apples, the estimated performance when using hourly temperatures can be higher than when using the average daily temperature in Figure 6.5.1.

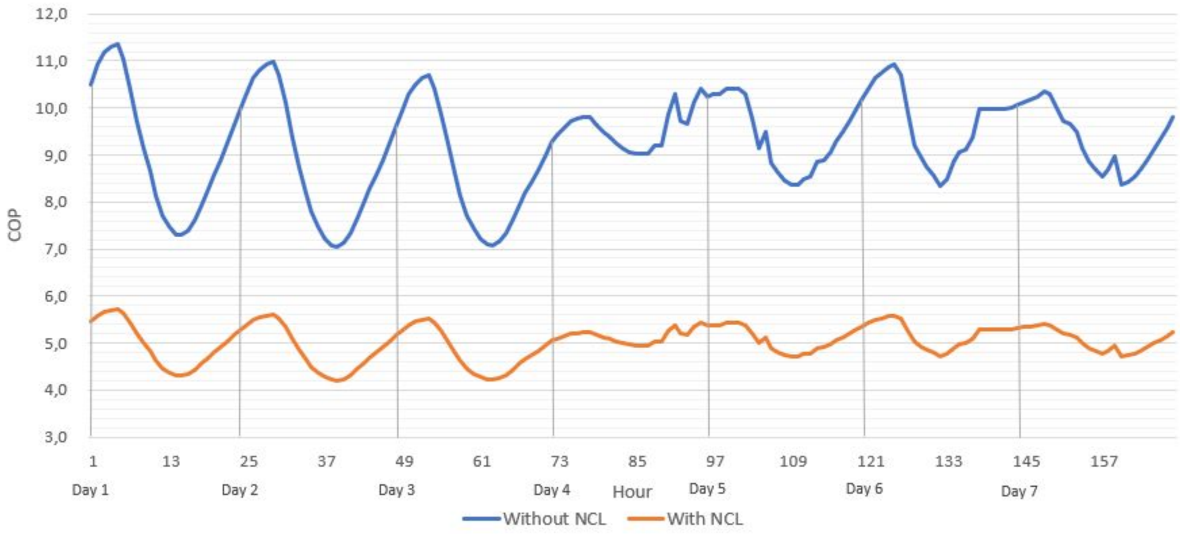



**Figure 6.5.3:** COP during loading week of mangoes.

### Grapes

The COPs during the loading week of grapes are presented in Figure 6.5.4. The COP varies from about 4.2 to 5.8. The performance of the NCL system is slightly worse than the performance of the standard system, with a COP of about 0.2 lower. Despite this, the NCL system is considered to be competitive for these conditions. The average COP when using hourly temperatures can be, similar to apples and mangoes, higher than when using daily average temperatures.

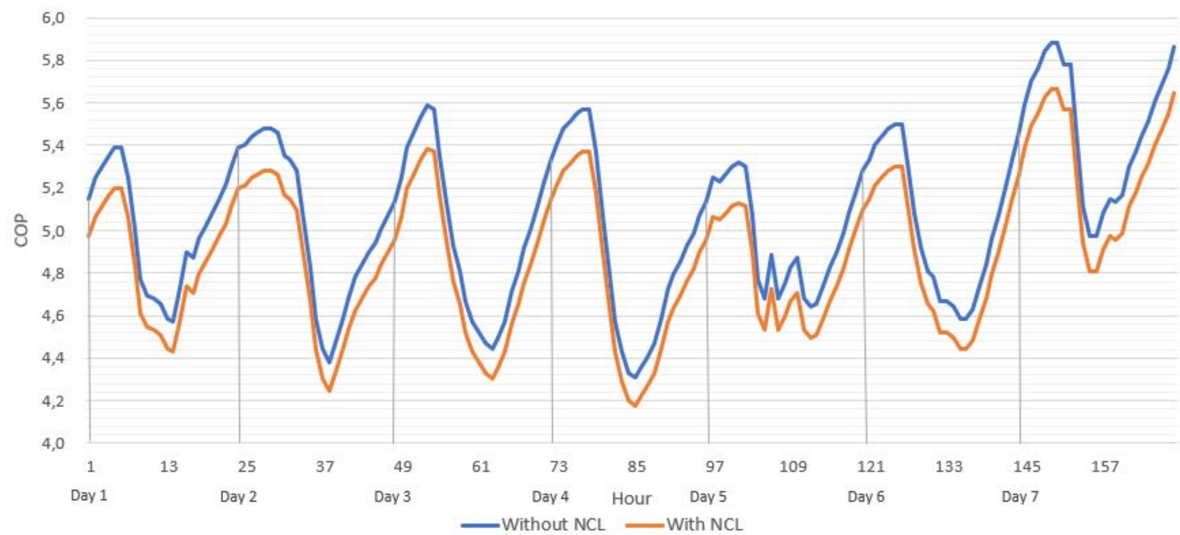



**Figure 6.5.4:** COP during loading week of grapes.

## 6.6 Revenue

The profit from storing apples, mangoes and grapes were investigated in subsection 4.6.2 and presented in Table 4.6.2. Knowing the required compressor work, presented in Figure 6.6.1, the operational costs can be estimated and finally, an estimate of operating profit can be done. Investment costs are not studied in this thesis, as they will be dependent on producer, materials, location and availability. Information about similar types of systems are scarce and estimating investment costs will therefore be inaccurate without any reliant sources for material and equipment costs.

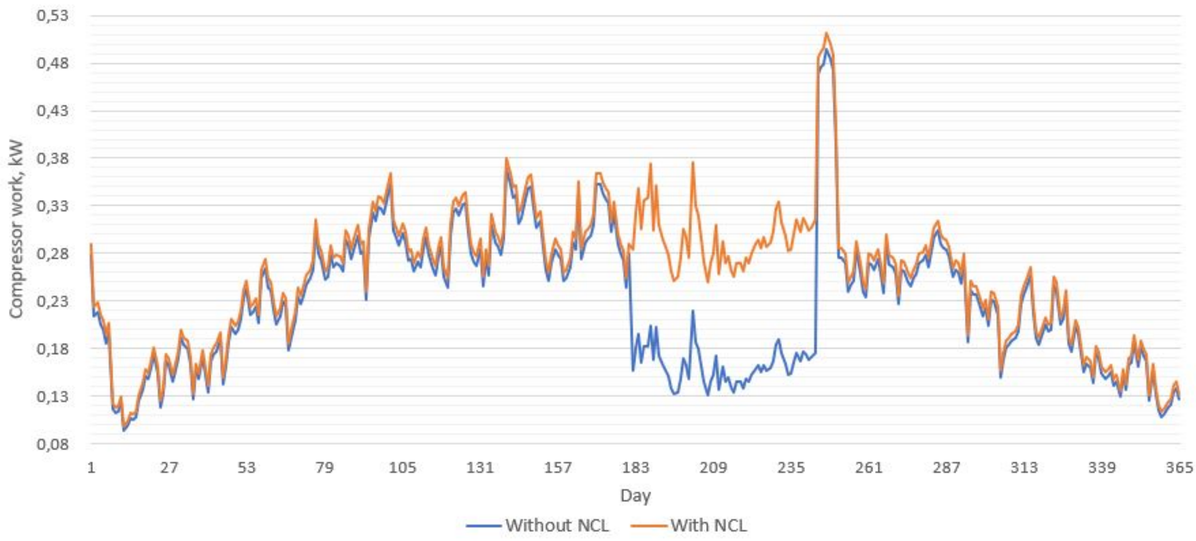



**Figure 6.6.1:** Daily compressor work.

Electricity rates in India vary between states, in addition to whether it is a domestic or commercial consumer and the amount of power used. The average rates of electricity for each state for relevant consumer profiles are presented in Table A.7.1 in Appendix A. A summary of the average prices are presented in Table 6.6.1.

| **Domestic consumer below 400 kWh/month** | **Commercial consumer below 300 kWh/month** | **Commercial consumer below 1 500 kWh/month** |
|---|---|---|
| 5.04 INR/kWh | 6.88 INR/kWh | 7.59 INR/kWh |

**Table 6.6.1:** Average rates of electricity in India, as on 01.04.2017 (Datanet India 2017).

In further calculations, the average electricity price will be used. To decide the consumer profile, the required compressor power is summarised for each month. The storage is assumed to be powered for 24 hours during each day. The total energy consumption for both system configurations each month are presented in Table 6.6.2 on page 99. As expected, the required power for the NCL system is higher than the standard system, especially in July and August. The total consumption is below 300 $^{\mathrm{kWh}}/_{\mathrm{month}}$ and the commercial consumer profile when using less than 300 $^{\mathrm{kWh}}/_{\mathrm{month}}$ can be used. Further, the operating profit for the domestic consumer rate and the chosen commercial consumer rate will be presented.

| Month | Standard system, kWh | NCL system, kWh |
|---|---:|---:|
| January | 114.26 | 119.55 |
| February | 126.62 | 131.83 |
| March | 186.21 | 193.15 |
| April | 207.89 | 215.27 |
| May | 230.08 | 238.06 |
| June | 210.52 | 217.97 |
| July | 122.24 | 223.38 |
| August | 118.78 | 217.10 |
| September | 222.08 | 230.10 |
| October | 188.41 | 195.37 |
| November | 143.81 | 149.57 |
| December | 108.84 | 113.72 |

**Table 6.6.2:** Monthly power consumption.

### 6.6.1 Domestic consumer rate

If the domestic consumer rate is used, the electricity rate will be, on average, 5.04 $^{\mathrm{INR}}/_{\mathrm{kWh}}$. The storage can hold 3 914 kg of each product. Operating profits for each system configuration are presented in Table 6.6.3 and Table 6.6.4. The difference in income due to the lower efficiency of the NCL system is negligible, only about 1 300 INR. The total operating profit for both configurations are just above 477 000 INR, making both solutions economically favourable. The power costs are very low, only about 2% of the total income. In other words, many of the other crops investigated in chapter 3 can yield a positive profit even for just a short time period. Due to the increased complexity of the NCL system, the investment costs using this configuration will be higher.

| Commodity | Storage time | Income $^{\mathrm{INR}}/_{\mathrm{kg}}$ | Capacity kg | Income INR | Power consumption, kWh | Electricity rate, $^{\mathrm{INR}}/_{\mathrm{kWh}}$ | Power costs INR | Profit INR |
|---|---|---:|---:|---:|---:|---:|---:|---:|
| Apples | Jan-Jun | 40 | 3 914 | 156 560 | 1 076 | 5.04 | 5 419 | 151 141 |
| Mangoes | Jul-Aug | 41 | 3 914 | 160 474 | 241 | 5.04 | 1 214 | 159 260 |
| Grapes | Sep-Dec | 44 | 3 914 | 172 216 | 663 | 5.04 | 3 341 | 168 875 |
| **Total** | Jan-Dec | 125 | 3 914 | 489 250 | 1 980 | 5.04 | 9 978 | **479 275** |

**Table 6.6.3:** Operating profits for standard system configuration using domestic consumer rate.

| Commodity | Storage time | Income INR/kg | Capacity kg | Income INR | Power consumption, kWh | Electricity rate, INR/kWh | Power costs INR | Profit INR |
|---|---|---|---|---|---|---|---|---|
| Apples | Jan-Jun | 40 | 3 914 | 156 560 | 1 116 | 5.04 | 5 622 | 150 938 |
| Mangoes | Jul-Aug | 41 | 3 914 | 160 474 | 440 | 5.04 | 2 219 | 158 255 |
| Grapes | Sep-Dec | 44 | 3 914 | 172 216 | 689 | 5.04 | 3 470 | 168 748 |
| **Total** | Jan-Dec | 125 | 3 914 | 489 250 | 2 245 | 5.04 | 11 311 | **477 939** |

**Table 6.6.4:** Operating profits for NCL system configuration using domestic consumer rate.

### 6.6.2 Commercial consumer rate

An electricity rate of 6.88 INR/kWh is used when profits are calculated with a commercial consumer rate. As discussed, the power costs are very low and the profit will naturally be high even though a higher electricity rate is used. Operating profits for the standard system are presented in Table 6.6.5 and for the NCL system in Table 6.6.6. Both configurations results in a profit of above 473 000 INR, when investment costs are excluded. The standard system configuration will yield a profit of about 1 800 INR more, which is a negligible difference. When increasing the electricity rate from 5.04 INR/kWh to 6.88 INR/kWh, the power costs will be about 3% of the the total income during the year. Even with a higher power tariff, both system configurations results in good operating profits. Other crops investigated in chapter 3, even those with lower potential for income, can yield a positive profit over a short period of time.

| Commodity | Storage time | Income INR/kg | Capacity kg | Income INR | Power consumption, kWh | Electricity rate, INR/kWh | Power costs INR | Profit INR |
|---|---|---|---|---|---|---|---|---|
| Apples | Jan-Jun | 40 | 3 914 | 156 560 | 1 076 | 6.88 | 7 405 | 149 155 |
| Mangoes | Jul-Aug | 41 | 3 914 | 160 474 | 241 | 6.88 | 1 659 | 158 815 |
| Grapes | Sep-Dec | 44 | 3 914 | 172 216 | 663 | 6.88 | 4 565 | 167 651 |
| **Total** | Jan-Dec | 125 | 3 914 | 489 250 | 1 980 | 6.88 | 13 629 | **475 621** |

**Table 6.6.5:** Operating profits for standard system configuration using commercial consumer rate.

| Commodity | Storage time | Income INR/kg | Capacity kg | Income INR | Power consumption, kWh | Electricity rate, INR/kWh | Power costs INR | Profit INR |
|---|---|---|---|---|---|---|---|---|
| Apples | Jan-Jun | 40 | 3 914 | 156 560 | 1 116 | 6.88 | 7 682 | 148 878 |
| Mangoes | Jul-Aug | 41 | 3 914 | 160 474 | 440 | 6.88 | 3 032 | 157 442 |
| Grapes | Sep-Dec | 44 | 3 914 | 172 216 | 689 | 6.88 | 4 742 | 167 794 |
| **Total** | Jan-Dec | 125 | 3 914 | 489 250 | 2 245 | 6.88 | 15 456 | **473 794** |

**Table 6.6.6:** Operating profits for NCL system configuration using commercial consumer rate.

# Chapter 7

# Conclusion

## 7.1 Horticulture and cold chains

India is among the world's most prominent producers of fruits and vegetables, with more than 90 million tonnes of fruit and more than 169 million tonnes of vegetables. The most important fruits are considered to be, in the following order, mangoes, grapes, apples, oranges and bananas. Southern India is the most productive region. Except bananas, all fruits are seasonal crops and they experience relatively large fluctuations in wholesale price through the year. Especially mangoes, grapes and apples are considered ideal products for storage, both in terms of storage life and wholesale price increase. The only documented cold chains are for grapes, which are successfully exported. Mangoes are to some extent handled in packhouses, but lack of cold storage facilities cause post-harvest losses up to 34%. As revealed in relevant literature, growth in production is increasing, but post-harvest management and handling are not.

The most important vegetables are considered to be, in the following order, potatoes, onions, tomatoes, cauliflowers, cabbages and okra. Eastern and Central India are the most productive regions. Cabbages, cauliflowers and onions are seasonal crops, while okra, potatoes and tomatoes are annual crops. Cabbages, cauliflowers, okra and tomatoes experience some fluctuations in wholesale price through the year, but they are not as ideal for storage as the discussed fruits. The increase in price is small and the storage life is too short to fully utilise the increased price. However, as revealed when estimating the revenue of the storage, even a small increase in price can yield a positive profit, as operating costs are low. Storing vegetables might therefore be economically feasible if supply of the chosen fruits are unavailable.

When investigating typical cold chains for export and domestic sale of horticultural crops, it is revealed that there are major deficiencies in all investigated chains. The lack of refrigerated transport and pre-cooling are highlighted as the major inhibitors in the export chain. One solution proposed is to use the experience from exporting grapes, to export other products. The deficiencies are larger for the domestic cold chain, compared to the export chain, as there is less money to be made on domestic sale. It suffers from the same challenges as the export chain, but in addition, there is a great need for cold storages. From the literature study, it is known that India have cold storage capacity for about 30 million tonnes of food, but need capacity to handle above 60 million tonnes. In addition, 75% of the cold storages are already used to store potato, while 16% are out of operation. 80% of them also run on outdated technology. Another issue with the domestic chain is the high number of intermediates, which is especially inhibiting the product flow through the Indian mandis.

The Indian mandis', the fruit and vegetable wholesale markets throughout the country, are associated with low quality, poor remuneration and high wastes. This was revealed to be due to the high number of intermediates and lack of cold chain facilities. From harvest at the farm, to retail at the mandis, there might be several independent agents, like an itinerary merchant, pre-harvest contractor, commissioning agent and transport agent. The number of intermediates are difficult to change, but the wastes can be lowered by supplying appropriate cold chain facilities, as more or less no food flowing through the mandis are cooled. The mandis also form a crucial link in the export chain, thus, modernising and improving the cold chain facilities at the mandis is concluded as the most promising solution.

The field investigation conducted at IIT Kharagpur in India confirms many of the discussed problems. As expected, the fruit and vegetable vendors answered that they do not refrigerate their food. They favour selling high quality products and they are aware that refrigeration is very important. Yet, they do not refrigerate their products or care if the products they buy are cooled. It seems like they just don't care for refrigeration as long as they are able to sell their product. The major inhibitor was concluded to be economy, but it was also revealed to be linked to their mindset and knowledge. Many people in India do not consider food fresh if it is refrigerated. They prefer consuming food without refrigeration and do not see the need for refrigeration. One of the fruit and vegetable vendors admitted to finding deteriorated food when buying his products from the distribution market. He was aware that the lack of refrigeration was an issue and answered that he would use a cold storage if it was available. This confirmed the need for a cold storage at the mandis or other small markets.

## 7.2 Cold storage and refrigeration system

From the investigated cold chains and the field investigation, it was concluded that designing a cold storage intended to be used at the Indian mandis or other small markets is a good solution. From the literature review on refrigerants in India it was revealed that the focus is mainly on HFCs, as natural refrigerants not are considered competitive. To prove otherwise, using natural refrigerants like $NH_3$ and $CO_2$ was decided. The refrigeration systems investigated are therefore a single stage $NH_3$ system, with and without $CO_2$ in a NCL. A movable cold storage the size of a 20ft container was considered a good option, as the cold storage could be delivered to the agents at the market, instead of them coming to the storage. Renewable energy sources like a solar panel were discussed, but not considered feasible due to economical reasons.

The choice of products to store was based on the average wholesale price variations. After investigating how the price for each fruit or vegetable changes, it was decided that storing apples from January to June, mangoes from July to August and grapes from September to December resulted in the highest income. Apples can be bought for 66 $^{INR}/_{kg}$ in January and sold for 106 $^{INR}/_{kg}$ in June. Mangoes can be bought for 84 $^{INR}/_{kg}$ in July and sold for 125 $^{INR}/_{kg}$ in August. Grapes can be bought for 39 $^{INR}/_{kg}$ in September and sold for 83 $^{INR}/_{kg}$ in December. Knowing that the electricity rates are low, other products can be stored with positive profit, if supply of apples, mangoes or grapes are unavailable.

By studying the I,x-diagram for moist air, it was concluded that an evaporation temperature of -2°C, when storing apples and grapes, was the best option with regards to relative humidity, condensation and frost. This meant that the NCL system had to operate with an evaporation temperature of -2°C, even when mangoes are stored at a room temperature of 13°C. The standard system is be able to change its evaporation temperature to 11.5°C when storing mangoes and operate with a temperature difference of 1.5°C in the evaporator. This resulted in a surface area of 64.8 $m^2$. By considering the width of the aisle, the most practical size was considered to be 80 cm wide, about 61 cm high and 20 cm deep. Results of changing temperature temperature difference in the IHX was investigated and after consideration, the temperature difference was decided to be 1°C, resulting in a surface area of 0.97 $m^2$.

When the NCL was designed, heights between 1.0 m and 2.5 m and circulation rates between 1 and 5 was investigated. The resulting driving force was positive for all height and circulation rates, but highest at low circulation rates and high height. To ensure a good distribution of cold air in the storage and a good heat transfer in the evaporator, it was concluded that a height of 1.0 m and circulation rate of 2 was the best option. Further investigation showed that the driving force, at this height and circulation rate, would be sufficient at all loads from 0.8 kW to 2.5 kW. One problem with NCLs discussed is the issue with instability. This problem is yet not solved for the relevant applications.

When estimating the SCOPs for both system configurations, the results were considered very good compared to the COPs presented from other cooling applications in literature. For most parts of the year the COP for the NCL system was just slightly below the standard system configuration. The only exception was, as expected, when storing mangoes. The standard system configuration resulted in an average annual SCOP of 6.47, while the NCL system resulted in an annual average SCOP of 5.57. In conclusion, both systems have a good performance and the NCL system is definitively competitive if the evaporation temperature can be kept constant.

The revenue of the system is also considered good. Operating profits are high, as electricity rates are low. With a domestic consumer electricity rate, the standard system configuration will result in an operating profit about 479 000 INR, while the NCL system is just below with about 478 000 INR. If a higher, commercial consumer, rate is used, the operating profit of the standard system is estimated to about 476 000 INR, while the NCL system is estimated to 474 000 INR. Based on this, it is concluded that both system configurations are highly feasible in economical terms, as they can yield a positive operating profit even for low-value products with a short storage life time.

Hopefully, this proves that such a system is feasible and can be profitable when used at Indian mandis' or small markets. It will extend the season and availability of the stored product for the consumer, reduce post-harvest wastes, improve the much needed cold chain facilities in the Indian food cold chain and increase the profit and revenue of the salesman. This might show other agents that one can benefit from using cold storages for more than just potatoes. As discussed in section 2.2 and 2.3, much of the cold storage industry in India is unorganised and based on environmentally harmful refrigerants. It is important that a system like the one investigated in this thesis is integrated in a larger chain of refrigerating and processing facilities. Just placing a storage at one market is not enough. The cold chain must be maintained from harvest, through the mandis, and to the consumer. This cold storage address one of the weakest links in both the domestic and export cold chain and it can be a crucial step in the right direction. The technology is modern and use of natural refrigerants are emphasised. However, it will require training in both maintenance and operation of the storage, to keep the equipment in good condition.

# Chapter 8

# Further Work

**Investment costs**

Investment costs are not considered in this thesis. Information about similar types of systems are scarce and estimating investment costs will therefore be inaccurate without any reliant sources for material and equipment costs. With more time, different suppliers of refrigeration systems in India can be contacted in order to create an estimation of investment costs. Operating profits are high, but investment costs will probably exceed them and the payback time might be several years.

**NCL instability**

One of the mentioned challenges with NCLs are the issues around instability as there are no equipment governing the flow. The instability of NCLs are not investigated further in this thesis. Only the driving force for the circulation is investigated and decided. In reality, even small disturbances might heavily affect the driving force. For a better modelling of the NCL, this instability should be investigated.

**Controlling the NCL**

In relation to future studies on the instability of NCLs, different methods for controlling the flow through the NCL externally can be investigated. It might be possible to control the NCL by altering the evaporation fan or the circulation of $NH_3$ through the IHX.

**Condenser**

The condenser is not designed in this thesis. Only the evaporator and IHX are investigated. Future work on this cold storage and refrigeration system should include design of the condenser as ambient temperatures in India might become very high and heat rejection can become an issue.

**Larger scale**

The proposed solution in this thesis is a small-scale system. For larger mandis' or markets it might be to small. It is proven to be feasible both in terms of products and revenue. A part of the future work can therefore be to estimate performance, revenue and usefulness of a larger system, which can handle a much larger portion of the produced fruits or vegetables.

**Cold chain integration**

As discussed, such a system should be integrated in a larger cold chain to ensure that a larger parts of the cold chains are maintained. Future studies around the cold storage solution, can include additional refrigeration systems and ways to integrate several system into a larger cold chain. This way, the problem with unorganised cold chains and numerous intermediates can be addressed.

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# Appendix A

# Additional material

# A.1 Current and alternative refrigerants in India

| Sector | Current Refrigerants Used | Alternative Refrigerants | Low GWP Refrigerants (GWP < 750) | ISHRAE Assessment of Low GWP options for India |
|---|---|---|---|---|
| **Domestic Refrigeration**<br>Single /Double Door | HC-600a , HFC-134a | | HC-600a, HFC-1234yf, HFC-1234ze | HC-600a |
| **Commercial Refrigeration**<br>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**<br>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**<br>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**<br>Refrigerated Transport Supply Chain | HCFC-22, HFC-134a, R-404A | *HFC-134a, R-407C, HFC-1234yf, R-744* | | None at the moment. |
| **Industrial Refrigeration**<br>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<br>R-717 | R-717 |
| **Chillers**<br>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,<br>HFC-1336mzz | |

**Figure A.1.1:** Current and alternative refrigerants in India (ISHRAE 2015).

## A.2 Effects of various ammonia concentrations

| Concentration, ppm | Effect |
|---:|---|
| 5 | Average odour threshold |
| 100-200 | Irritating eyes |
| 400 | Immediate throat irritation |
| Below 500 | No permanent eye damage to even chronic exposure |
| 1700 | Cough |
| 2400 | Threat to life after 30 minutes |
| 5000, pure liquid | Second degree burns with blisters |
| 7338 | Lethal concentration, one hour $LC_{50}$ |

**Table A.2.1:** Effect of various ammonia concentrations (Rule et al. 2017).

## A.3 Ammonia compressor efficiency chart

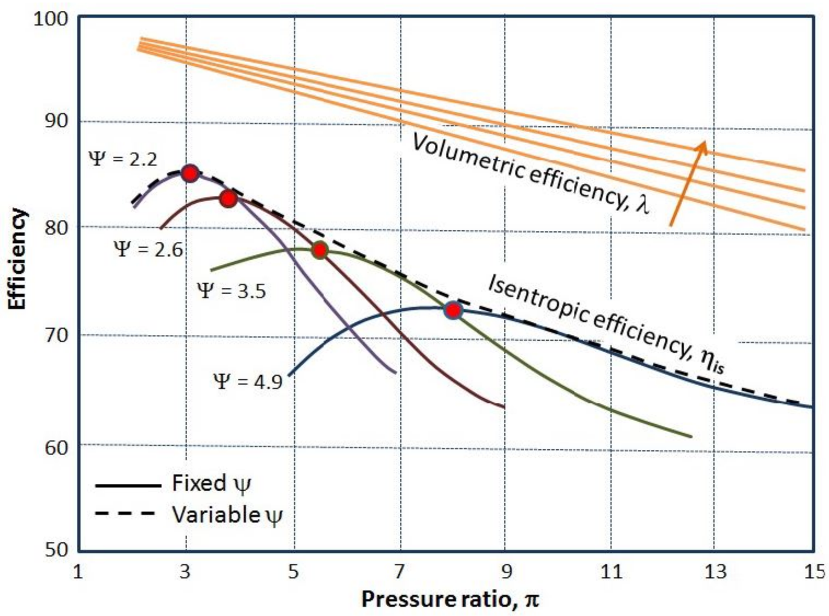


**Figure A.3.1:** Isentropic efficiency for twin screw ammonia compressors (Eikevik 2018).

## A.4 Temperatures during loading week for apples

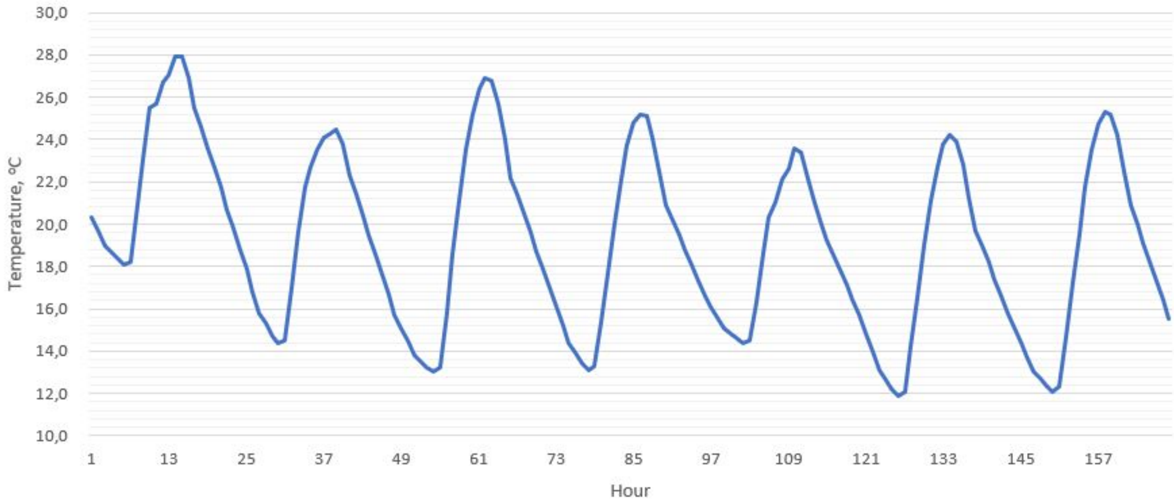


**Figure A.4.1:** Hourly temperatures during loading week for apples.

## A.5 Temperatures during loading week for mangoes

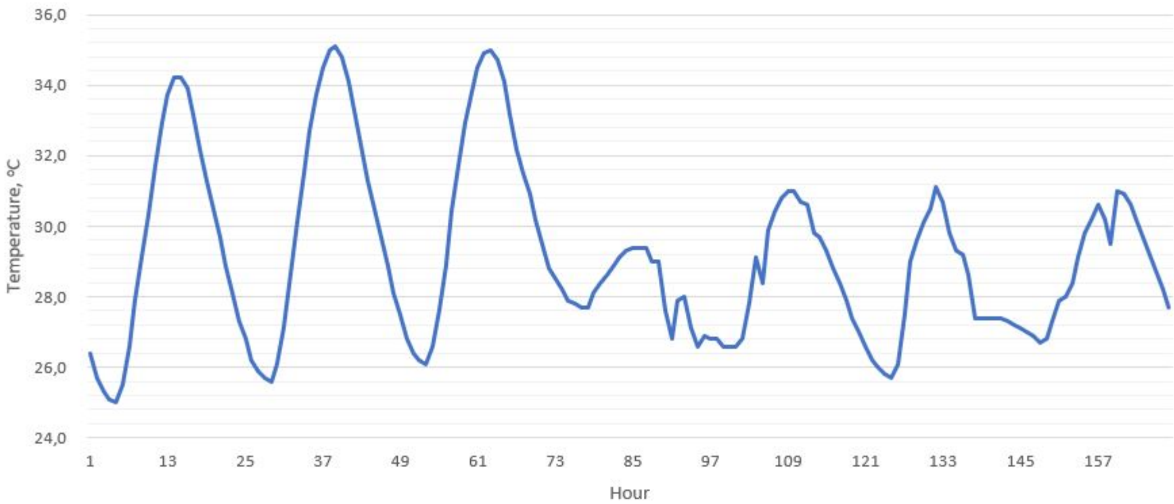


**Figure A.5.1:** Hourly temperatures during loading week for mangoes.

## A.6 Temperatures during loading week for grapes

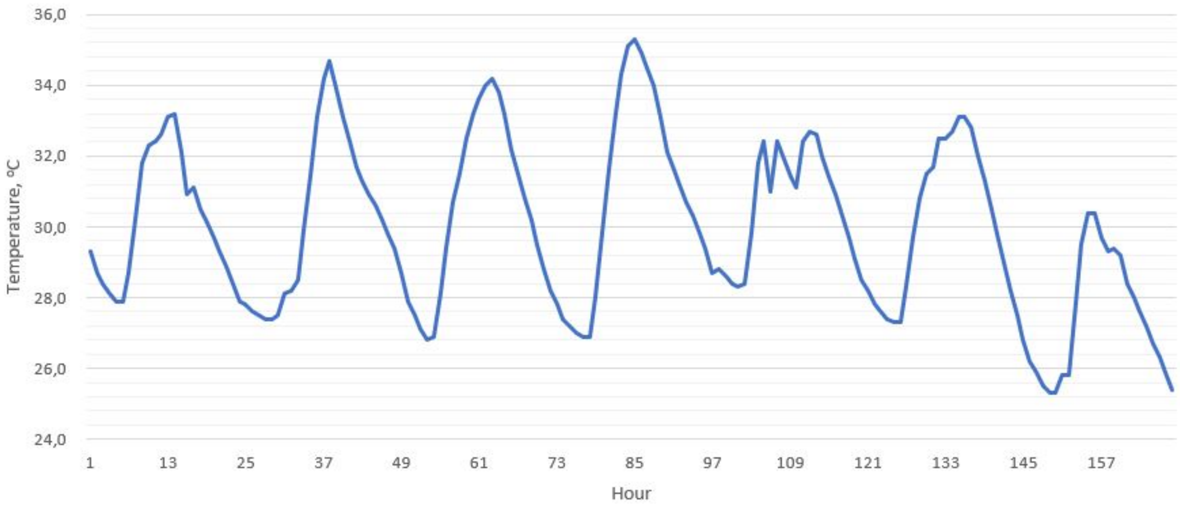


**Figure A.6.1:** Hourly temperatures during loading week for grapes.

## A.7 State-wise average rates of electricity in India

| State | Domestic consumer below 400 kWh/month | Commercial consumer below 300 kWh/month | Commercial consumer below 1 500 kWh/month |
|---|---:|---:|---:|
| Andaman and Nicobar Islands | 4.56 | 6.78 | 8.40 |
| Andhra Pradesh | 4.92 | 8.57 | 9.81 |
| Arunachal Pradesh | 4.00 | 5.00 | 5.00 |
| Assam | 6.36 | 8.14 | 8.34 |
| Bihar | 4.62 | 6.45 | 7.89 |
| Chandigarh | 4.15 | 5.88 | 6.14 |
| Chhattishgarh | 5.23 | 7.02 | 8.66 |
| Dadra and Nagar Haveli | 1.93 | 3.08 | 3.30 |
| Daman and Diu | 1.93 | 3.32 | 3.58 |
| Delhi (BYPL/BRPL/NDPL) | 5.49 | 9.94 | 9.94 |
| Delhi (NDMC) | 4.33 | 8.51 | 8.51 |
| Goa | 2.43 | 4.68 | 5.23 |
| Gujarat | 5.18 | 5.85 | 5.85 |
| Haryana | 5.31 | 6.15 | 6.85 |
| Himachal Pradesh | 3.04 | 5.81 | 5.53 |
| Jammu and Kashmir | 2.94 | 4.02 | 6.28 |
| Jharkhand | 3.23 | 7.17 | 7.21 |
| Karnataka | 6.67 | 8.82 | 8.96 |
| Kerala | 6.91 | 8.54 | 10.63 |
| Lakshadweep | 3.56 | 6.68 | 7.50 |
| Madhya Pradesh | 8.04 | 7.39 | 7.44 |
| Maharashtra | 9.66 | 10.20 | 12.28 |
| Manipur | 4.70 | 5.57 | 6.26 |
| Meghalaya | 4.78 | 6.99 | 7.38 |
| Mizoram | 4.50 | 5.00 | 5.75 |
| Nagaland | 5.66 | 7.58 | 8.48 |
| Odisha | 4.88 | 6.27 | 7.08 |
| Puducherry | 2.84 | 6.01 | 6.45 |
| Punjab | 6.60 | 7.54 | 7.61 |
| Rajasthan | 7.29 | 9.53 | 9.86 |
| Sikkim | 3.63 | 5.34 | 6.12 |
| Tamil Nadu | 4.70 | 8.37 | 9.33 |
| Telangana | 6.69 | 8.91 | 9.75 |
| Tripura | 7.55 | 6.92 | 7.68 |
| Uttar Pradesh | 5.86 | 8.28 | 10.05 |
| Uttarakhand | 3.86 | 5.62 | 5.62 |
| West Bengal | 8.44 | 8.81 | 10.27 |
| **Average** | **5.04** | **6.88** | **7.59** |

**Table A.7.1:** State-wise average rates of electricity in India, as on 01.04.2017 (Datanet India 2017). Rates in INR/kWh.

# Appendix B

# EES code

# B.1 NCL design

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```
$UnitSystem SI Radian Mass kJ kg C Pa

Procedure liquidheight(CO2$;T;d_pipe;d_receiver;CR;H;H_receiver_min;L_evaporator:H_L;H_receiver)

x_liquid = 0 [-]
x_gas = 1 [-]

rho_liquid = density(CO2$; x=x_liquid; T=T)
rho_gas = density(CO2$; x=x_gas; T=T)

V_downcomer = 1/4*pi*d_pipe^2*H
V_riser = 1/4*pi*d_pipe^2*H
V_evaporator = 1/4*pi*d_pipe^2*L_evaporator

V_receiver_standstill = 1/4*pi*d_receiver^2*H_receiver_min

m_tot = rho_liquid*(V_downcomer+V_riser+V_evaporator+V_receiver_standstill)
m_downcomer = rho_liquid*V_downcomer
m_riser = 1/CR*rho_gas*V_riser + (1-1/CR)*rho_liquid*V_riser
m_evaporator = 1/CR*rho_gas*V_evaporator + (1-1/CR)*rho_liquid*V_evaporator

m_receiver = m_tot-m_downcomer-m_riser-m_evaporator
V_receiver = m_receiver/rho_liquid

H_receiver = V_receiver/(1/4*pi*d_receiver^2)
H_L = H+H_receiver

End procedure



Procedure maxliquidheight(CO2$;T;d_pipe;d_receiver;H;H_receiver_min;L_evaporator:H_L_max)

CR_max = 1 [-]

x_liquid = 0 [-]
x_gas = 1 [-]

rho_liquid = density(CO2$; x=x_liquid; T=T)
rho_gas = density(CO2$; x=x_gas; T=T)

V_downcomer = 1/4*pi*d_pipe^2*H
V_riser = 1/4*pi*d_pipe^2*H
V_evaporator = 1/4*pi*d_pipe^2*L_evaporator

V_receiver_standstill = 1/4*pi*d_receiver^2*H_receiver_min

m_tot = rho_liquid*(V_downcomer+V_riser+V_evaporator+V_receiver_standstill)
m_downcomer = rho_liquid*V_downcomer
m_riser = 1/CR_max*rho_gas*V_riser + (1-1/CR_max)*rho_liquid*V_riser
m_evaporator = 1/CR_max*rho_gas*V_evaporator + (1-1/CR_max)*rho_liquid*V_evaporator

m_receiver = m_tot-m_downcomer-m_riser-m_evaporator
V_receiver = m_receiver/rho_liquid

H_receiver = V_receiver/(1/4*pi*d_receiver^2)
H_L_max = H+H_receiver

End procedure
```

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```


Procedure downcomer(CO2$;g;x_liquid;m;rho_liquid;T;H;H_L;d_pipe;l_eq;epsilon:dP_downcomer)

"Static pressure increase in downcomer"
dP_static = rho_liquid*g*H_L

"Major head loss in downcomer, liquid flow"
mu = viscosity(CO2$; x=x_liquid; T=T)
Re = ( 4/pi )*(( m )/( d_pipe*mu ))
f = ( -2 * log10 ( (epsilon/d_pipe)/(3,7) + (5,74)/(Re^(0,9)) ) )^(-2)
dP_major = f * ( (2)/(pi) ) * ( (H)/(d_pipe^3) ) * ((m^2)/(rho_liquid))

"Minor head loss, one 90 degree bend"
dP_minor = f * ((2)/(pi)) * ((l_eq)/(d_pipe^3)) * ((m^2)/(rho_liquid))

"Total downcomer pressure difference"
dP_downcomer = dP_static - dP_major - dP_minor

End procedure



Procedure riser(CO2$;g;x;m;rho;rho_liquid;rho_gas;mu_gas;mu_liquid;T;H_L;H_L_max;d_pipe;l_eq;epsilon:dP_riser)

H_riser = H_L_max + 0,2

"Static pressure loss"
dP_static = rho*g*H_riser

"Major loss, two-phase fluid"
Re = ( (4000*m)/(pi*d_pipe) ) * ( (x^2 + (1-x)^2 *((rho_gas)/(rho_liquid)) )/( mu_gas*x + mu_liquid*(1-x)*((rho_gas)
/(rho_liquid)) ) )
f_inv = -2* log10( 269,7963 * ((epsilon)/(d_pipe)) - ((5,0452)/(Re)) * log10 ( ((1)/(2,8257)) * ((1000*epsilon)/(d_pipe))^(1,1098
) + ((5,8506)/(Re^(0,8981))) ) )
f = (1/f_inv)^2
dP_major = f * ( (2)/(pi) ) * ( (H_riser)/(d_pipe^3) ) * ((m^2)/(rho))

"Minor loss, two 90 degree bends"
dP_minor = 2*( f * ((2)/(pi)) * ((l_eq)/(d_pipe^3)) * ((m^2)/(rho)) )

"Total riser pressure difference"
dP_riser = dP_static + dP_major + dP_minor

End procedure



Procedure evaporator(CO2$;g;x;x_liquid;m;rho_liquid;rho_gas;mu_gas;mu_liquid;T;d_pipe;N_pipes
;L_evaporator_single_pipe;l_eq;epsilon:dP_evaporator)
$Arrays on

"Major loss, two-phase fluid"
dP_major = 0 [Pa]

Duplicate i=1;N_pipes

dx = (x-x_liquid)/N_pipes
x_maj[i] = x_liquid + i*dx

```

```
rho_maj[i] = density(CO2$; x=x_maj[i]; T=T)
Re_maj[i] = ( ( 4000*m ) / ( pi*d_pipe ) ) * ( ( x_maj[i]^2 + (1-x_maj[i])^2 *((rho_gas)/(rho_liquid)) ) / ( mu_gas*x_maj[i] + mu_liquid*(1-x_maj[i])*(rho_gas/rho_liquid) ) )
f_inv = -2* log10( 269,7963 * ((epsilon)/(d_pipe)) - ((5,0452)/(Re_maj[i])) * log10 ( ((1)/(2,8257)) * ((1000*epsilon)/(d_pipe))^(1,1098) + ((5,8506)/(Re_maj[i]^(0,8981))) ) )
f_maj[i] = (1/f_inv)^2
dP_major_dx[i] = f_maj[i] * ( (2)/(pi) ) * ( (L_evaporator_single_pipe)/(d_pipe^3) ) * ((m^2)/(rho_maj[i]))
dP_major = dP_major + dP_major_dx[i]
End duplicate
"Minor loss, 180 degree U-bend aT end of each pipe except last pipe"
dP_minor = 0 [Pa]
N_bends = N_pipes-1
Duplicate i=1;N_bends
dx = (x-x_liquid)/N_pipes
x_min[i] = x_liquid + i*dx
rho_min[i] = density(CO2$; x=x_min[i]; T=T)
Re_min[i] = ( ( 4000*m ) / ( pi*d_pipe ) ) * ( ( x_min[i]^2 + (1-x_min[i])^2 *((rho_gas)/(rho_liquid)) ) / ( mu_gas*x_min[i] + mu_liquid*(1-x_min[i])*(rho_gas/rho_liquid) ) )
f_inv = -2* log10( 269,7963 * ((epsilon)/(d_pipe)) - ((5,0452)/(Re_min[i])) * log10 ( ((1)/(2,8257)) * ((1000*epsilon)/(d_pipe))^(1,1098) + ((5,8506)/(Re_min[i]^(0,8981))) ) )
f_min[i] = (1/f_inv)^2
dP_minor_dx[i] = f_min[i] * ((2)/(pi)) * ((l_eq)/(d_pipe^3)) * ((m^2)/(rho_min[i]))
dP_minor = dP_minor + dP_minor_dx[i]
End duplicate
dP_evaporator = dP_major + dP_minor
End Procedure
Procedure drivingforce(dP_downcomer;dP_riser;dP_evaporator:dP_tot_Pa;dP_tot_bar)
dP_tot_Pa = dP_downcomer - dP_riser - dP_evaporator
dP_tot_bar = dP_tot_Pa/10^5
End procedure
CO2$ = 'carbondioxide'
g = 9,81 [m/s^2]
T = -2 [C]
CR = 2 [-]
x_gas = 1 [-]
x_liquid = 0 [-]
x = 1/CR
h_downcomer = enthalpy(CO2$; x=x_liquid; T=T)
h_riser = enthalpy(CO2$; x=x; T=T)
```

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```
"Q_evap = 2,426 [kW]"
m = Q_evap/(h_riser-h_downcomer)
P = pressure(CO2$; x=x_gas; T=T)
rho = density(CO2$; x=x; T=T)
rho_liquid = density(CO2$; x=x_liquid; T=T)
rho_gas = density(CO2$; x=x_gas; T=T)
mu_gas = viscosity(CO2$; x=x_gas; T=T)
mu_liquid = viscosity(CO2$; x=x_liquid; T=T)
H = 1 [m]
L_evaporator = 128,8 [m]
L_evaporator_single_pipe = 0,8 [m]
epsilon = 0,0000015 [m]
H_receiver_min = 0,1 [m]
d_receiver = 0,3 [m]
N_pipes = 161 [-]
{"Use for 3/8" pipes"
d_outer = 0,00953 [m]
thickness_pipe = 0,00076 [m]
l_eq = 0,9 [m]}
{"Use for 1/2" pipes"
d_outer = 0,0127 [m]
thickness_pipe = 0,00089 [m]
l_eq = 1,1 [m]}
"Use for 5/8" pipes"
d_outer = 0,01588 [m]
thickness_pipe = 0,00102 [m]
l_eq = 1,2 [m]
d_pipe = d_outer - 2*thickness_pipe
Call liquidheight(CO2$;T;d_pipe;d_receiver;CR;H;H_receiver_min;L_evaporator:H_L;H_receiver)
Call maxliquidheight(CO2$;T;d_pipe;d_receiver;H;H_receiver_min;L_evaporator:H_L_max)
Call downcomer(CO2$;g;x_liquid;m;rho_liquid;T;H;H_L;d_pipe;l_eq;epsilon:dP_downcomer)
Call riser(CO2$;g;x;m;rho;rho_liquid;rho_gas;mu_gas;mu_liquid;T;H_L;H_L_max;d_pipe;l_eq;epsilon:dP_riser)
Call evaporator(CO2$;g;x;x_liquid;m;rho_liquid;rho_gas;mu_gas;mu_liquid;T;d_pipe;N_pipes;L_evaporator_single_pipe;l_eq;epsilon:dP_evaporator)
Call drivingforce(dP_downcomer;dP_riser;dP_evaporator:dP_tot_Pa;dP_tot_bar)
```

# B.2 Storing apples

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```
$UnitSystem SI Radian Mass kJ kg C bar


Procedure transmissionload(T_room;T_amb:Q_Transmission)

"Cold storage exterior size"
L_ext = 6,1 [m]                                   "Length"
W_ext = 2,44 [m]                                  "Width"
H_ext = 2,6 [m]                                   "Height"

"Surface areas"
A_north = W_ext*H_ext                             "North wall area"
A_south = W_ext*H_ext                             "South wall area"
A_east = L_ext*H_ext                              "East wall area"
A_west = L_ext*H_ext                              "West wall area"
A_roof = W_ext*L_ext                              "Roof area"
A_floor = W_ext*L_ext                             "Floor area"

"Insulation, expanded polysterene"
delta_ins = 0,075 [m]                             "Insulation thickness"
k_ins = 0,037 [W/(m*K)]                           "Thermal conductivity of insulation"
U_ins = k_ins/delta_ins                           "Insulation heat transfer coefficient"

"Allowance for sun effect"
dT_sun_east = 3 [C]                               "East wall allowance"
dT_sun_west = 3 [C]                               "West wall allowance"
dT_sun_south = 2 [C]                              "South wall allowance"
dT_sun_roof = 5 [C]                               "Flat roof allowance"

T_wall_east = T_amb+dT_sun_east                   "East wall"
T_wall_west = T_amb+dT_sun_west                   "West wall"
T_wall_south = T_amb+dT_sun_south                 "South wall"
T_wall_north = T_amb                              "North wall, with door"
T_roof = T_amb+dT_sun_roof                        "Flat roof"
T_floor = T_amb                                   "Floor"


"Transmission load"
Q_T_south = U_ins*A_south*(T_wall_south-T_room)   "South wall, [W]"
Q_T_east = U_ins*A_east*(T_wall_east-T_room)      "East wall, [W]"
Q_T_west = U_ins*A_west*(T_wall_west-T_room)      "West wall, [W]"
Q_T_north = U_ins*A_north*(T_wall_north-T_room)   "North wall, [W]"
Q_T_roof = U_ins*A_roof*(T_roof-T_room)           "Flat roof, [W]"
Q_T_floor = U_ins*A_floor*(T_floor-T_room)        "Floor, [W]"
```

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```

Q_Transmission = (Q_T_south+Q_T_east+Q_T_west+Q_T_north+Q_T_roof+Q_T_floor)/1000    "Total transmission load, [kW]"

End


Procedure infiltrationload(T_amb;T_room:Q_Infiltration)

air$ = 'air'
P_amb = 1,01325 [bar]    "Atmospheric pressure"
g = 9,81 [m/s^2]    "Gravity"

H_door = 2,045 [m]    "Door height"
W_door = 0,8 [m]    "Door width"
A_door = H_door*W_door    "Door area"

D_f = 0,8 [-]    "Doorway flow factor"
E = 0,9 [-]    "New strip curtains"
Theta_d = 24 [h]    "Time period"
Theta_o = 5 [min]    "Door simply stands open"
Theta_p = 30 [s]    "Door open-close time"
N = 1 [-]    "Door is opened once a day"

h_amb = enthalpy(air$; T=T_amb)    "Ambient air enthalpy"
rho_amb = density(air$; T=T_amb; P=P_amb)    "Density ambient air"

h_room = enthalpy(air$; T=T_room)    "Cold storage air enthalpy"
rho_room = density(air$; T=T_room; P=P_amb)    "Density cold storage air"

D_t = (N*Theta_p+60*Theta_o)/(3600*Theta_d)    "Doorway open-time factor"
F_m = ((2)/(1+(rho_room/rho_amb)^(1/3)))^(1,5)    "Density factor"
Q_s = 0,221*A_door*(h_amb-h_room)*rho_room*(1-(rho_amb/rho_room))^(0,5)*(g*H_door)^(0,5)*F_m    "Sensible and latent refrigeration load, [kW]"

Q_Infiltration = Q_s*D_t*D_f*(1-E)    "Total infiltration load, [kW]"

End


Procedure respirationheat(:Q_Respiration)

"Cold storage interior size, without insulation"
L_int_ex_ins = 5,87 [m]    "Length"
W_int_ex_ins = 2,34 [m]    "Width"
H_int_ex_ins = 2,38 [m]    "Height"

```

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```
delta_ins = 0,075 [m]    "Insulation thickness"

"Interior size, including insulation thickness"
L_int = L_int_ex_ins-delta_ins    "Length"
W_int = W_int_ex_ins-delta_ins    "Width"
H_int = H_int_ex_ins-delta_ins    "Height"
A_int = L_int*W_int    "Floor area"

L_aisle=L_int    "Aisle length"
W_aisle=0,8 [m]    "Aisle width"

V_storage = (W_int-W_aisle)*L_int*H_int    "Available storage space"
rho_storage = 200 [kg/m^3]    "Storage density"
m_apple = (7/7)*rho_storage*V_storage    "Mass of apples stored"

q_resp_apple = 0,0102 [W/kg]    "Respiration rate, apple"

Q_Respiration = (m_apple*q_resp_apple)/1000    "Respiration heat, [kW]"

End


Procedure equipmentload(Q_Transmission;Q_Infiltration;Q_Respiration:Q_Equipment)

Q_Equipment = 0,1*(Q_Transmission+Q_Infiltration+Q_Respiration)    "10 % of total load, [kW]"

End


Procedure holdingload(Q_Transmission;Q_Infiltration;Q_Respiration;Q_Equipment:Q_HoldingLoad)

Q_HoldingLoad = 1,1*(Q_Transmission+Q_Infiltration+Q_Respiration+Q_Equipment)    "Total steady state holding refrigeration load, with safety factor of 10%, [kW]"

End


Procedure pulldownload(T_room;T_amb:Q_Pulldown)

T_apple = T_amb    "Apple loading temperature"

"Cold storage interior size, without insulation"
L_int_ex_ins = 5,87 [m]    "Length"
W_int_ex_ins = 2,34 [m]    "Width"
H_int_ex_ins = 2,38 [m]    "Height"

delta_ins = 0,075 [m]    "Insulation thickness"

"Interior size, including insulation thickness"
L_int = L_int_ex_ins-delta_ins    "Length"
W_int = W_int_ex_ins-delta_ins    "Width"
```

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```
H_int = H_int_ex_ins-delta_ins "Height"

L_aisle=L_int "Aisle length"
W_aisle=0,8 [m] "Aisle width"

V_storage = (W_int-W_aisle)*L_int*H_int "Available storage space"
rho_storage = 200 [kg/m^3] "Storage density"
m_apple = (1/7)*rho_storage*V_storage "Mass of apples loaded each day"

C_P_apple = 3,81 [kJ/(kg*K)]

q_pulldown_apple = m_apple*C_P_apple*(T_apple-T_room) "Heat removed for apples, [kJ]"

t_Pulldown = 24 "Pull down time, [h]"

Q_Pulldown = 1,1*((q_pulldown_apple)/(3600*t_Pulldown))
"Pulldown load, including safety factor of 10%, [kW]"

"Q_Pulldown = 0 [kW]" "Use when no pull down load"

End


Procedure refrigerationload(Q_HoldingLoad;Q_Pulldown:Q_TotalLoad)

Q_TotalLoad = Q_HoldingLoad+Q_Pulldown "Total refrigeration load, [kW]"

End

Procedure ammonia(T_amb;T_room;Q_TotalLoad:COP;V_compressor;m_cond;m_evap;W;Q_cond;dP)
$Arrays on

NH3$ = 'ammonia'

T_evap = -2 [C] "Evaporator temperature"
T_cond = T_amb+5 "Condenser temperature"

eta = 0,8 [-] "Isentropic efficiency compressor"

"Decide load"
Q_L = Q_TotalLoad

"Point 5: Inlet evaporator"
x[5] = 0 [-]
T[5] = T_evap
P[5] = pressure(NH3$; x=x[5]; T=T[5])
h[5] = enthalpy(NH3$; x=x[5]; T=T[5])
s[5] = entropy(NH3$; x=x[5]; T=T[5])
v[5] = volume(NH3$; x=x[5]; T=T[5])
```

```
"Point 6: Exit evaporator"
x[6] = 1 [-]
P[6] = P[5]
T[6] = temperature(NH3$; x=x[6]; P=P[6])
h[6] = enthalpy(NH3$; x=x[6]; P=P[6])
s[6] = entropy(NH3$; x=x[6]; P=P[6])
v[6] = volume(NH3$; x=x[6]; P=P[6])

"Point 1: Inlet compressor"
x[1] = 1 [-]
P[1] = P[5]
T[1] = temperature(NH3$; x=x[1]; P=P[1])
h[1] = enthalpy(NH3$; x=x[1]; P=P[1])
s[1] = entropy(NH3$; x=x[1]; P=P[1])
v[1] = volume(NH3$; x=x[1]; P=P[1])

"Point 3: Exit condenser"
x[3] = 0 [-]
T[3] = T_cond
P[3] = pressure(NH3$; x=x[3]; T=T[3])
h[3] = enthalpy(NH3$; x=x[3]; T=T[3])
s[3] = entropy(NH3$; x=x[3]; T=T[3])
v[3] = volume(NH3$; x=x[3]; T=T[3])

"Point 4: Two-phase inlet receiver, after expansion"
h[4] = h[3]
P[4] = P[5]
T[4] = temperature(NH3$; h=h[4]; P=P[4])
s[4] = entropy(NH3$; h=h[4]; P=P[4])
x[4] = quality(NH3$; h=h[4]; P=P[4])
v[4] = volume(NH3$; h=h[4]; P=P[4])

"Point 2s: Isentropic exit compressor"
ss[2] = s[1]
P[2] = P[3]
Ts[2] = temperature(NH3$; s=ss[2]; P=P[2])
hs[2] = enthalpy(NH3$; s=ss[2]; P=P[2])
xs[2] = quality(NH3$; s=ss[2]; P=P[2])
vs[2] = volume(NH3$; s=ss[2]; P=P[2])

"Mass flows"
m_evap = Q_L/(h[6]-h[5])                          "Mass flow through evaporator"
m_cond = m_evap*((h[5]-h[6])/(h[4]-h[1]))         "Mass flow through condenser"

"Compressor work"
W_is = m_cond*(hs[2]-h[1])
W = W_is/eta

"Point 2: Real exit compressor"
h[2] = h[1]+W/m_cond
T[2] = temperature(NH3$; h=h[2]; P=P[2])
s[2] = entropy(NH3$; h=h[2]; P=P[2])
x[2] = quality(NH3$; h=h[2]; P=P[2])
v[2] = volume(NH3$; h=h[2]; P=P[2])

"Rejected heat condenser"
Q_cond = m_cond*(h[2]-h[3])
```

```
"Pressure ratio"
dP = P[2]/P[1]

"COP"
COP = Q_L/W

"Volumetric floWs"
V_compressor = m_cond*v[1]

End


Procedure ammonianclx_exit_evap;T_amb;T_room;Q_TotalLoad:COP_NCL;V_compressor_NCL;m_cond_NCL
;m_evap_NCL;W_NCL;Q_cond_NCL;dP_NCL)
$Arrays on

NH3$ = 'ammonia'
CO2$ = 'carbondioxide'

T_evap = -2 [C]                                  "Evaporator temperature"
T_cond = T_amb+5                                 "Condenser temperature"
T_HX = T_evap-1                                  "NH3/CO2 heat exchanger temperature"

eta = 0,8 [-]                                    "Isentropic efficiency compressor"

"Decide load"
Q_L = Q_TotalLoad

"Point 5: NH3 inlet intermediate HX"
x[5] = 0 [-]
T[5] = T_HX
P[5] = pressure(NH3$; x=x[5]; T=T[5])
h[5] = enthalpy(NH3$; x=x[5]; T=T[5])
s[5] = entropy(NH3$; x=x[5]; T=T[5])
v[5] = volume(NH3$; x=x[5]; T=T[5])

"Point 6: NH3 exit intermediate HX"
x[6] = 1 [-]
P[6] = P[5]
T[6] = temperature(NH3$; x=x[6]; P=P[6])
h[6] = enthalpy(NH3$; x=x[6]; P=P[6])
s[6] = entropy(NH3$; x=x[6]; P=P[6])
v[6] = volume(NH3$; x=x[6]; P=P[6])

"Point 1: Inlet compressor"
x[1] = 1 [-]
P[1] = P[5]
T[1] = temperature(NH3$; x=x[1]; P=P[1])
h[1] = enthalpy(NH3$; x=x[1]; P=P[1])
s[1] = entropy(NH3$; x=x[1]; P=P[1])
v[1] = volume(NH3$; x=x[1]; P=P[1])

"Point 3: Exit condenser"
x[3] = 0 [-]
T[3] = T_cond
P[3] = pressure(NH3$; x=x[3]; T=T[3])
```

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```
h[3] = enthalpy(NH3$; x=x[3]; T=T[3])
s[3] = entropy(NH3$; x=x[3]; T=T[3])
v[3] = volume(NH3$; x=x[3]; T=T[3])

"Point 4: Two-phase inlet receiver, after expansion"
h[4] = h[3]
P[4] = P[5]
T[4] = temperature(NH3$; h=h[4]; P=P[4])
s[4] = entropy(NH3$; h=h[4]; P=P[4])
x[4] = quality(NH3$; h=h[4]; P=P[4])
v[4] = volume(NH3$; h=h[4]; P=P[4])

"Point 2s: Isentropic exit compressor"
ss[2] = s[1]
P[2] = P[3]
Ts[2] = temperature(NH3$; s=ss[2]; P=P[2])
hs[2] = enthalpy(NH3$; s=ss[2]; P=P[2])
xs[2] = quality(NH3$; s=ss[2]; P=P[2])
vs[2] = volume(NH3$; s=ss[2]; P=P[2])

"Point 7: CO2 inlet evaporator"
x[7] = 0 [-]
T[7] = T_evap
P[7] = pressure(CO2$; x=x[7]; T=T[7])
h[7] = enthalpy(CO2$; x=x[7]; T=T[7])
s[7] = entropy(CO2$; x=x[7]; T=T[7])
v[7] = volume(CO2$; x=x[7]; T=T[7])

"Point 8: CO2 exit evaporator"
P[8] = P[7]
x[8] = x_exit_evap
T[8] = temperature(CO2$; P=P[8]; x=x[8])
h[8] = enthalpy(CO2$; P=P[8]; x=x[8])
s[8] = entropy(CO2$; P=P[8]; x=x[8])
v[8] = volume(CO2$; P=P[8]; x=x[8])

"Mass flows"
m_evap_NCL = Q_L/(h[8]-h[7])                                   "Mass flow
of CO2 through evaporator"
m_HX_NH3 = Q_L/(h[6]-h[5])                                     "Mass flow
of NH3 through intermediate HX"
m_cond_NCL = m_HX_NH3*((h[5]-h[6])/(h[4]-h[1]))                "Mass flow
through condenser"

"Compressor work"
W_is = m_cond_NCL*(hs[2]-h[1])
W_NCL = W_is/eta

"Point 2: Real exit compressor"
h[2] = h[1]+W_NCL/m_cond_NCL
T[2] = temperature(NH3$; h=h[2]; P=P[2])
s[2] = entropy(NH3$; h=h[2]; P=P[2])
x[2] = quality(NH3$; h=h[2]; P=P[2])
v[2] = volume(NH3$; h=h[2]; P=P[2])

"Rejected heat condenser"
Q_cond_NCL = m_cond_NCL*(h[2]-h[3])

"Pressure ratio"
dP_NCL = P[2]/P[1]
```

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```
"COP"
COP_NCL = Q_L/W_NCL

"Volumetric floWs"
V_compressor_NCL = m_cond_NCL*v[1]

End


T_room_K = T_room + 273,15
T_amb_K = T_amb + 273,15
COP_Ca = (T_room_K)/(T_amb_K - T_room_K)          "Carnot COP"

"Room and ambient temperatures"
T_room = -0,5 [C]          "Cold storage temperature, -0,5 degrees"
T_amb = 33,5 [C]          "Ambient temperature"
CR = 2 [-]          "Circulation rate"
x_exit_evap = 1/CR          "Gas quality at exit of CO2 evaporator"
"Day = x"

Call transmissionload(T_room;T_amb:Q_Transmission)
Call infiltrationload(T_amb;T_room:Q_Infiltration)
Call respirationheat(T_room:Q_Respiration)
Call equipmentload(Q_Transmission;Q_Infiltration;Q_Respiration:Q_Equipment)
Call holdingload(Q_Transmission;Q_Infiltration;Q_Respiration;Q_Equipment:Q_HoldingLoad)
Call pulldownload(T_room;T_amb:Q_Pulldown)
Call refrigerationload(Q_HoldingLoad;Q_Pulldown:Q_TotalLoad)
Call ammonia(T_amb;T_room;Q_TotalLoad:COP;V_compressor;m_cond;m_evap;W;Q_cond;dP)
Call ammoniancl(x_exit_evap;T_amb;T_room;Q_TotalLoad:COP_NCL;V_compressor_NCL;m_cond_NCL;m_evap_NCL
;W_NCL;Q_cond_NCL;dP_NCL)
```

# B.3 Storing mangoes

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```
$UnitSystem SI Radian Mass kJ kg C bar


Procedure transmissionload(T_room;T_amb:Q_Transmission)

"Cold storage exterior size"
L_ext = 6,1 [m]                                   "Length"
W_ext = 2,44 [m]                                  "Width"
H_ext = 2,6 [m]                                   "Height"

"Surface areas"
A_north = W_ext*H_ext                             "North wall area"
A_south = W_ext*H_ext                             "South wall area"
A_east = L_ext*H_ext                              "East wall area"
A_west = L_ext*H_ext                              "West wall area"
A_roof = W_ext*L_ext                              "Roof area"
A_floor = W_ext*L_ext                             "Floor area"

"Insulation, expanded polystyrene"
delta_ins = 0,075 [m]                             "Insulation thickness"
k_ins = 0,037 [W/(m*K)]                           "Thermal conductivity of insulation"
U_ins = k_ins/delta_ins                           "Insulation heat transfer coefficient"

"Allowance for sun effect"
dT_sun_east = 3 [C]                               "East wall allowance"
dT_sun_west = 3 [C]                               "West wall allowance"
dT_sun_south = 2 [C]                              "South wall allowance"
dT_sun_roof = 5 [C]                               "Flat roof allowance"

T_wall_east = T_amb+dT_sun_east                   "East wall"
T_wall_west = T_amb+dT_sun_west                   "West wall"
T_wall_south = T_amb+dT_sun_south                 "South wall"
T_wall_north = T_amb                              "North wall, with door"
T_roof = T_amb+dT_sun_roof                        "Flat roof"
T_floor = T_amb                                   "Floor"


"Transmission load"
Q_T_south = U_ins*A_south*(T_wall_south-T_room)   "South wall, [W]"
Q_T_east = U_ins*A_east*(T_wall_east-T_room)      "East wall, [W]"
Q_T_west = U_ins*A_west*(T_wall_west-T_room)      "West wall, [W]"
Q_T_north = U_ins*A_north*(T_wall_north-T_room)   "North wall, [W]"
Q_T_roof = U_ins*A_roof*(T_roof-T_room)           "Flat roof, [W]"
Q_T_floor = U_ins*A_floor*(T_floor-T_room)        "Floor, [W]"
```

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```

Q_Transmission = (Q_T_south+Q_T_east+Q_T_west+Q_T_north+Q_T_roof+Q_T_floor)/1000    "Total transmission load, [kW]"

End


Procedure infiltrationload(T_amb;T_room:Q_Infiltration)

air$ = 'air'
P_amb = 1,01325 [bar]    "Atmospheric pressure"
g = 9,81 [m/s^2]    "Gravity"

H_door = 2,045 [m]    "Door height"
W_door = 0,8 [m]    "Door width"
A_door = H_door*W_door    "Door area"

D_f = 0,8 [-]    "Doorway flow factor"
E = 0,9 [-]    "New strip curtains"
Theta_d = 24 [h]    "Time period"
Theta_o = 5 [min]    "Door simply stands open"
Theta_p = 30 [s]    "Door open-close time"
N = 1 [-]    "Door is opened once a day"

h_amb = enthalpy(air$; T=T_amb)    "Ambient air enthalpy"
rho_amb = density(air$; T=T_amb; P=P_amb)    "Density ambient air"

h_room = enthalpy(air$; T=T_room)    "Cold storage air enthalpy"
rho_room = density(air$; T=T_room; P=P_amb)    "Density cold storage air"

D_t = (N*Theta_p+60*Theta_o)/(3600*Theta_d)    "Doorway open-time factor"
F_m = ((2)/(1+(rho_room/rho_amb)^(1/3)))^(1,5)    "Density factor"
Q_s = 0,221*A_door*(h_amb-h_room)*rho_room*(1-(rho_amb/rho_room))^(0,5)*(g*H_door)^(0,5)*F_m    "Sensible and latent refrigeration load, [kW]"

Q_Infiltration = Q_s*D_t*D_f*(1-E)    "Total infiltration load, [kW], during holding"

End


Procedure respirationheat(:Q_Respiration)

"Cold storage interior size, without insulation"
L_int_ex_ins = 5,87 [m]    "Length"
W_int_ex_ins = 2,34 [m]    "Width"
H_int_ex_ins = 2,38 [m]    "Height"

```

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```
delta_ins = 0,075 [m]                                   "Insulation thickness"

"Interior size, including insulation thickness"
L_int = L_int_ex_ins-delta_ins                          "Length"
W_int = W_int_ex_ins-delta_ins                          "Width"
H_int = H_int_ex_ins-delta_ins                          "Height"
A_int = L_int*W_int                                     "Floor area"

L_aisle=L_int                                           "Aisle length"
W_aisle=0,8 [m]                                         "Aisle width"

V_storage = (W_int-W_aisle)*L_int*H_int                 "Available storage space"
rho_storage = 200 [kg/m^3]                              "Storage density"
m_mango = (7/7)*rho_storage*V_storage                   "Mass of mango stored"

q_resp_mango = 0,1334 [W/kg]                            "Respiration rate, mango"

Q_Respiration = (m_mango*q_resp_mango)/1000             "Respiration heat, [kW]"

End


Procedure equipmentload(Q_Transmission;Q_Infiltration;Q_Respiration:Q_Equipment)

Q_Equipment = 0,1*(Q_Transmission+Q_Infiltration+Q_Respiration)     "10 % of total load, [kW]"

End


Procedure holdingload(Q_Transmission;Q_Infiltration;Q_Respiration;Q_Equipment:Q_HoldingLoad)

Q_HoldingLoad = 1,1*(Q_Transmission+Q_Infiltration+Q_Respiration+Q_Equipment)     "Total steady state holding refrigeration load, with safety factor of 10%, [kW]"

End


Procedure pulldownload(T_room;T_amb:Q_Pulldown)

T_mango = T_amb                                         "Mango loading temperature"

"Cold storage interior size, without insulation"
L_int_ex_ins = 5,87 [m]                                 "Length"
W_int_ex_ins = 2,34 [m]                                 "Width"
H_int_ex_ins = 2,38 [m]                                 "Height"

delta_ins = 0,075 [m]                                   "Insulation thickness"

"Interior size, including insulation thickness"
L_int = L_int_ex_ins-delta_ins                          "Length"
W_int = W_int_ex_ins-delta_ins                          "Width"
```

```
H_int = H_int_ex_ins-delta_ins "Height"
L_aisle=L_int "Aisle length"
W_aisle=0,8 [m] "Aisle width"
V_storage = (W_int-W_aisle)*L_int*H_int "Available storage space"
rho_storage = 200 [kg/m^3] "Storage density"
m_mango = (1/7)*rho_storage*V_storage "Mass of mango loaded each day"
C_P_mango = 3,74 [kJ/(kg*K)]
q_pulldown_mango = m_mango*C_P_mango*(T_mango-T_room) "Heat removed for mango, [kJ]"
t_Pulldown = 24 "Pull down time, [h]"
Q_Pulldown = 1,1*((q_pulldown_mango)/(3600*t_Pulldown)) "Pulldown load, including safety factor of 10%, [kW]"
End
Procedure refrigerationload(Q_HoldingLoad;Q_Pulldown:Q_TotalLoad)
Q_TotalLoad = Q_HoldingLoad+Q_Pulldown "Total refrigeration load, [kW]"
End
Procedure ammonia(T_amb;T_room;Q_TotalLoad:COP;V_compressor;m_cond;m_evap;W;Q_cond;dP)
$Arrays on
NH3$ = 'ammonia'
T_evap = 11,5 [C] "Evaporator temperature"
T_cond = T_amb+5 "Condenser temperature"
eta = 0,8 [-] "Isentropic efficiency compressor"
"Decide load"
Q_L = Q_TotalLoad
"Point 5: Inlet evaporator"
x[5] = 0 [-]
T[5] = T_evap
P[5] = pressure(NH3$; x=x[5]; T=T[5])
h[5] = enthalpy(NH3$; x=x[5]; T=T[5])
s[5] = entropy(NH3$; x=x[5]; T=T[5])
v[5] = volume(NH3$; x=x[5]; T=T[5])
"Point 6: Exit evaporator"
x[6] = 1 [-]
```

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```
P[6] = P[5]
T[6] = temperature(NH3$; x=x[6]; P=P[6])
h[6] = enthalpy(NH3$; x=x[6]; P=P[6])
s[6] = entropy(NH3$; x=x[6]; P=P[6])
v[6] = volume(NH3$; x=x[6]; P=P[6])

"Point 1: Inlet compressor"
x[1] = 1 [-]
P[1] = P[5]
T[1] = temperature(NH3$; x=x[1]; P=P[1])
h[1] = enthalpy(NH3$; x=x[1]; P=P[1])
s[1] = entropy(NH3$; x=x[1]; P=P[1])
v[1] = volume(NH3$; x=x[1]; P=P[1])

"Point 3: Exit condenser"
x[3] = 0 [-]
T[3] = T_cond
P[3] = pressure(NH3$; x=x[3]; T=T[3])
h[3] = enthalpy(NH3$; x=x[3]; T=T[3])
s[3] = entropy(NH3$; x=x[3]; T=T[3])
v[3] = volume(NH3$; x=x[3]; T=T[3])

"Point 4: Two-phase inlet receiver, after expansion"
h[4] = h[3]
P[4] = P[5]
T[4] = temperature(NH3$; h=h[4]; P=P[4])
s[4] = entropy(NH3$; h=h[4]; P=P[4])
x[4] = quality(NH3$; h=h[4]; P=P[4])
v[4] = volume(NH3$; h=h[4]; P=P[4])

"Point 2s: Isentropic exit compressor"
ss[2] = s[1]
P[2] = P[3]
Ts[2] = temperature(NH3$; s=ss[2]; P=P[2])
hs[2] = enthalpy(NH3$; s=ss[2]; P=P[2])
xs[2] = quality(NH3$; s=ss[2]; P=P[2])
vs[2] = volume(NH3$; s=ss[2]; P=P[2])

"Mass flows"
m_evap = Q_L/(h[6]-h[5])                    "Mass flow through evaporator"
m_cond = m_evap*((h[5]-h[6])/(h[4]-h[1]))   "Mass flow through condenser"

"Compressor work"
W_is = m_cond*(hs[2]-h[1])
W = W_is/eta

"Point 2: Real exit compressor"
h[2] = h[1]+W/m_cond
T[2] = temperature(NH3$; h=h[2]; P=P[2])
s[2] = entropy(NH3$; h=h[2]; P=P[2])
x[2] = quality(NH3$; h=h[2]; P=P[2])
v[2] = volume(NH3$; h=h[2]; P=P[2])

"Rejected heat condenser"
Q_cond = m_cond*(h[2]-h[3])

"Pressure ratio"
dP = P[2]/P[1]
```

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```

"COP"
COP = Q_L/W

"Volumetric floWs"
V_compressor = m_cond*v[1]

End


Procedure ammoniancl(x_exit_evap;T_amb;T_room;Q_TotalLoad:COP_NCL;V_compressor_NCL;m_cond_NCL
;m_evap_NCL;W_NCL;Q_cond_NCL;dP_NCL)
$Arrays on

NH3$ = 'ammonia'
CO2$ = 'carbondioxide'

T_evap = -2 [C]          "Evaporator temperature"
T_cond = T_amb+5         "Condenser temperature"
T_HX = T_evap-1          "NH3/CO2 heat exchanger temperature"

eta = 0,8 [-]            "Isentropic efficiency compressor"

"Decide load"
Q_L = Q_TotalLoad

"Point 5: NH3 inlet intermediate HX"
x[5] = 0 [-]
T[5] = T_HX
P[5] = pressure(NH3$; x=x[5]; T=T[5])
h[5] = enthalpy(NH3$; x=x[5]; T=T[5])
s[5] = entropy(NH3$; x=x[5]; T=T[5])
v[5] = volume(NH3$; x=x[5]; T=T[5])

"Point 6: NH3 exit intermediate HX"
x[6] = 1 [-]
P[6] = P[5]
T[6] = temperature(NH3$; x=x[6]; P=P[6])
h[6] = enthalpy(NH3$; x=x[6]; P=P[6])
s[6] = entropy(NH3$; x=x[6]; P=P[6])
v[6] = volume(NH3$; x=x[6]; P=P[6])

"Point 1: Inlet compressor"
x[1] = 1 [-]
P[1] = P[5]
T[1] = temperature(NH3$; x=x[1]; P=P[1])
h[1] = enthalpy(NH3$; x=x[1]; P=P[1])
s[1] = entropy(NH3$; x=x[1]; P=P[1])
v[1] = volume(NH3$; x=x[1]; P=P[1])

"Point 3: Exit condenser"
x[3] = 0 [-]
T[3] = T_cond
P[3] = pressure(NH3$; x=x[3]; T=T[3])
h[3] = enthalpy(NH3$; x=x[3]; T=T[3])
s[3] = entropy(NH3$; x=x[3]; T=T[3])
```

```
v[3] = volume(NH3$; x=x[3]; T=T[3])

"Point 4: Two-phase inlet receiver, after expansion"
h[4] = h[3]
P[4] = P[5]
T[4] = temperature(NH3$; h=h[4]; P=P[4])
s[4] = entropy(NH3$; h=h[4]; P=P[4])
x[4] = quality(NH3$; h=h[4]; P=P[4])
v[4] = volume(NH3$; h=h[4]; P=P[4])

"Point 2s: Isentropic exit compressor"
ss[2] = s[1]
P[2] = P[3]
Ts[2] = temperature(NH3$; s=ss[2]; P=P[2])
hs[2] = enthalpy(NH3$; s=ss[2]; P=P[2])
xs[2] = quality(NH3$; s=ss[2]; P=P[2])
vs[2] = volume(NH3$; s=ss[2]; P=P[2])

"Point 7: CO2 inlet evaporator"
x[7] = 0 [-]
T[7] = T_evap
P[7] = pressure(CO2$; x=x[7]; T=T[7])
h[7] = enthalpy(CO2$; x=x[7]; T=T[7])
s[7] = entropy(CO2$; x=x[7]; T=T[7])
v[7] = volume(CO2$; x=x[7]; T=T[7])

"Point 8: CO2 exit evaporator"
P[8] = P[7]
x[8] = x_exit_evap
T[8] = temperature(CO2$; P=P[8]; x=x[8])
h[8] = enthalpy(CO2$; P=P[8]; x=x[8])
s[8] = entropy(CO2$; P=P[8]; x=x[8])
v[8] = volume(CO2$; P=P[8]; x=x[8])

"Mass flows"
m_evap_NCL = Q_L/(h[8]-h[7])                                "Mass flow
of CO2 through evaporator"
m_HX_NH3 = Q_L/(h[6]-h[5])                                  "Mass flow
of NH3 through intermediate HX"
m_cond_NCL = m_HX_NH3*((h[5]-h[6])/(h[4]-h[1]))             "Mass flow
through condenser"

"Compressor work"
W_is = m_cond_NCL*(hs[2]-h[1])
W_NCL = W_is/eta

"Point 2: Real exit compressor"
h[2] = h[1]+W_NCL/m_cond_NCL
T[2] = temperature(NH3$; h=h[2]; P=P[2])
s[2] = entropy(NH3$; h=h[2]; P=P[2])
x[2] = quality(NH3$; h=h[2]; P=P[2])
v[2] = volume(NH3$; h=h[2]; P=P[2])

"Rejected heat condenser"
Q_cond_NCL = m_cond_NCL*(h[2]-h[3])

"Pressure ratio"
dP_NCL = P[2]/P[1]

"COP"
```

File:Refrigeration load mango.EES 26.06.2019 11.27.38 Page 8
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```
COP_NCL = Q_L/W_NCL
"Volumetric flows"
V_compressor_NCL = m_cond_NCL*v[1]
End
T_room_K = T_room + 273,15
T_amb_K = T_amb + 273,15
COP_Ca = (T_room_K)/(T_amb_K - T_room_K)          "Carnot COP"
"Room and ambient temperatures"
T_room = 13 [C]          "Cold storage temperature, 13 degrees"
T_amb = 27,1 [C]          "Ambient temperature"
CR = 2 [-]          "Circulation rate"
x_exit_evap = 1/CR          "Gas quality at exit of CO2 evaporator"
"Day = x"
Call transmissionload(T_room;T_amb:Q_Transmission)
Call infiltrationload(T_amb;T_room:Q_Infiltration)
Call respirationheat(T_room:Q_Respiration)
Call equipmentload(Q_Transmission;Q_Infiltration;Q_Respiration:Q_Equipment)
Call holdingload(Q_Transmission;Q_Infiltration;Q_Respiration;Q_Equipment:Q_HoldingLoad)
Call pulldownload(T_room;T_amb:Q_Pulldown)
Call refrigerationload(Q_HoldingLoad;Q_Pulldown:Q_TotalLoad)
Call ammonia(T_amb;T_room;Q_TotalLoad:COP;V_compressor;m_cond;m_evap;W;Q_cond;dP)
Call ammoniancl(x_exit_evap;T_amb;T_room;Q_TotalLoad:COP_NCL;V_compressor_NCL;m_cond_NCL;m_evap_NCL
;W_NCL;Q_cond_NCL;dP_NCL)
```

## B.4 Storing grapes

File:Refrigeration load grapes.EES 26.06.2019 11.26.14 Page 1
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```
$UnitSystem SI Radian Mass kJ kg C bar


Procedure transmissionload(T_room;T_amb:Q_Transmission)

"Cold storage exterior size"
L_ext = 6,1 [m]                                         "Length"
W_ext = 2,44 [m]                                        "Width"
H_ext = 2,6 [m]                                         "Height"

"Surface areas"
A_north = W_ext*H_ext                                   "North wall area"
A_south = W_ext*H_ext                                   "South wall area"
A_east = L_ext*H_ext                                    "East wall area"
A_west = L_ext*H_ext                                    "West wall area"
A_roof = W_ext*L_ext                                    "Roof area"
A_floor = W_ext*L_ext                                   "Floor area"

"Insulation, expanded polysterene"
delta_ins = 0,075 [m]                                   "Insulation thickness"
k_ins = 0,037 [W/(m*K)]                                 "Thermal conductivity of insulation"
U_ins = k_ins/delta_ins                                 "Insulation heat transfer coefficient"

"Allowance for sun effect"
dT_sun_east = 3 [C]                                     "East wall allowance"
dT_sun_west = 3 [C]                                     "West wall allowance"
dT_sun_south = 2 [C]                                    "South wall allowance"
dT_sun_roof = 5 [C]                                     "Flat roof allowance"

T_wall_east = T_amb+dT_sun_east                         "East wall"
T_wall_west = T_amb+dT_sun_west                         "West wall"
T_wall_south = T_amb+dT_sun_south                       "South wall"
T_wall_north = T_amb                                    "North wall, with door"
T_roof = T_amb+dT_sun_roof                              "Flat roof"
T_floor = T_amb                                         "Floor"


"Transmission load"
Q_T_south = U_ins*A_south*(T_wall_south-T_room)         "South wall, [W]"
Q_T_east = U_ins*A_east*(T_wall_east-T_room)            "East wall, [W]"
Q_T_west = U_ins*A_west*(T_wall_west-T_room)            "West wall, [W]"
Q_T_north = U_ins*A_north*(T_wall_north-T_room)         "North wall, [W]"
Q_T_roof = U_ins*A_roof*(T_roof-T_room)                 "Flat roof, [W]"
Q_T_floor = U_ins*A_floor*(T_floor-T_room)              "Floor, [W]"
```

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```
Q_Transmission = (Q_T_south+Q_T_east+Q_T_west+Q_T_north+Q_T_roof+Q_T_floor)/1000 "Total transmission load, [kW]"

End


Procedure infiltrationload(T_amb;T_room:Q_Infiltration)

air$ = 'air'
P_amb = 1,01325 [bar] "Atmospheric pressure"
g = 9,81 [m/s^2] "Gravity"

H_door = 2,045 [m] "Door height"
W_door = 0,8 [m] "Door width"
A_door = H_door*W_door "Door area"

D_f = 0,8 [-] "Doorway flow factor"
E = 0,9 [-] "New strip curtains"
Theta_d = 24 [h] "Time period"
Theta_o = 60 [min] "Door simply stands open"
Theta_p = 30 [s] "Door open-close time"
N = 1 [-] "Door is opened once a day"

h_amb = enthalpy(air$; T=T_amb) "Ambient air enthalpy"
rho_amb = density(air$; T=T_amb; P=P_amb) "Density ambient air"

h_room = enthalpy(air$; T=T_room) "Cold storage air enthalpy"
rho_room = density(air$; T=T_room; P=P_amb) "Density cold storage air"

D_t = (N*Theta_p+60*Theta_o)/(3600*Theta_d) "Doorway open-time factor"
F_m = ((2)/(1+(rho_room/rho_amb)^(1/3)))^(1,5) "Density factor"
Q_s = 0,221*A_door*(h_amb-h_room)*rho_room*(1-(rho_amb/rho_room))^(0,5)*(g*H_door)^(0,5)*F_m "Sensible and latent refrigeration load, [kW]"

Q_Infiltration = Q_s*D_t*D_f*(1-E) "Total infiltration load, [kW], during holding"

End


Procedure respirationheat(:Q_Respiration)

"Cold storage interior size, without insulation"
L_int_ex_ins = 5,87 [m] "Length"
W_int_ex_ins = 2,34 [m] "Width"
H_int_ex_ins = 2,38 [m] "Height"
```

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```
delta_ins = 0,075 [m]    "Insulation thickness"

"Interior size, including insulation thickness"
L_int = L_int_ex_ins-delta_ins    "Length"
W_int = W_int_ex_ins-delta_ins    "Width"
H_int = H_int_ex_ins-delta_ins    "Height"
A_int = L_int*W_int    "Floor area"

L_aisle=L_int    "Aisle length"
W_aisle=0,8 [m]    "Aisle width"

V_storage = (W_int-W_aisle)*L_int*H_int    "Available storage space"
rho_storage = 200 [kg/m^3]    "Storage density"
m_grape = (4/7)*rho_storage*V_storage    "Mass of grapes stored"

q_resp_grape = 0,0058 [W/kg]    "Respiration rate, grapes"

Q_Respiration = (m_grape*q_resp_grape)/1000    "Respiration heat, [kW]"

End


Procedure equipmentload(Q_Transmission;Q_Infiltration;Q_Respiration:Q_Equipment)

Q_Equipment = 0,1*(Q_Transmission+Q_Infiltration+Q_Respiration)    "10 % of total load, [kW]"

End


Procedure holdingload(Q_Transmission;Q_Infiltration;Q_Respiration;Q_Equipment:Q_HoldingLoad)

Q_HoldingLoad = 1,1*(Q_Transmission+Q_Infiltration+Q_Respiration+Q_Equipment)    "Total steady state holding refrigeration load, with safety factor of 10%, [kW]"

End


Procedure pulldownload(T_room;T_amb:Q_Pulldown)

T_grape = T_amb    "Grape loading temperature"

"Cold storage interior size, without insulation"
L_int_ex_ins = 5,87 [m]    "Length"
W_int_ex_ins = 2,34 [m]    "Width"
H_int_ex_ins = 2,38 [m]    "Height"

delta_ins = 0,075 [m]    "Insulation thickness"

"Interior size, including insulation thickness"
L_int = L_int_ex_ins-delta_ins    "Length"
W_int = W_int_ex_ins-delta_ins    "Width"
```

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```
H_int = H_int_ex_ins-delta_ins "Height"

L_aisle=L_int "Aisle length"
W_aisle=0,8 [m] "Aisle width"

V_storage = (W_int-W_aisle)*L_int*H_int "Available storage space"
rho_storage = 200 [kg/m^3] "Storage density"
m_grape = (1/7)*rho_storage*V_storage "Mass of grapes loaded each day"

C_P_grape = 3,70 [kJ/(kg*K)]

q_pulldown_grape = m_grape*C_P_grape*(T_grape-T_room) "Heat removed for grapes, [kJ]"

t_Pulldown = 24 "Pull down time, [h]"

Q_Pulldown = 1,1*((q_pulldown_grape)/(3600*t_Pulldown)) "Pulldown load, including safety factor of 10%, [kW]"

"Q_Pulldown = 0 [kW]" "Use when no pull down"

End


Procedure refrigerationload(Q_HoldingLoad;Q_Pulldown:Q_TotalLoad)

Q_TotalLoad = Q_HoldingLoad+Q_Pulldown "Total refrigeration load, [kW]"

End


Procedure ammonia(T_amb;T_room;Q_TotalLoad:COP;V_compressor;m_cond;m_evap;W;Q_cond;dP)
$Arrays on

NH3$ = 'ammonia'

T_evap = -2 [C] "Evaporator temperature"
T_cond = T_amb+5 "Condenser temperature"

eta = 0,8 [-] "Isentropic efficiency compressor"

"Decide load"
Q_L = Q_TotalLoad

"Point 5: Inlet evaporator"
x[5] = 0 [-]
T[5] = T_evap
P[5] = pressure(NH3$; x=x[5]; T=T[5])
h[5] = enthalpy(NH3$; x=x[5]; T=T[5])
s[5] = entropy(NH3$; x=x[5]; T=T[5])
v[5] = volume(NH3$; x=x[5]; T=T[5])
```

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```

"Point 6: Exit evaporator"
x[6] = 1 [-]
P[6] = P[5]
T[6] = temperature(NH3$; x=x[6]; P=P[6])
h[6] = enthalpy(NH3$; x=x[6]; P=P[6])
s[6] = entropy(NH3$; x=x[6]; P=P[6])
v[6] = volume(NH3$; x=x[6]; P=P[6])

"Point 1: Inlet compressor"
x[1] = 1 [-]
P[1] = P[5]
T[1] = temperature(NH3$; x=x[1]; P=P[1])
h[1] = enthalpy(NH3$; x=x[1]; P=P[1])
s[1] = entropy(NH3$; x=x[1]; P=P[1])
v[1] = volume(NH3$; x=x[1]; P=P[1])

"Point 3: Exit condenser"
x[3] = 0 [-]
T[3] = T_cond
P[3] = pressure(NH3$; x=x[3]; T=T[3])
h[3] = enthalpy(NH3$; x=x[3]; T=T[3])
s[3] = entropy(NH3$; x=x[3]; T=T[3])
v[3] = volume(NH3$; x=x[3]; T=T[3])

"Point 4: Two-phase inlet receiver, after expansion"
h[4] = h[3]
P[4] = P[5]
T[4] = temperature(NH3$; h=h[4]; P=P[4])
s[4] = entropy(NH3$; h=h[4]; P=P[4])
x[4] = quality(NH3$; h=h[4]; P=P[4])
v[4] = volume(NH3$; h=h[4]; P=P[4])

"Point 2s: Isentropic exit compressor"
ss[2] = s[1]
P[2] = P[3]
Ts[2] = temperature(NH3$; s=ss[2]; P=P[2])
hs[2] = enthalpy(NH3$; s=ss[2]; P=P[2])
xs[2] = quality(NH3$; s=ss[2]; P=P[2])
vs[2] = volume(NH3$; s=ss[2]; P=P[2])

"Mass flows"
m_evap = Q_L/(h[6]-h[5])                          "Mass flow
 through evaporator"
m_cond = m_evap*((h[5]-h[6])/(h[4]-h[1]))         "Mass flow
through condenser"

"Compressor work"
W_is = m_cond*(hs[2]-h[1])
W = W_is/eta

"Point 2: Real exit compressor"
h[2] = h[1]+W/m_cond
T[2] = temperature(NH3$; h=h[2]; P=P[2])
s[2] = entropy(NH3$; h=h[2]; P=P[2])
x[2] = quality(NH3$; h=h[2]; P=P[2])
v[2] = volume(NH3$; h=h[2]; P=P[2])

"Rejected heat condenser"
Q_cond = m_cond*(h[2]-h[3])
```

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```

"Pressure ratio"
dP = P[2]/P[1]

"COP"
COP = Q_L/W

"Volumetric floWs"
V_compressor = m_cond*v[1]

End


Procedure ammoniancl(x_exit_evap;T_amb;T_room;Q_TotalLoad:COP_NCL;V_compressor_NCL;m_cond_NCL;m_evap_NCL;W_NCL;Q_cond_NCL;dP_NCL)
$Arrays on

NH3$ = 'ammonia'
CO2$ = 'carbondioxide'

T_evap = -2 [C]          "Evaporator temperature"
T_cond = T_amb+5         "Condenser temperature"
T_HX = T_evap-1          "NH3/CO2 heat exchanger temperature"

eta = 0,8 [-]            "Isentropic efficiency compressor"

"Decide load"
Q_L = Q_TotalLoad

"Point 5: NH3 inlet intermediate HX"
x[5] = 0 [-]
T[5] = T_HX
P[5] = pressure(NH3$; x=x[5]; T=T[5])
h[5] = enthalpy(NH3$; x=x[5]; T=T[5])
s[5] = entropy(NH3$; x=x[5]; T=T[5])
v[5] = volume(NH3$; x=x[5]; T=T[5])

"Point 6: NH3 exit intermediate HX"
x[6] = 1 [-]
P[6] = P[5]
T[6] = temperature(NH3$; x=x[6]; P=P[6])
h[6] = enthalpy(NH3$; x=x[6]; P=P[6])
s[6] = entropy(NH3$; x=x[6]; P=P[6])
v[6] = volume(NH3$; x=x[6]; P=P[6])

"Point 1: Inlet compressor"
x[1] = 1 [-]
P[1] = P[5]
T[1] = temperature(NH3$; x=x[1]; P=P[1])
h[1] = enthalpy(NH3$; x=x[1]; P=P[1])
s[1] = entropy(NH3$; x=x[1]; P=P[1])
v[1] = volume(NH3$; x=x[1]; P=P[1])

"Point 3: Exit condenser"
x[3] = 0 [-]
T[3] = T_cond
```

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```
P[3] = pressure(NH3$; x=x[3]; T=T[3])
h[3] = enthalpy(NH3$; x=x[3]; T=T[3])
s[3] = entropy(NH3$; x=x[3]; T=T[3])
v[3] = volume(NH3$; x=x[3]; T=T[3])

"Point 4: Two-phase inlet receiver, after expansion"
h[4] = h[3]
P[4] = P[5]
T[4] = temperature(NH3$; h=h[4]; P=P[4])
s[4] = entropy(NH3$; h=h[4]; P=P[4])
x[4] = quality(NH3$; h=h[4]; P=P[4])
v[4] = volume(NH3$; h=h[4]; P=P[4])

"Point 2s: Isentropic exit compressor"
ss[2] = s[1]
P[2] = P[3]
Ts[2] = temperature(NH3$; s=ss[2]; P=P[2])
hs[2] = enthalpy(NH3$; s=ss[2]; P=P[2])
xs[2] = quality(NH3$; s=ss[2]; P=P[2])
vs[2] = volume(NH3$; s=ss[2]; P=P[2])

"Point 7: CO2 inlet evaporator"
x[7] = 0 [-]
T[7] = T_evap
P[7] = pressure(CO2$; x=x[7]; T=T[7])
h[7] = enthalpy(CO2$; x=x[7]; T=T[7])
s[7] = entropy(CO2$; x=x[7]; T=T[7])
v[7] = volume(CO2$; x=x[7]; T=T[7])

"Point 8: CO2 exit evaporator"
P[8] = P[7]
x[8] = x_exit_evap
T[8] = temperature(CO2$; P=P[8]; x=x[8])
h[8] = enthalpy(CO2$; P=P[8]; x=x[8])
s[8] = entropy(CO2$; P=P[8]; x=x[8])
v[8] = volume(CO2$; P=P[8]; x=x[8])

"Mass flows"
m_evap_NCL = Q_L/(h[8]-h[7])          "Mass flow of CO2 through evaporator"
m_HX_NH3 = Q_L/(h[6]-h[5])            "Mass flow of NH3 through intermediate HX"
m_cond_NCL = m_HX_NH3*((h[5]-h[6])/(h[4]-h[1]))          "Mass flow through condenser"

"Compressor work"
W_is = m_cond_NCL*(hs[2]-h[1])
W_NCL = W_is/eta

"Point 2: Real exit compressor"
h[2] = h[1]+W_NCL/m_cond_NCL
T[2] = temperature(NH3$; h=h[2]; P=P[2])
s[2] = entropy(NH3$; h=h[2]; P=P[2])
x[2] = quality(NH3$; h=h[2]; P=P[2])
v[2] = volume(NH3$; h=h[2]; P=P[2])

"Rejected heat condenser"
Q_cond_NCL = m_cond_NCL*(h[2]-h[3])

"Pressure ratio"
```

```
dP_NCL = P[2]/P[1]

"COP"
COP_NCL = Q_L/W_NCL

"Volumetric floWs"
V_compressor_NCL = m_cond_NCL*v[1]

End


T_room_K = T_room + 273,15
T_amb_K = T_amb + 273,15
COP_Ca = (T_room_K)/(T_amb_K - T_room_K)                                    "Carnot COP"


"Room and ambient temperatures"
T_room = -0,5 [C]                                    "Cold storage temperature, -0.5 degree"
T_amb = 30,9 [C]                                    "Ambient temperature"
CR = 2 [-]                                    "Circulation rate"
x_exit_evap = 1/CR                                    "Gas quality at exit of CO2 evaporator"
"Day = x"

Call transmissionload(T_room;T_amb:Q_Transmission)
Call infiltrationload(T_amb;T_room:Q_Infiltration)
Call respirationheat(T_room:Q_Respiration)
Call equipmentload(Q_Transmission;Q_Infiltration;Q_Respiration:Q_Equipment)
Call holdingload(Q_Transmission;Q_Infiltration;Q_Respiration;Q_Equipment:Q_HoldingLoad)
Call pulldownload(T_room;T_amb:Q_Pulldown)
Call refrigerationload(Q_HoldingLoad;Q_Pulldown:Q_TotalLoad)
Call ammonia(T_amb;T_room;Q_TotalLoad:COP;V_compressor;m_cond;m_evap;W;Q_cond;dP)
Call ammonianl(x_exit_evap;T_amb;T_room;Q_TotalLoad:COP_NCL;V_compressor_NCL;m_cond_NCL;m_evap_NCL
;W_NCL;Q_cond_NCL;dP_NCL)
```

# Appendix C

# Risk assesment

| 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:** Trygve Magne Eikevik

**Participants in the identification process:** Trygve Magne Eikevik (Norwegian supervisor) and Maddali Ramgopal (Indian supervisor)

**Short description of the main activity/main process:** Master project for student Tom André Bredesen. Project title: *Design and simulation of a small cold storage with $NH_3$ refrigeration system and $CO_2$ as indirect cooling loop for storing of fresh fruits and vegetables*

**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:* Tom André Bredesen

| ID nr. | Activity/process | Responsible person | Existing documentation | Existing safety measures | Laws, regulations etc. | Comment |
|---|---|---|---|---|---|---|
| 1 | Transport in India | Tom André Bredesen | | Seat belts, travel insurance | | |
| 2 | Recreational activities | Tom André Bredesen | | Don't walk alone, listen to local students, use common sense | | |
| 3 | Food and water | Tom André Bredesen | | Drink bottled water and be careful with hygiene | | |
| 4 | Disease and general health | Tom André Bredesen | | Vaccines, travel insurance and common sense | | |
| 5 | Visiting local farmers/cold storages | Tom André Bredesen | | Careful with hygiene, travel insurance, common sense | | |
| 6 | | | | | | |

| NTNU<br>HSE/KS | Risk assessment | Prepared by | Number | Date |
|---|---|---|---|---|
| | | HSE section | HMSRV2603E | 04.02.2011 |
| | | Approved by | | Replaces |
| | | The Rector | | 01.12.2006 |

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

**Line manager:** Trygve Magne Eikevik

**Participants in the identification process:** Trygve Magne Eikevik (Norwegian supervisor) and Maddali Ramgopal (Indian supervisor)

**Short description of the main activity/main process:** Master project for student Tom André Bredesen. Project title: *Design and simulation of a small cold storage with $NH_3$ refrigeration system and $CO_2$ as indirect cooling loop for storing of fresh fruits and vegetables*

**Signatures:** *Responsible supervisor:* *Student:* Tom André Bredesen

| 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*
4. *High*
5. *Very high*

***Consequence, e.g.:***
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*
E. *Very critical*

***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***

**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<br>1 | Low<br>2 | Medium<br>3 | High<br>4 | Very high<br>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<br>Very critical | May produce fatality/ies | Very prolonged, non-reversible damage | Shutdown of work >1 year. |
| D<br>Critical | Permanent injury, may produce serious serious health damage/sickness | Prolonged damage. Long recovery time. | Shutdown of work 0.5-1 year. |
| C<br>Dangerous | Serious personal injury | Minor damage. Long recovery time | Shutdown of work < 1 month |
| B<br>Relatively safe | Injury that requires medical treatment | Minor damage. Short recovery time | Shutdown of work < 1week |
| A<br>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. |

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