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Development of a methodology for the determination of the life cycle climate performance (LCCP) of supermarket refrigeration systems and other integrated system with a reduced number of experiments

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Summary in English

The SuperSmart Rack is an innovative prototype of a refrigeration system running with CO_2 as only refrigerant with the aim to reduce the environmental impacts. It is discussed in the present report how to assess these impacts.

It is furtherly seen how to generally proceed to the LCCP (Life Cycle Climate Performance) of a refrigeration system. The LCCP methodology consists in calculating the different terms contributing to worsen the greenhouse effect. The main contribution is depending on the energy consumption of the refrigeration system. It is quite challenging to know the energy consumption of a prototype as if it were running in a real supermarket. In order to deal with it, it is presented an extrapolation methodology on assumptions and approximations and using prototype tests on a few working points.

The energy consumption calculation that is hereby detailed uses the dataset of a refrigeration system running on field at the Rema 1000 supermarket located at Kroppanmarka, Trondheim, Norway -the reference supermarket. This dataset enables a comprehension of the load demands evolution and their dependency with the ambient temperature. The ambient temperature has a great importance in the unit's performances so the location where the prototype wants to be tested matters. The presented methodology helps one to build up a set of working points to test on the prototype, just starting from the weather database of a location.

Three different methods to assess the energy consumption of a prototype are detailed. The MT load is the one changing the most and each method has its own way to determine the MT load. The first method is based on the assumption that the MT (Medium temperature) load is depending on the hour of the day. It is quite accurate, but it leads to too many working points. The second consists in correlating the MT load and the ambient temperature at the location of the reference supermarket so that the accuracy and the number of working points are good but the location of the energy consumption calculation can only be the same as the reference supermarket's. The third is a greater approximation saying that the MT load has only two values opened/closed shop; It gives a small working point set but with a worse accuracy.

Introduction

The main consumption of energy in supermarkets is refrigeration. Recently, the energy design of commercial refrigeration systems has become challenging as it is also needed to minimize safety risk and to fit the new environmental regulations. CO_2 had been forsaken because of the development of synthetic refrigerants that achieved a breakthrough in energy efficiency. To match the higher expectancy of recent environmental regulations, CO_2 seems to be a competitive solution. The Norwegian supermarket chains *REMA 1000* and *Norgesgruppen* associated with the Norwegian research institute SINTEF, initiated the SuperSmart Rack project. Its main goal is to develop high-performance integrated refrigeration systems running with R-744 (CO_2) as only refrigerant. In the NTNU laboratory, different energy-cutting strategies are tested on a real-sized prototype. The system can be set on a conventional booster configuration or it can also be added parallel compressors and ejectors. Once the experimental facility has the best control to reach its optimal performances and the measurements tools are calibrated, its environmental impacts will finally need to be compared to those of other refrigeration system using actual measurements to assess the relevancy of the SuperSmart Rack project. Hereby, it will be used the LCCP (Life Cycle Climate Performance) method as it is reckoned as the new standard LCA (Life Cycle Assessment) methodology for heat pumps and refrigeration systems since January 2016. (energy.gov, 2016)

The LCCP is an LCA calculation method to determinate the environmental impacts on global warming of a given refrigeration or heat pump system. It is holistic because it takes into account the emissions occurring from cradle to grave: from the manufacturing of the facility and the refrigerant, passing by the operating phase (leakages and electricity consumption), to the disposal of the system. (see Appendix I)

The major contributor of the LCCP of a refrigeration system is assumed to be by far the electricity consumption. The wisest functional unit to choose here is the cooling & heating to be supplied by a given supermarket at a given location during one year. The method is therefore straightforward provided that this energy consumption is known over the representative period for this LCA: one year. This data is often easy to collect on a field-running system or it can be computed from a simulated model, but it is not imaginable to log a prototype data over an as long period as one year. It is neither possible to build a performance map of the system to then apply it to the one-year conditions of a real supermarket for the same reasons, it would take too much time. Moreover, the prototype is meant to be constantly improved so that a performance map would quickly become outdated. Therefore, the tools to extrapolate a supposed year electricity consumption of a refrigeration system from a limited number of tests will be constructed in the present report. Three methods will be presented as, depending on how rough the approximation is, the number of tests and the accuracy will change. For the roughest approximation, one should be able to obtain the electricity consumption as if it was working at whatever location, as long as the weather database of the location is available.

In order to do so, the data from a supermarket located in Trondheim will be used to have a better understanding of the interdependency between the multiple load demands, the ambient temperature and the time of the day.

In the present thesis, one can first find a brief introduction to CO_2 systems and to the unique characteristics of the SuperSmart Rack in terms of energy efficiency and integration. In a second part, the new standard method for environmental impact assessment of refrigeration system – the LCCP – is explained. In a third part, tools are developed to obtain the crucial energy consumption of the experimental facility.

I) The SuperSmart Rack, an innovative technology

1) CO_2 refrigerant as an alternative to conventional refrigerants

Natural refrigerants like CO_2 and ammonia were commonly used before the Second World War. CO_2 was used as an alternative to ammonia because it represents much less safety risk. It is not toxic compared to ammonia and non-flammable compared to hydrocarbons as butane. During the Second World War, higher efficiency synthetic refrigerants had been developed. It made CO_2 less used in refrigeration so that it has been out of use from the sixties to recently. The reason we are coming back into it is that it has a negligible impact on compared to synthetic refrigerants: it has no ozone depleting potential (ODP) and a global warming potential much lower than CFCs (chlorofluorocarbons) HCFC (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons). (see Table 1 below)

Table 1 : ODP and GWP of typical refrigerants (source: https://en.wikipedia.org/wiki/List_of_refrigerants)

Refrigerant No.	Name	Class	ODP	GWP
R-12	Dichlorofluoromethane	CFC	1.0	2400
R-22	Difluoromonochloromethane	HCFC	0,05	1700
R-134a	Tetrafluoroethane	HFC	0	1300
R-1234yf	Tetrafluoropropene	HFO	0	4
R-600	Butane	HC	0	3
R-717	Ammonia	Natural	0	0
R-744	Carbon dioxide	Natural	0	1

2) Different configurations and the ejector technology

Moreover, technological improvements make it now possible to reach greater pressure with CO_2 so that it is now more competitive from an energy efficiency point of view. (Lorentzen, 1994)

Different configurations of CO_2 refrigeration system can be built depending on where the supermarket is located. The basic configuration implying the less of components is the booster mode, which can provide cooling and freezing with a high performance in locations where the climate is mild or cold. Then can be added a stage of parallel compression to increase the efficiency mainly at ambient conditions of high temperature. Finally, ejectors can replace the high-pressure valve to enhance further the performance of CO_2 refrigeration systems in warm climates. Each of them is of interest depending on the inputs of the system. As a result, the controller will switch from one configuration to another to keep the performance of the system at its best.

a) The booster mode configuration

The booster mode is a configuration of refrigeration system that delivers both refrigerant to the Low Temperature (LT) evaporators of freezing cabinets and to the Medium Temperature (MT) evaporators of cooling cabinets. The first operates at around -30°C in the refrigerant side and keeps the temperature of the air at -18°C or lower, to store products such as meat, vegetables, pizza, ice cream… The second works with a refrigerant evaporation temperature of -5°C to -10°C approximately, to keep the temperature of the air around 4°C and store products such as dairies, non-frozen meat or fish, etc. The 'booster' is so-called because the two stages are connected so that the low stage is 'boosting' the high stage compressor.

The MT compressor compresses the refrigerant to the high-pressure stage (from 1 to 2). At this point occurs the cooling of the CO_2 through the GC (Gas Cooler) and an HR (Heat Recovery) exchanger. The refrigerant is then expanded through the HPV (High Pressure Valve) to reach the intermediate pressure level of the liquid receiver. In this component, the refrigerant is separated in a liquid and a gas phase. The liquid phase is sucked to supply both cooling demands. It is expanded to the MT pressure level and absorbs the heat form the MT cabinet through the MT evaporators before being reinjected to the suction of the MT Compressor stage. The same happens to the LT but the pressure is lowered to the LT pressure level and before being reinjected to the suction of the MT Compressors, the pressure is raised by a LT Compressor stage followed by a de-superheat exchanger (optional). In order to regulate the pressure in the liquid receiver, a flash gas bypass valve expands gas from the liquid receiver to the MT Compressors suction.

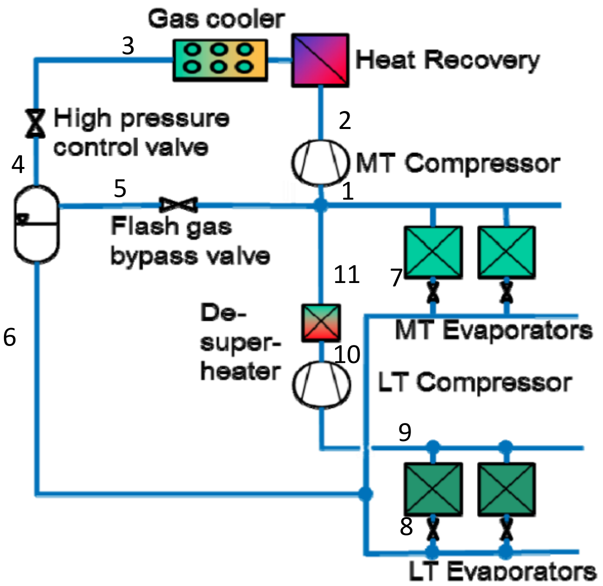


Figure 1 : Circuit scheme of the booster mode configuration // Source: Integrated_Ref_Systems_foredrag.pdf by Armin Hafner

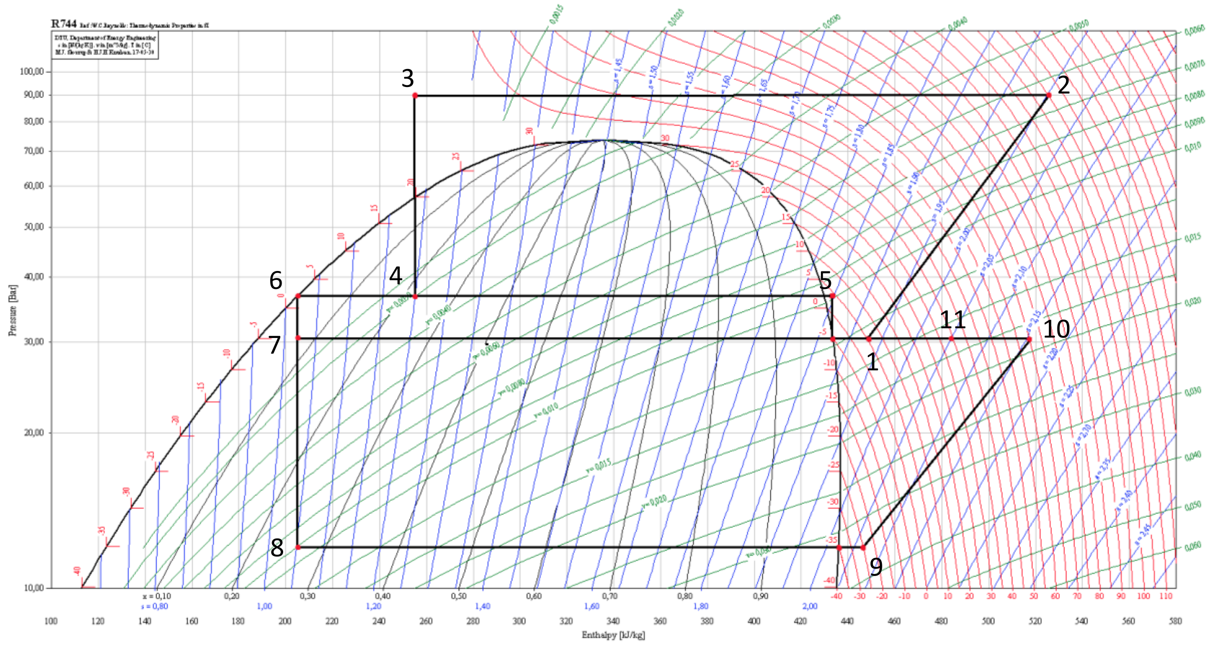


Figure 2 : P,h diagram of the booster mode configuration

The two other configurations are followingly explained briefly and if one wants a detailed explanation, it can be found in the report (SINTEF, 2016).

b) The booster mode with parallel compression

It is possible to have a configuration where a parallel compressor stage directly compresses the flash gas from the liquid receiver to the high-pressure level. In this way, there is no useless expansion loss to then have to raise this fluid in pressure again. These parallel compressors are running with a smaller pressure ratio than the MT compressors so that their efficiency is higher.

This configuration particularly applies when the ambient temperature at the location is high. The temperature at the outlet of the gas cooler will be high as it can only be higher than the ambient temperature to enable the heat transfer. As a result, there will be a lot of flash gas in the liquid receiver making the use of parallel compressors more relevant.

c) The booster mode with parallel compression and ejectors

A configuration including the use of ejectors is also possible. For some conditions, it will increase the efficiency. The idea of the ejector equipment is to combine the high-pressure fluid expansion that was before done through the high-pressure expansion valve with the compression/pumping of the MT stage fluid by mixing them.

II) Literature review: LCCP (Life Cycle Climate Performance) for refrigeration systems

1) Definition of the LCCP

The GWP (Global Warming Potential) of a refrigerant is the most basic indicator that can be looked at. It represents the greenhouse impact of a chemical compound in comparison to CO_2. The higher the GWP, the more harmful is the refrigerant. Nevertheless, it would be inaccurate to only take this indicator into account as it doesn't depend on the system's efficiency or the charge of refrigerant.

Since January 2016, the TEWI (Total Equivalent Warming Impact) is the standard methodology used for the evaluation of environmental impacts of refrigeration and heat pump systems in general. It is described in the *European standard EN-378 Refrigerating systems and heat pumps – Safety and environmental requirements*. Following this methodology is straightforward and leads easily to a first overview of the environmental performance of a system. It takes into account two kinds of emission: direct emissions due to refrigerant leakages and indirect emissions due to the energy consumption.

The LCCP is an extension of the TEWI made to be more comprehensive. It includes all the contributions accounted for in the TEWI but with additional contributions such as transportation, disposal… (see Figure 3) As a result, it will be preferred to the TEWI in this report.

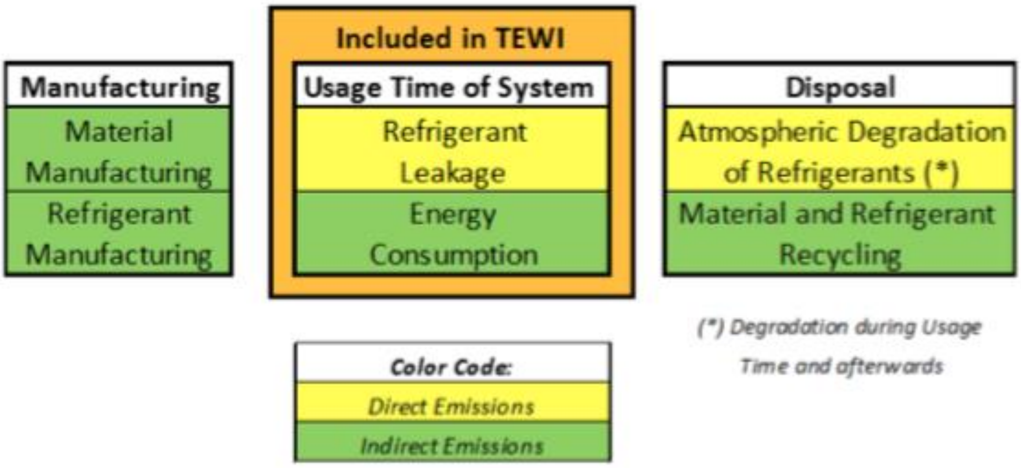


Figure 3: LCCP vs. TEWI Comparison // source: Guideline for Life Cycle Climate Performance, January 2016

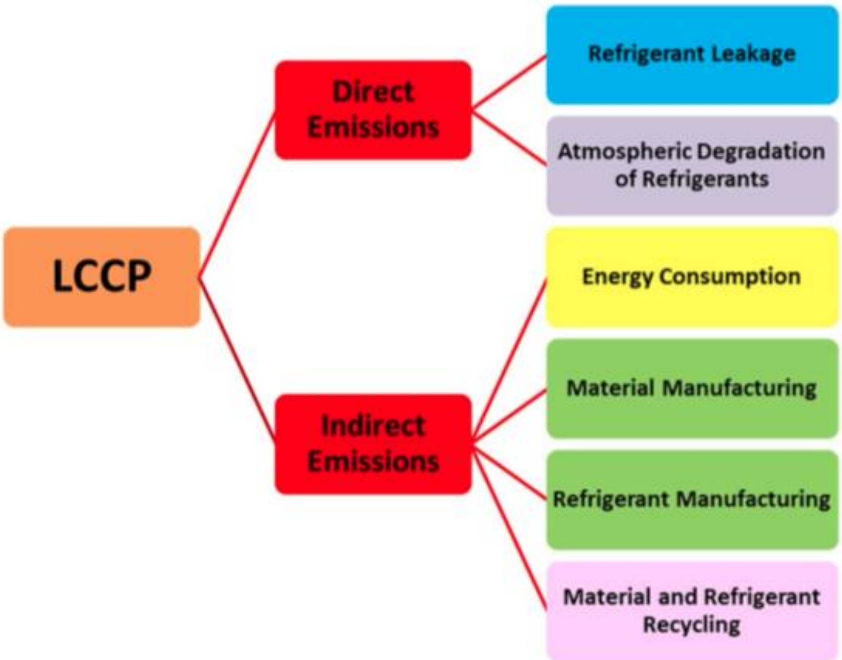


Figure 4: LCCP components // source: Guideline for Life Cycle Climate Performance, January 2016

LCCP impacts are expressed in kgCO2eq since it is a calculation for the GWP impact category. There are two different kinds of contributions for the LCCP of a refrigeration system: the direct emissions and the indirect emissions (see Figure 3 & Figure 4). The direct emissions are due to emission of refrigerant in the atmosphere whereas the indirect emissions are caused by emissions occurring further backwards on the process chain. Indirect emissions can for example be CO_2 emissions from an electricity power plant running with coal.

$$\mathrm{LCCP(kgCO2eq)} = \mathrm{Direct\ emissions} + \mathrm{Indirect\ emissions} \quad (1)$$

The direct emissions are dispersion of refrigerant into the atmosphere. These are unavoidable continuous leakages through the joints of the system's circuit, but there are also punctual leakages occurring at maintenance operations or at the disposal of the machine.
In the Guideline for Life Cycle Climate Performance 2016, the maintenance contribution is neglected. An annual leakage rate (LR_{annual}) is applied to the refrigerant charge (m_{ref}) over the system life (τ_{life}) and a punctual disposal leakage rate is defined (LR_{EOL}). The refrigerant has a certain impact per mass rate (GWP) and an atmospheric degradation factor (Adp.GWP). (see Equation 2)

$$\text{Direct emissions(kgCO2eq)} = \text{Refrigerant leakage} + \text{Atmospheric degradation of refrigerants} = m_{ref}.(\tau_{life}.LR_{annual} + LR_{EOL}).(\text{GWP} + \text{Adp.GWP}) \quad (2)$$

The indirect emissions are mostly due to energy consumption. The other contributors are the material and refrigerant manufacturing and their recycling. (see Equation 3)

$$Indirect\ emissions = Energy\ consumption + Material\&Refrigerant\ manufacturing + Material\&Refrigerant\ disposal \quad (3)$$

The Energy consumption can for example be calculated using the sum of operating energy consumption over a typical year multiplied by their specific impact contribution to GWP and the number of years of working life. (see Equation 4)

$$\text{Energy consumption} = \tau_{life} \times \Sigma\left(\text{equivalent}\frac{CO_2kg}{kWh} \times \text{operating energy kWh}\right)_{annual} \quad (4)$$

The manufacturing's contribution is calculated with a sum of the mass of each material multiplied with their specific manufacturing impact on GWP. To simplify the equation, the refrigerant is included in materials. (see Equation 5)

$$\text{Material\&Refrigerant manufacturing} = \Sigma\left(\text{equivalent}\frac{CO2kg}{kg}\text{material} \times \text{mass of materials kg}\right) \quad (5)$$

The disposal's contribution is more complex because a part of the material is recycled. But it is essentially the same formula as previously for manufacturing. The difference will be that each material will be divided into two terms, one for the recycled part and a second one for the non-recycled part. (see Equation 6)

$$\text{Material\&Refrigerant disposal} = \Sigma(\text{equivalent}\frac{CO2kg}{kg}\text{material} \times \text{mass of materials kg}) \quad (6)$$

The following equation (see Equation 7) includes all the contributions to the LCCP:

$$\begin{aligned} \text{LCCP} = {} & (\text{Ref.GWP} + \text{Adp.GWP}) \times (\text{annual leakage} \times \text{years of lifetime} + \text{refrigerant loss at EOL}) \\ & + \text{years of lifetime} \times \Sigma\left(\text{equivalent}\frac{CO_2kg}{kWh} \times \text{operating energy kWh}\right)_{annual} \\ & + \Sigma\left(\text{equivalent}\frac{CO2kg}{kg}\ \text{material manufacturing} \times \text{mass of materials kg}\right) \\ & + \Sigma(\text{equivalent}\frac{CO2kg}{kg}\text{material disposal} \times \text{mass of materials kg}) \quad (7) \end{aligned}$$

In Appendix I, a flow chart of the process chain for a refrigeration system of supermarket can be seen in order to have a better visual comprehension of the previous equations.

2) Example of a LCCP from a simulated model

Hereby will be presented how to run a LCCP when the integrated refrigeration system can be simulated on a computer. Using a model enables to calculate the energy consumption of the system as if it were running at different locations using at the same time: model simulated performances, weather data from the locations and the typical load demand curve for a supermarket of this size. This has been done by the US department of Energy and explained in the paper (Beshr, 2015). The purpose of the paper is to show the influence of the location and the refrigerant on the greenhouse effect issue.

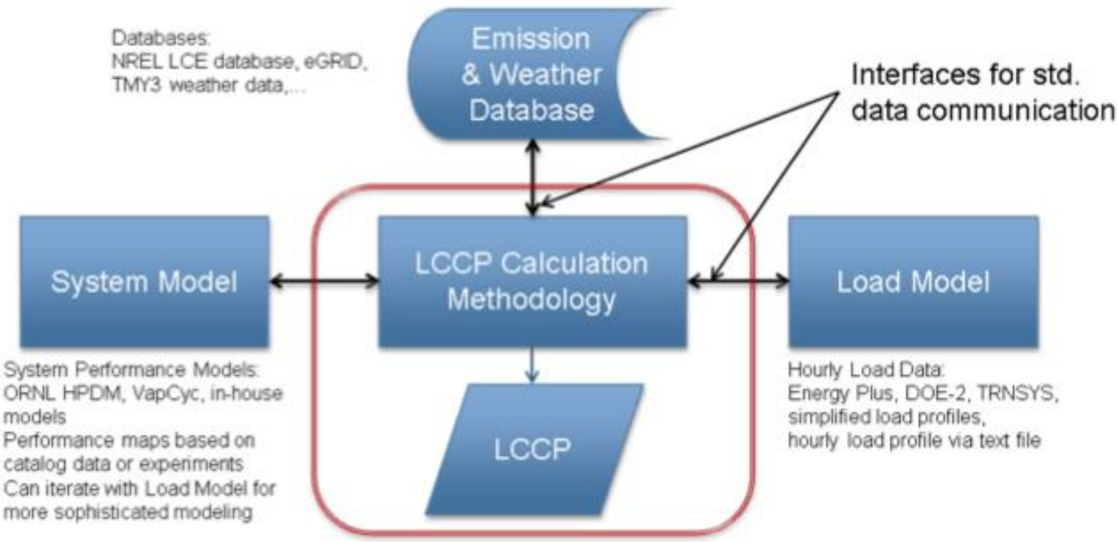


Figure 1: LCCP Framework

Figure 5 : LCCP Framework // Source: A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerant

The software used is EnergyPlus. When filled with the supermarket characteristics (surface of 41282m2, single story…), it gives a typical load demand for that kind of supermarket. Other input parameters are the weather database of the location (different locations chosen for the study listed in Table 2) and the refrigerant (see Table 3).

Table 2: Climate zones and cities used in the LCCP analysis // Source: A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerant

Climate Zone	City	Annual Average Temperature (°C)
1A	Miami, FL	24.9
2B	Phoenix, AZ	23.8
3B	Los Angeles, CA	17.3
4C	Seattle, WA	11.4
5A	Chicago, IL	10.0
6B	Helena, MT	7.2
7	Duluth, MN	4.3
8	Fairbanks, AK	-2.1

Table 3: Compared refrigerant blend compositions and GWP values // Source: A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerant

Refrigerant	Composition	GWP
R-404A	R-125/R-134a/R-143a	3943
R-407F	R-125/ R-134a /R-32	1674
N-40	R-125/ R-134a /R-32/R-1234yf/R-1234ze	1273

The type of refrigeration system has been set on Multiplex DX. A scheme of the circuit components and of the refrigerant evolution in the P-h diagram is presented below. It is very similar to the booster configuration for the CO_2 but here there is neither a high-pressure valve, nor a liquid receiver. Indeed, the refrigerant is here directly expanded nearby each evaporator and this explains the DX (Direct eXpansion) name.

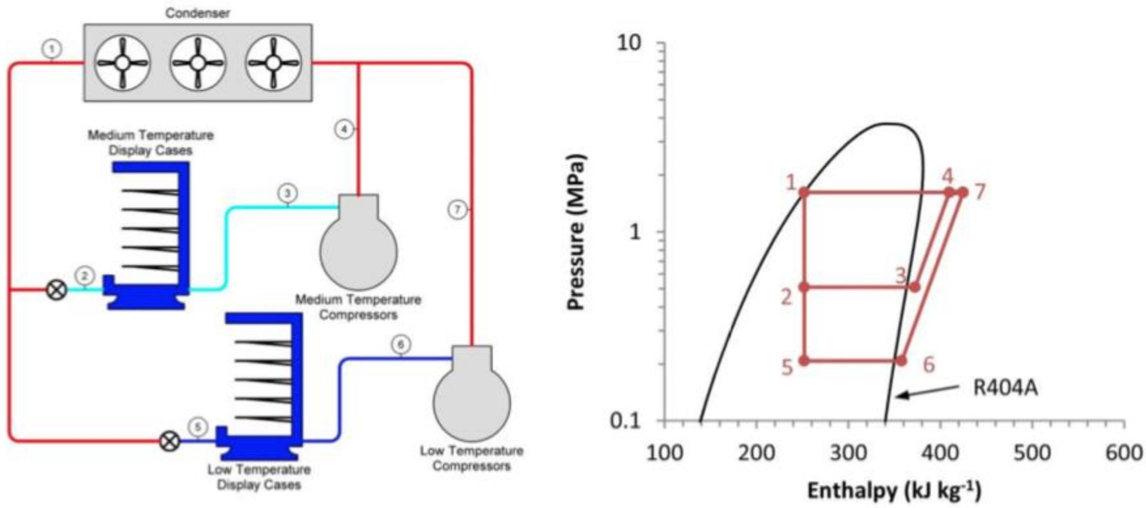


Figure 6 : Scheme of the circuit component and P-h diagram // Source: https://www.energy.gov/sites/prod/files/2016/04/f30/32210a_Fricke_040616-1405.pdf

Once all the inputs entered in the EnergyPlus software, it automatically calculates the designed load for the compressors and the charge of refrigerant (see Table 4 below).

Table 4 : Multiplex DX system specifications // Source: A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerant

Compressor Rack	Refrigeration Load (kW)	Charge (kg)	Source of Mechanical Subcooling
MT1	167.1	748	--
MT2	52.8	236	--
LT1	64.6	290	MT1
LT2	23.4	104	MT2
Total:	**307.9**	**1378**	

In the software EnergyPlus, a simulation of the refrigeration system running over one year for different locations (different weather datasets) and different refrigerants is done. It gives simulated energy consumption for each variant. From there, the carbon emissions are calculated using the emission per kWh of electricity. This ratio can depend on the location as the electricity is not made from the same energy mix at different locations.

The formulas to obtain all the other contributing components to the LCCP have been described in II-1). In these formulas appear some factors that are quite impossible to know perfectly and should be arbitrarily fixed. For example, it is impossible to predict perfectly the annual leakage rate, the refrigerant loss at end-of-life, the system lifetime… In this study these parameters have been listed and set to a certain value (see Table 5). As the goal here is to compare the refrigerants between each other, it is of importance to set the same parameters for all of them and slight particularities of each system could be neglected.

Table 5 : Refrigerant leakage rates and system operating parameters

Annual leakage rate	10	%
Refrigerant loss at end-of-life	10	%
System lifetime	20	years
Service interval	2	years
Service leakage rate	5	%
Reused refrigerant	85	%

III) Tools to calculate the actual energy consumption

As previously mentioned, the LCCP method is straightforward provided that the energy consumption is known over one year. This data is often easy to collect on a field-running system or it can be computed from a simulated model of the refrigeration system. It is though not imaginable to log a prototype data over an as long period as one year. It is neither possible to build a performance map of the system to then apply it to the one-year conditions of a real supermarket for the same reasons, it would take too much time. Moreover, the prototype is meant to be constantly improved so that a performance map would quickly become outdated.

Furtherly, the tools to extrapolate a supposed year electricity consumption of a refrigeration system will be described. Ideally, one should be able to use these tools to obtain the electricity consumption as if the unit was working at a certain location, as long as the weather database of the location is available. In order to do so, a methodology explaining how to obtain a few working points to test on the assessed refrigeration system from just a weather database will be described. The approximations made throughout the reasoning will be pointed out and discussed.

1) The input loads evolution during the day

The data from refrigeration systems actually working in supermarkets is used to have a better understanding of the shape of the inputs applied to the system and their relation between one another. Those inputs are the load demands (MT, LT, AC, HR) and the ambient temperature. It will also be seen that the time of the day has an importance.

The Department of Energy and Process Engineering of NTNU has access to the integrated refrigeration system unit running in the Rema 1000 supermarket located at Kroppanmarka (Trondheim, Norway). It is possible, through the software StoreView powered by Danfoss, to download data from all the sensors installed to control the facility. Unfortunately, this data retrieving process leads to many errors and it hindered the optimal exploitation of the data. Thereafter, the reasoning will be driven as accurate as possible considering the aforementioned issues. It is to say that the tools presented here will allow one to build the complete energy consumption calculation methodology, provided that a complete dataset from a supermarket is collected.

a) Using a previous NTNU study

In the paper (Pardiñas, 2017), the shapes of the load demand for a typical day in winter and a typical day in summer were approximated and plotted (see Figure 7 & Figure 8 below). Assumptions can be drawn from there in order to simplify the work.

At first sight, it is possible to notice that there is a behavior difference in the loads whether the shop is opened or closed. When the shop is closed, all loads are considered constant and lower than during the day.

The LT load is nearly constant during the day. The small alterations occur when adding/picking food in the freezers in the opened time. It will be assumed that the LT load is constant during the day and the same regardless it is opened or closed. The LT load value is not depending on the ambient temperature as the freezers are placed in the shop surrounded by the sales area constant temperature and cabinets frequently have glass doors to minimize any effect.

The MT load is steady while the shop is closed but becomes higher and unsteady during the whole opened period. It is due to the increased need in cooling caused by openings, defrosts… The shape can be considered as the same for both, winter and summer conditions. It is not actually true because the load will be increased in summer as there is a higher humidity during this period and therefore increased defrost needs.

Instead of rejecting the heat at the gas coolers to the ambient, it can be recovered for different usages as floor heating (to melt ice and snow), heating of sales area or tap water... This heat recovery demand is almost constant but for two peaks during the day. The assumption here was that, if the heat recovered is used by the buildings surrounding the supermarket, there is a consumption of DHW (Domestic Hot Water) in the morning and evening. The offset value depends on the ambient temperature. In summer it is zero and the Heat Recovery mode will be turned on as soon as the ambient temperature will go down below the heating of sales area setpoint often set around 18°C.

During the summer there can be an extra cooling demand for the Air Conditioning. It can be considered that the AC is constant throughout the opened period and null while the shop is closed. It is though not exactly correct because the shape is slightly parabolic as it follows the ambient temperature.

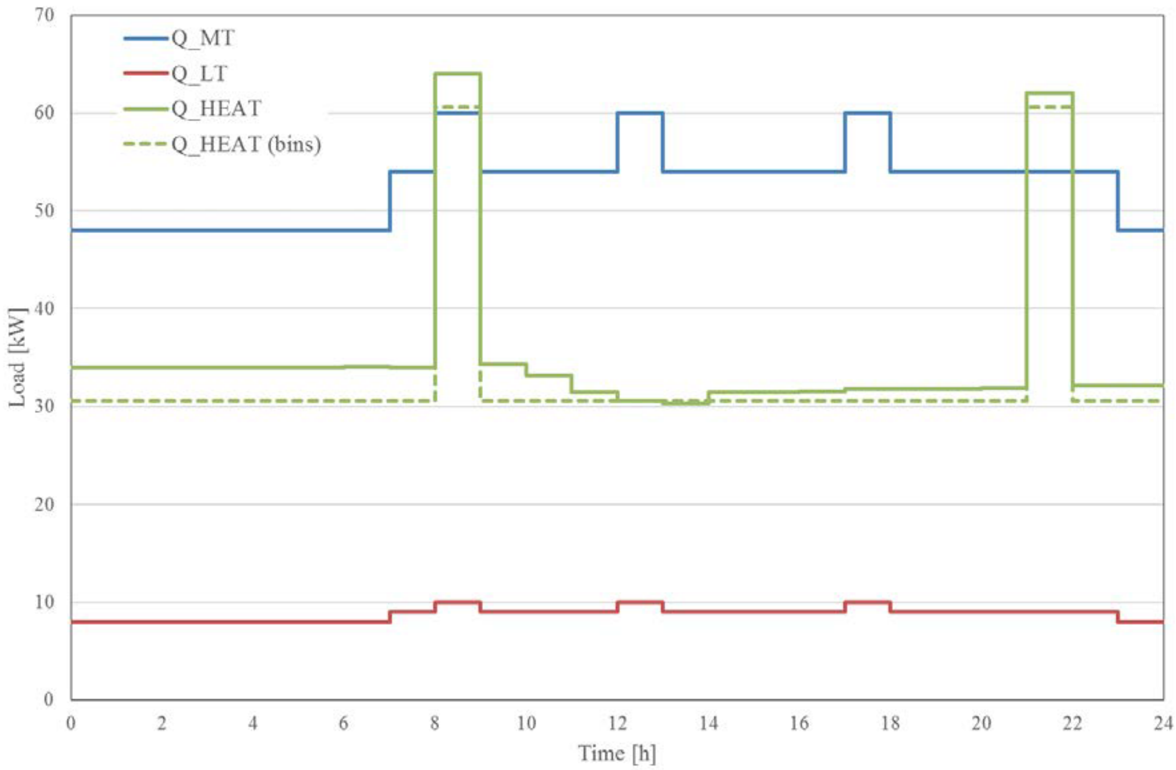


Figure 7 : Load demands for a typical day in winter // source: Performance test methodology for the LCCP determination of supermarket and other integrated systems (Á. Á. PARDIÑAS, A. HAFNER, K. BANASIAK, L. LARSEN)

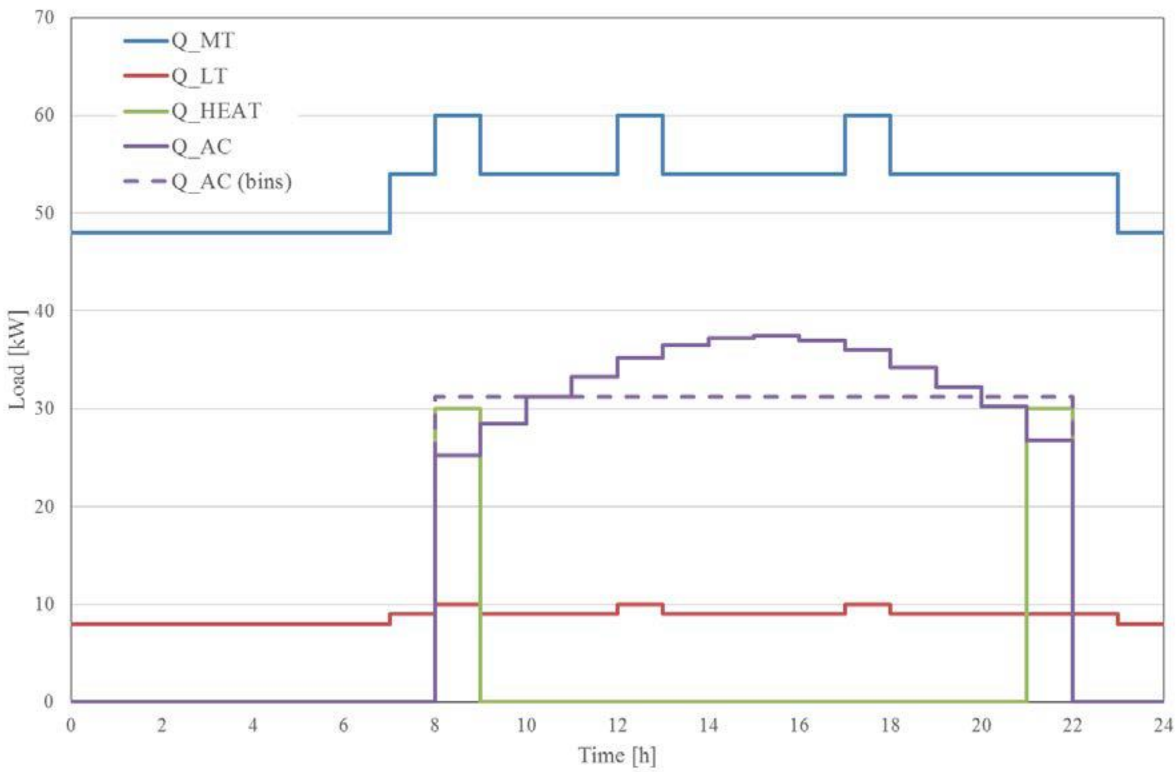


Figure 8 : Load demands for a typical day in summer // source: Performance test methodology for the LCCP determination of supermarket and other integrated systems (Á. Á. PARDIÑAS, A. HAFNER, K. BANASIAK, L. LARSEN)

b) Using the Rema Kroppanmarka supermarket data

The previous assumptions are valid in theory but when plotting the Loads for a day with the data from the Rema Kroppanmarka supermarket, it is obtained a different shape for the loads during the day (see Figure 9 & Figure 10 below). The loads are actually oscillating constantly. That could not be seen in the previous section because it was shown what happens for a typical day over a season, so the shape is smoothened when averaging.

The loads are imported from StoreView using the variables described in appendix (see II). AHU_HC and AHU_CC are actually absolute loads in kW. Their calculation method is described furtherly in the same section.

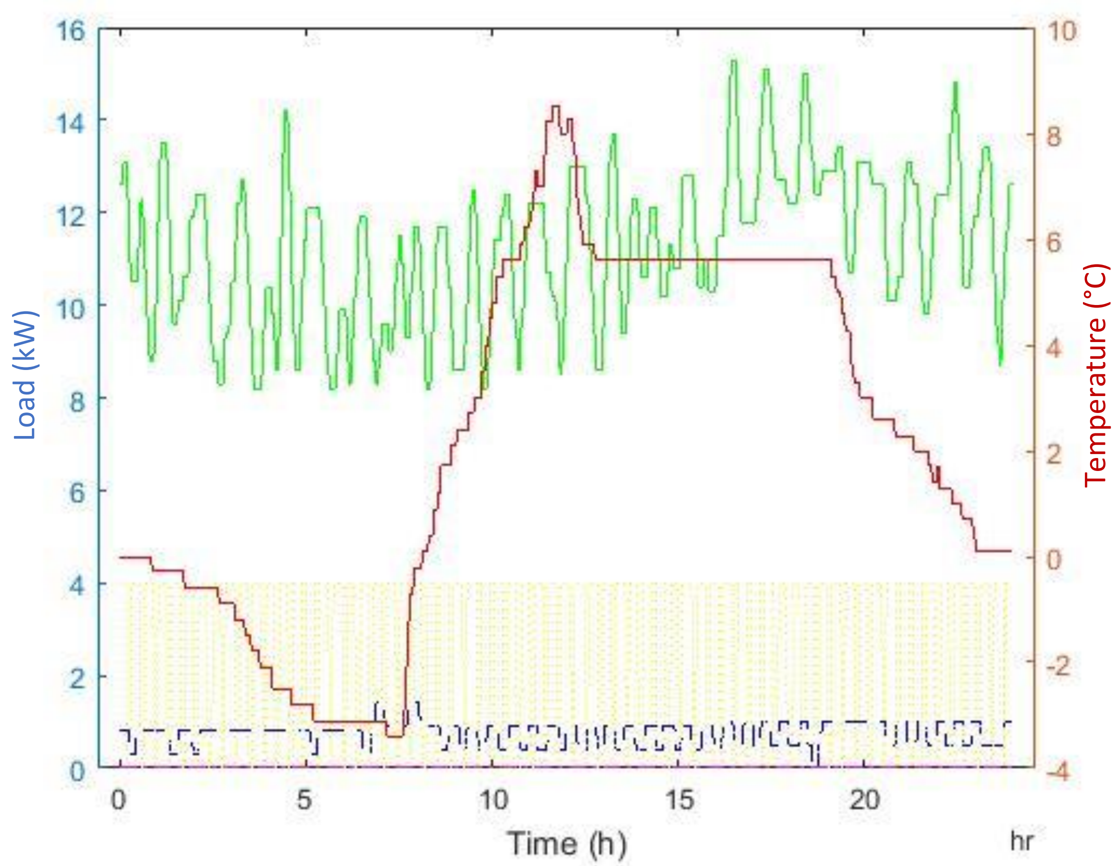


Figure 9 : Evolution of the ambient temperature (red) and loads during the day. MT Load (green), LT Load (blue), AHU_HC Load (yellow) and AHU_CC Load (purple) // Data: 03/30/2018 Rema Kroppanmarka

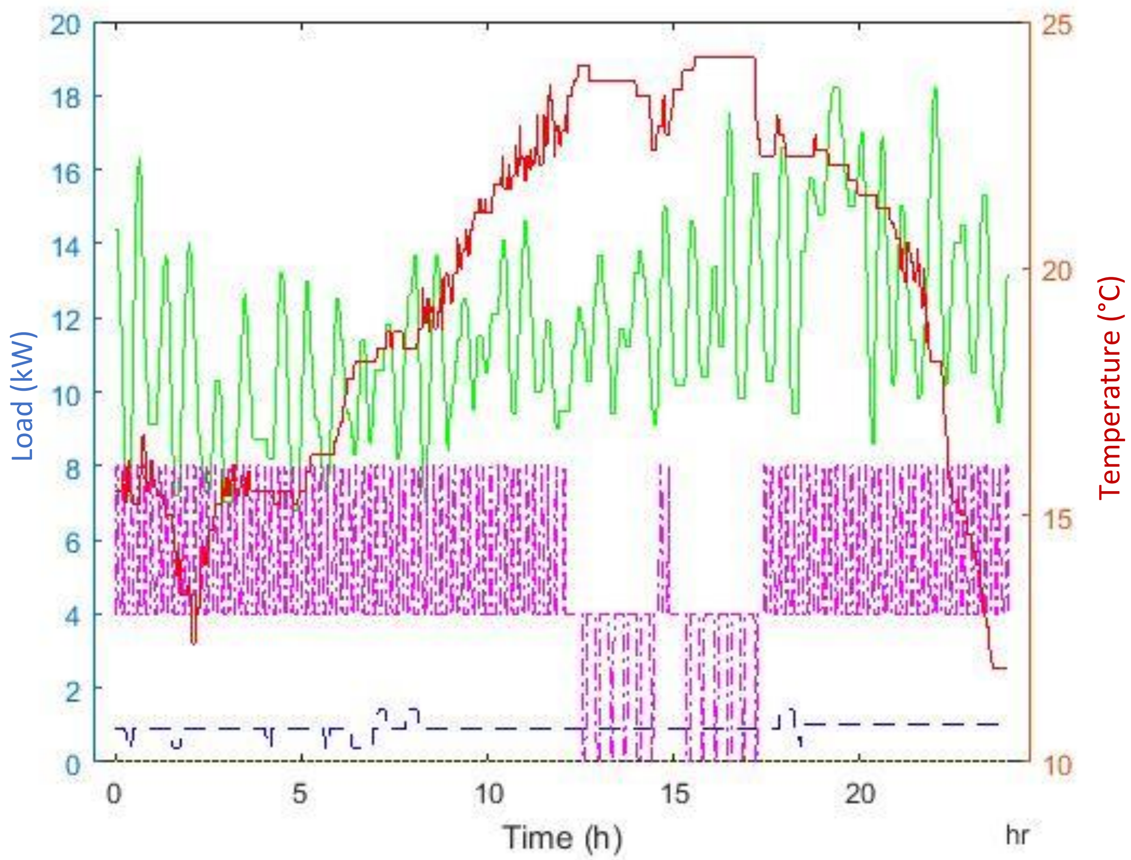


Figure 10 : Evolution of the ambient temperature (red) and loads during the day. MT Load (green), LT Load (blue), AHU Load (yellow) and AC Load (purple) // Data: 10/05/2018 Rema Kroppanmarka

The reader should first be warned that there might be a misunderstanding of the variables available in StoreView since the documentation available is not precise enough about what is exactly logged. It has been proceeded a reasoning by elimination and deduction that might be wrong.

The Kjølemaskin and Frysemaskin loads available in Storeview (see Appendix II) are guessed to be the cooling loads occurring respectively in the MT and LT cabinets. They are corresponding directly to the load demand in the cabinets called MT Load and LT Load in III) -1) -a). It is quite different from the MT and LT compressors power and one should not mix them up.

It seems that the MT Load is changing constantly, and it is visually hard to see a difference between an opened or closed shop. There is actually one because it tends to be higher around the opening time as seen when having a closer look to the MT Load behavior during the day, available in the III) -2) -b) section.
The refrigeration system controller regulation is made to reach a temperature setpoint so that the MT Load output will depend on the regulation strategy. For the Rema Kroppanmarka the MT Load is oscillating whereas the theoretical load demand seen previously with Figure 7 & Figure 8 is flatter.

The LT Load is quite constant, but some drops and peaks happen. It may be that the freezer, while its door is opened, switches off since the evaporation temperature is reached. The punctual raises are surely due to extra cooling demand after a programmed defrost of the evaporators. It can be averaged for a first overview, but it could be interesting to integrate a changing LT Load in a further work.

The report (Jorschick, 2014) gives a better understanding of the functioning of the Air Handling Unit (AHU). It is compound of a cool coil and a hot coil (seen on Figure 11). The coils are fed with heat from the hot storage and cooling from the energy well cycle. It is possible to have the percentage of each of them and the load of the whole unit. In the present report it will be multiplied the percentage with the global load to evaluate the air cooling load also named here AHU_CC and the hot load – AHU_HC. AHU_CC/AHU_HC loads are switching from off, to a certain value and the double of this value. It is then possible to average it and consider that the actual air conditioning load could be met by the refrigeration system using a more advanced control.

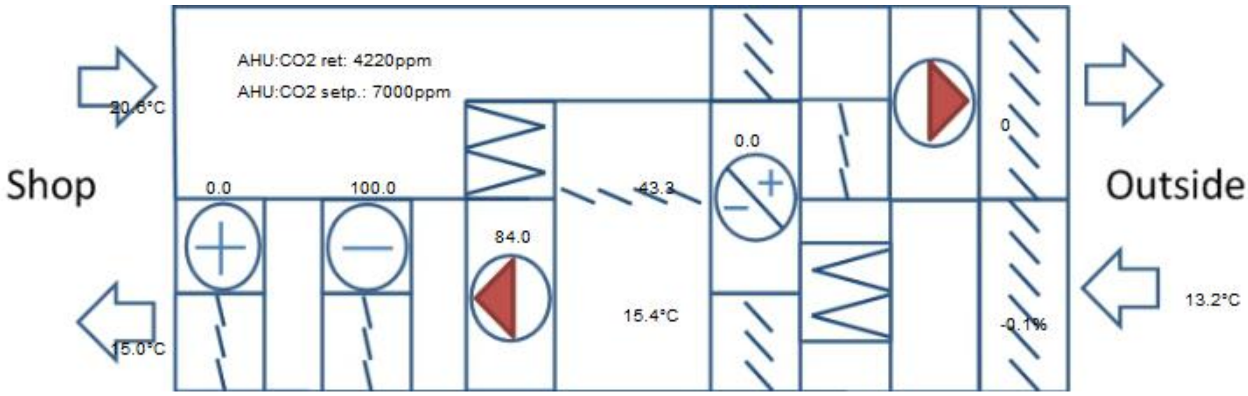


Figure 11: screenshot of the AHU graphic view in StoreView

The heat reclaim in a supermarket can be more than just helping the AHU unit to heat up the sales area ambient air. In order to avoid formation of ice on the floor of the cold storage room, it is installed a floor heating system. In some cold countries like Norway, it is even necessary to install this kind of system to heat up the ground/stairs in front of the shop so that it melts the snow and ice to make it safer. In the Rema Kroppanmarka dataset, there was no possibility to get data about the floor heating of the outside areas but only from the cold storage room floor heating. Unfortunately, the data of the inside floor heating seems to be defective as it leads to excessively high values. As a result, it will be here considered that the heat reclaim is restricted to the only sales area air heating in the AHU, AHU_HC.

In most of the supermarkets it is now installed a heat storage -typically glycol tanks- in order to partly dissociate heat recovery and heat reclaim. The dissociation is not complete as the storage is limited in space and in time (in time because of the heat losses through the storage envelop). It is the solution to the paradox that the higher the cooling demand, the higher the possible heat recovery but also the lower the heat reclaim. So, during a high cooling load period, it is done a maximum heat recovery that cannot be instantly used but it is stored for a later usage. At the Rema Kroppanmarka, an underground energy well was implemented for a longer-term storage.

It will then only be looked at the loads applied to the system (MT Load, LT Load, AHU load and heat reclaim) and not to the heat recovery load as it is depending on an energy-cutting strategy and the historic loads. The problem caused by this assumption is that normally the heat recovery does not correspond exactly to the heat reclaim as it gets smoother in the time thanks to the storage. It should then be remembered that the tested refrigeration system will not be tested at its best performances since it is tested as if there was no heat storage helping it to be more efficient.

2) Approximations

As mentioned in the III) -1) section, the AHU and HR loads are determined by the ambient temperature. The LT Load is constant all over the year and the MT Load has a particular evolution during the day that should not be too different from one day to another. Some peaks can occur during the opened period because of door openings, adding of new products, defrosts… It depends on the customer habits, the supermarket strategy about cabinet feeding and programmed defrost periods. Thanks to the data gathered from the Rema Kroppanmarka supermarket, it is possible to have a look into the evolution of the MT Load. There are unfortunately many errors occurring during the data collection so instead of showing -as it should ideally be done- a methodology applied to a one-year dataset, it will rather be shown for the April 2018 month.

There will be explained 3 different methods to deal with the MT load changes:

- The first (a)) is the most accurate because it takes into account the knowledge about how the MT Load changes during the day. It is though not practically applicable as it leads to too many working points.
- The second method (b)) consists in correlating the MT Load and the ambient temperature variables of the supermarket data available (here Rema Kroppanmarka). It is a good method to obtain the energy consumption of the studied refrigeration system (SuperSmart Rack) as if it was working in the supermarket we have data available about. The drawback is that it basically cannot be applied to any location.
- In the last and third method (c)), it is made a larger approximation differentiating only between a closed or opened shop so that it is selected only a reasonable amount of working points and the energy consumption assessing methodology can be easily proceeded for whatever location.

The ideal goal of the methodology is to be able to extrapolate the energy consumption of a refrigeration system for any location in the world, as long as the weather database of the location is available. The data that really matters in the weather database is the ambient temperature. It will be seen how to characterize a one-year temperature dataset wisely (d)).

Finally, in a last section (e)) there will be an explanation about how to reduce even more the number of working points keeping a reasonable accuracy of the results. It consists in using similarities between winter and summer conditions.

a) First method: the MT Load variation

The relationship between hour of the day and MT Load can be studied plotting the occurrences in a houroftheday/MT Load map (see Figure 12). The houroftheday-variable is plotted on the X-axis and the MT Load on the Y-axis. The MT Load is chosen to be converted to a percentage, with a biggest load occurring on the data period as reference. It enables to conduct a reasoning that could be applied regardless the size of the supermarket. This percentage conversion should be remembered since it is also used for the LT load and in all the reasoning thereafter.

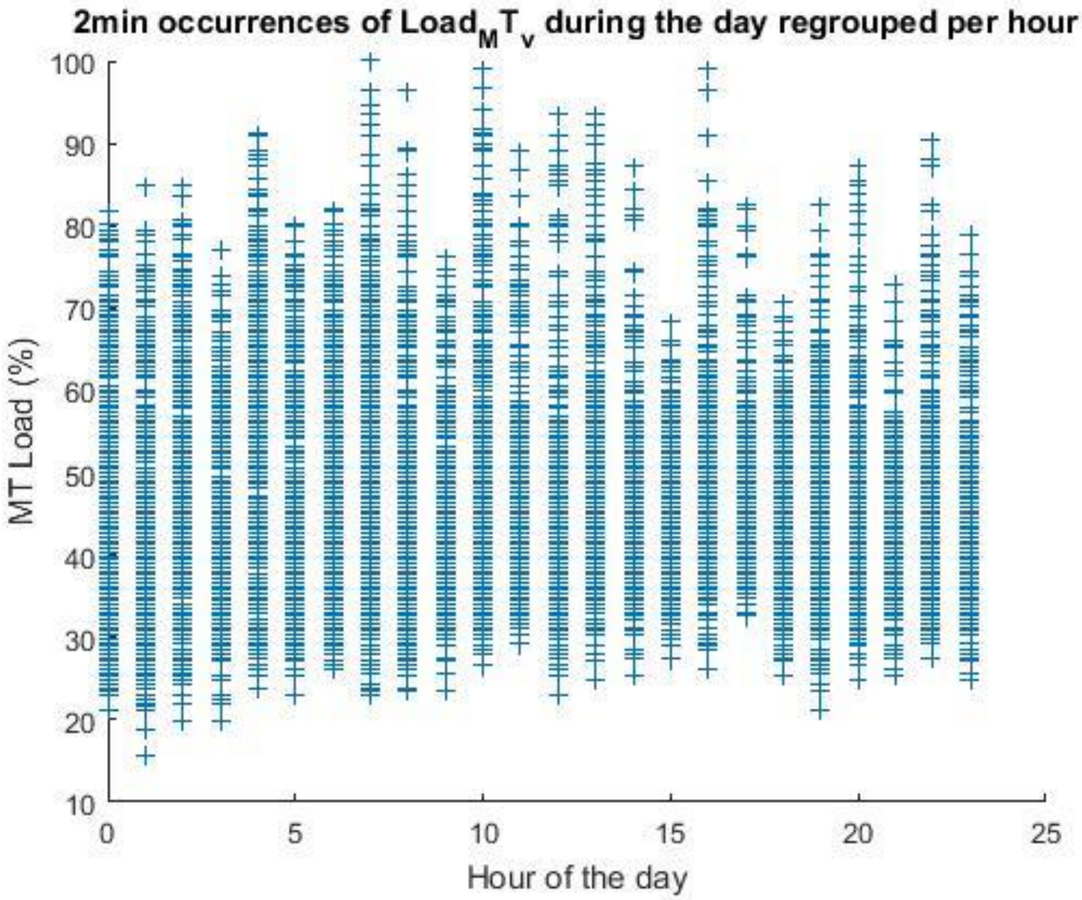


Figure 12 : 2min occurrences in the Houroftheday/MTLoad map // Data: Rema Kroppanmarka April 2018

In order to have a better visual view of the load repartition, a frame is applied to regroup the different occurrences into a limited number of packages (see Figure 13 below). It is defined first a matrix where the columns represent a regular subdivision of the MT Load range and each line corresponds to an hour of the day, this is what will be called the frame from now on. Then each occurrence -here taken every 2min- will be approximated to the closer point of the frame and it will increment by one the value at the corresponding place in the matrix. Finally, it is represented under MATLAB with the plotting function "scatter" in order to draw a bubble diagram.

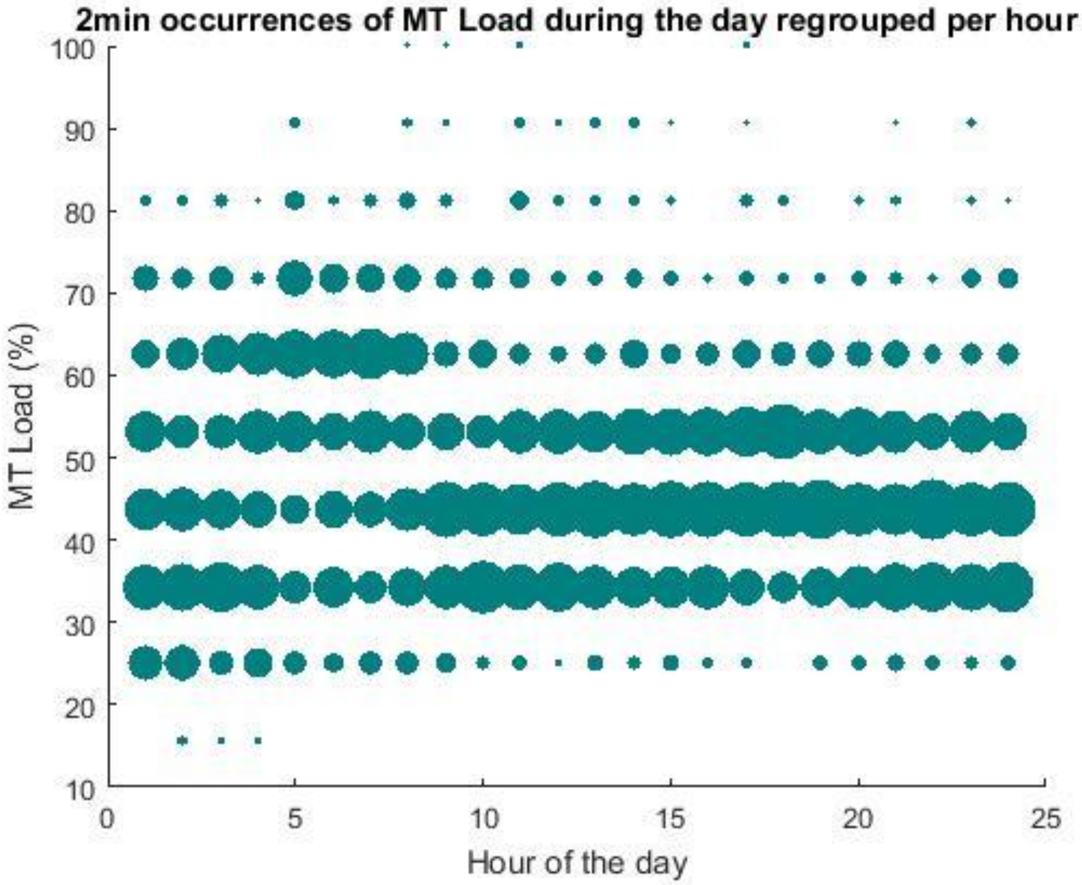


Figure 13 : regrouped 2min occurrences in the Houroftheday/MTLoad map // Data: Rema Kroppanmarka April 2018

This map (see Figure 13) gives visually the MT Load repartition for every hour of the day. It is possible to notice that the repartition is not depending so much of the time of the day except that during the morning, before the opening of the shop, the MT Load is higher. It is due to the daily cabinets' loading implying a long door opening with air from the shop coming inside the cabinets with their heat, humidity… and arrival of new food that may need to be cooled down. The same happens around the time when the shop should be the most frequented, when people use to end their working day. The MT Load is higher as more customers means more cabinet openings.

To conclude, there remains to use the load repartition for each hour of the day to choose the working points. Only a few loads per hour should be kept using the size of the circle-criteria. It allows us to combine it with the temperature from the location and finally have a set of working points. The problem with this method is that the number of working points will be huge so that this method is not really relevant… But it is still of interest as it is the most comprehensive one.

b) Second method: Combination MTLoad/Tamb with both data from the supermarket

Crossing the Tamb/MTLoad enables to have a good set of working points to compare the LCCP of the studied refrigeration system with the LCCP of the supermarket we had data from (here the Rema Kroppanmarka). This is an accurate method, but it cannot be transposed to whatever location.

To know which working points occur the most, it is possible to have a look at a map representing the occurrences of MTLoad/Tamb couples (see Figure 14 below).

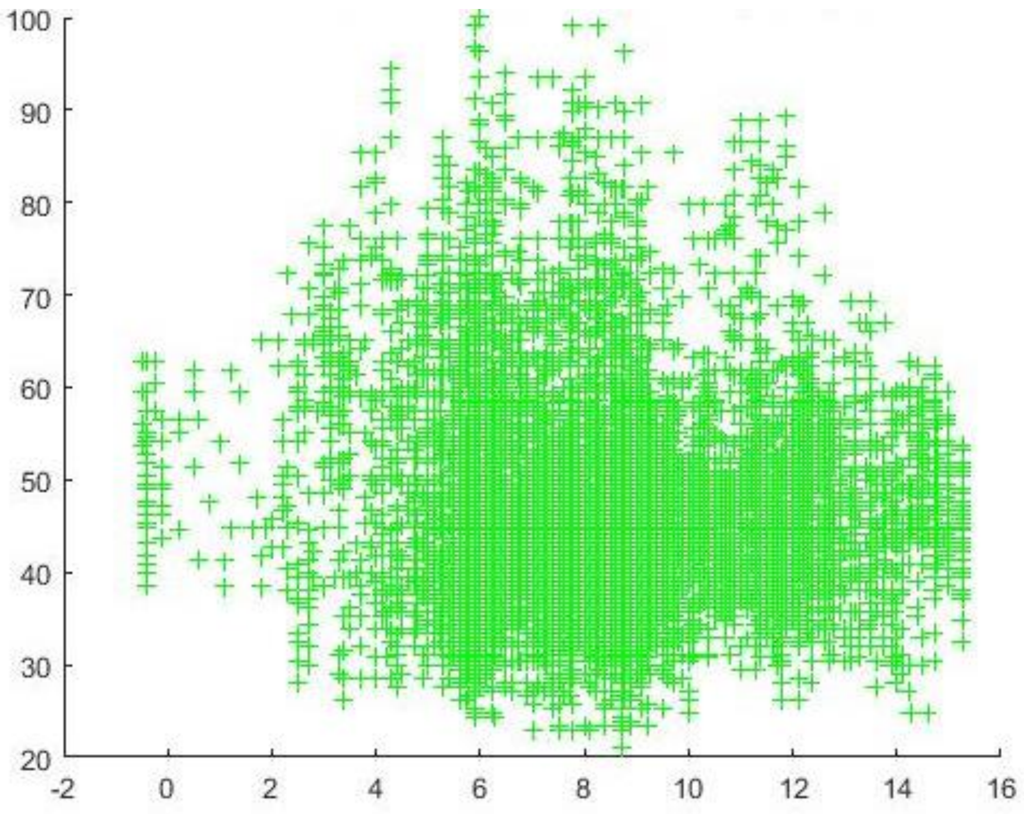


Figure 14 : 2min occurrences in the Tamb/MTLoad map for an opened shop // Data: Rema Kroppanmarka April 2018

When regrouping the working points into a frame -using the same method as in III) -2) -a)-, it is easier to visually select the main working points (see Figure 15 below). The bigger the circle, the more time is spent around the working point. The criteria to choose the most important working points should be the energy consumption. This energy consumption is directly proportional with the electric power and the time. It is then interesting to choose the most important working points by the time spent on it. But it will not be completely accurate as the electric power, that is unknown at this point of the reasoning, should ideally also matter for the working point selection.

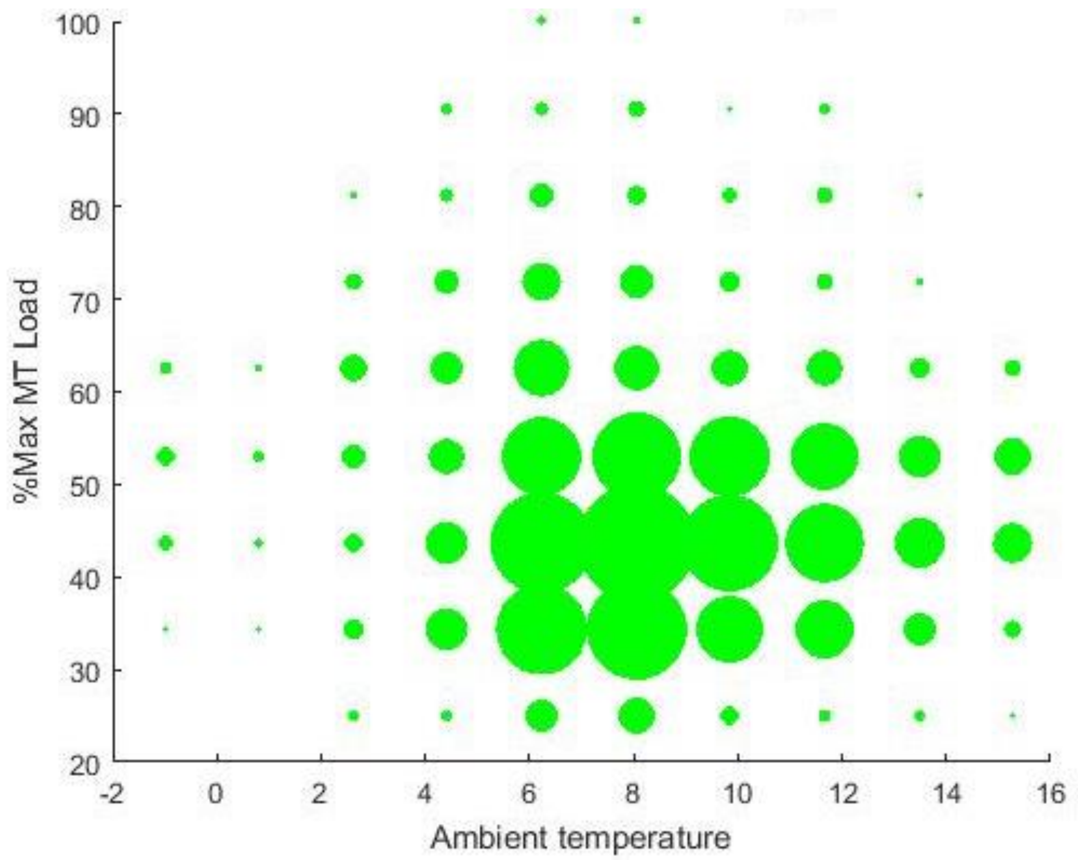


Figure 15 : regrouped 2min occurrences in the Tamb/MTLoad map for an opened shop // Data: Rema Kroppanmarka April 2018

The larger the number of circles plotted, the more accurate is the load repartition for each temperature. It is actually true in some extent because the number of circles plotted should stay low to make sure that there are enough points in each series of values. At this point, there is a selection to do. For each temperature a few loads can be chosen on the size of the circle criteria to keep only the most important points. Then it is considered that the whole time spent at an ambient temperature is actually shared with only those few chosen points.

The final number of working points will depend on how many temperatures are chosen for the temperature repartition subdivision, and then for the load repartition for each temperature. Therefore, if we consider nT the number of temperature in the temperature subdivision and nL_T the number of load kept for each temperature, the total number of working points nWP will be: $nWP = nT \times nL_T$.

c) Third method: Combination MTLoad/Tamb with MTLoad from the supermarket and Tamb from the location

The third method consists in assuming that the MT Load is constant at its average value differentiating only between whether the shop is OPENED or CLOSED. This larger approximation leads to a smaller set of working points and from it, the energy consumption of whatever location can be obtained.

If we consider nT the number of temperature in the temperature subdivision and $nL_{O/C}$ the number of load kept for each period opened/closed, the total number of working points nWP will be: $nWP = 2 \times nT \times nL_{O/C}$.

This method is not explained exhaustively here because an example is detailed in the III) -3) section.

d) Temperature choice

The ambient temperature influences the refrigeration system performance. The COP (Coefficient Of Performance) of a refrigeration system is depending on the temperature of the heat sources and sinks. Heat is taken from the cold source, the cabinets, and is transferred to the hot sink, the ambient air. From a local weather station, it is possible to retrieve the ambient temperature logged with a certain time step. From here, the occurring frequency of each temperature during a year is rather of interest. It will be proceeded a distinction between the shop opened or closed as it has previously been demonstrated that the load behavior can be different.

In order to reduce significantly the number of working points to test on the SuperSmart Rack, a first approximation is applied to the dataset using MATLAB. The easiest is to set a regular frame on the temperature vector. It means that for a given number of ambient temperature points wanted, it is possible to divide the ambient temperature range into a regular subdivision. It has been plotted an example of a regular subdivision applied to the month of April 2018 at the Rema Kroppanmarka supermarket. The number of points in the subdivision has been set to 20 and since the temperature range is 15.28-(-1)=16.28°C, the step is 0.87°C. (see Figure 16 below).

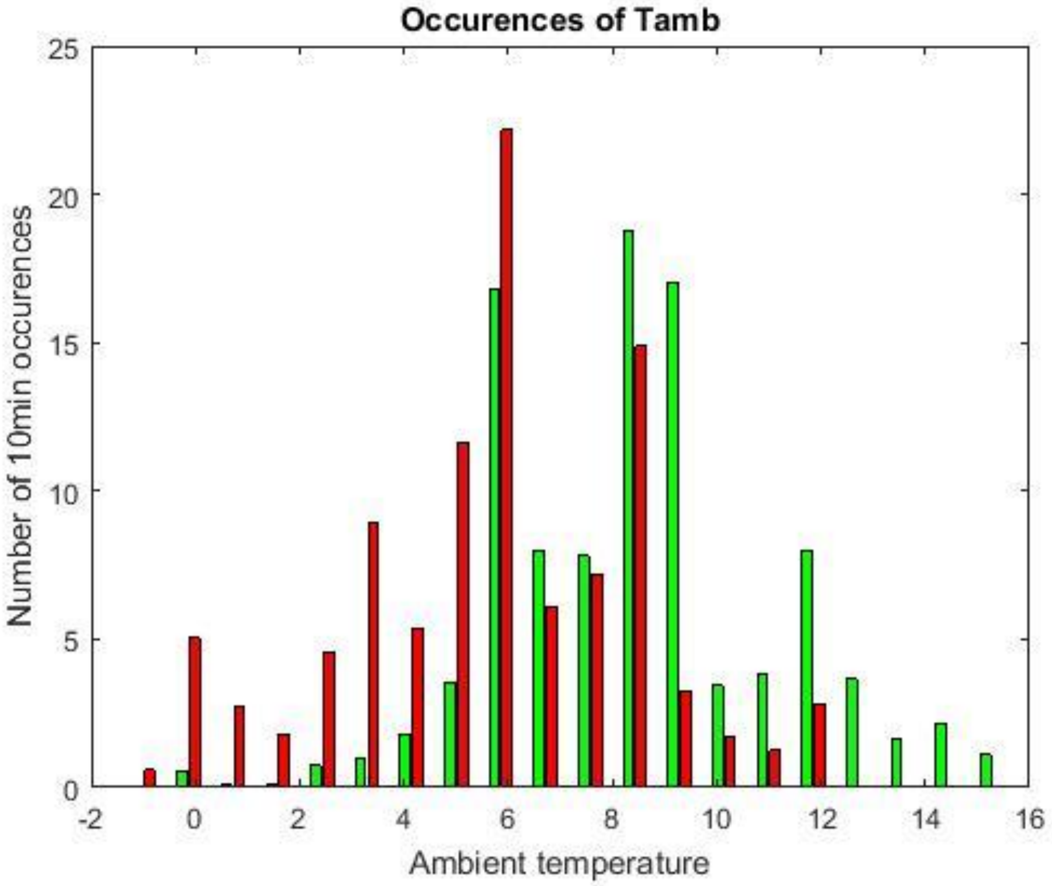


Figure 16 : Occurrences of Tamb- OPENED (green) and CLOSED (red) // Data: Rema Kroppanmarka April 2018

To ensure a better choice of temperature, it will be preferred to use what will be furtherly called an integral subdivision. It is to say that the dataset will be divided into regular sized packages (each package has the same number of occurrences) and the temperature of each package is the average of its temperatures. As for the regular subdivision, the number of packages is set by the user. If it had to be done manually, one should first divide the number of occurrences in the dataset N_t by the willed number of packages n to find the number N_p of occurrences to count in a package. The occurrences are listed ordered by ambient temperature so that it can be defined the first package being the first N_p occurrences. Then will come the N_p occurrences of the second package, etc… Finally, the temperature representing each package should be calculated making the average of the temperatures in the package. By construction, the frequency of each package is equal altogether to N_p/N_t. (see Figure 17 below).

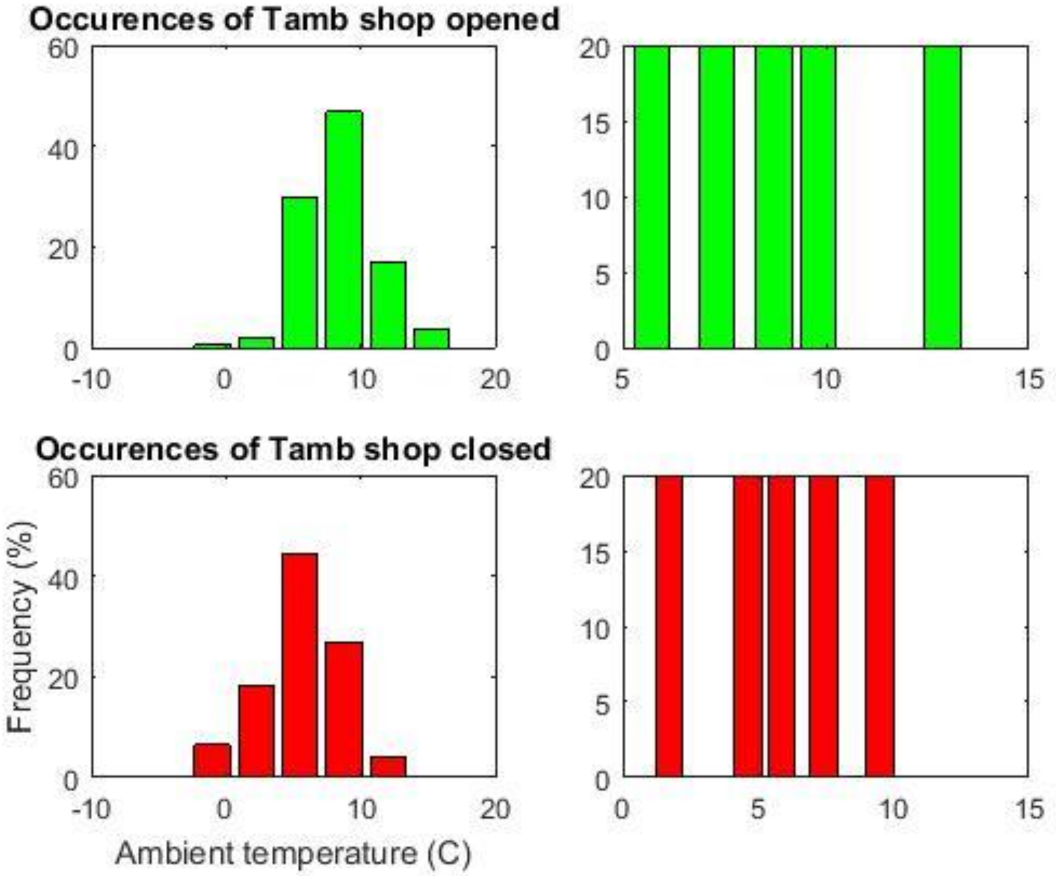


Figure 17 : Occurences of Tamb - left: regular frame - right: integral frame // Data: Rema Kroppanmarka April 2018

In this way, it will be chosen a limited number of temperatures on which the refrigeration system will be tested on. In order to construct completely the set of tests, it is necessary to know which load values correspond to each temperature III) -2) -c).

e) Similarities between HR and summer conditions

To go further in the reduction of the number of working points it is possible to see that there are similarities between conditions that are actually not at the same ambient temperature.
The idea here is based on the fact that the gas cooler outlet temperature raises when the ambient temperature raises. Indeed, it can be considered a constant pinch for the heat exchange occurring in the gas cooler so that the gas cooler outlet temperature “follows” the ambient temperature.

Although, there is an ambient temperature below which there is no change in the gas cooler outlet temperature. The gas cooler is bypassed, or the heat transfer is limited (by reducing the speed of the fan) in order to maintain the temperature of the CO_2 at the outlet of the GC high enough to prevent the pressure in the liquid receiver from sinking. This is though not happening when the HR mode is on.

The HR has an impact on the CO_2 characteristics at the gas cooler. The HR is a heat exchanger placed in series with the GC, but preferably upstream in order to use the elevated temperatures of the CO_2. As a matter of fact, the compressors will compress the CO_2 to a higher level of pressure in order to have a greater load (larger enthalpy range) in the GC and supply all the heat demand, even if it theoretically lessens the refrigeration COP. The COP must then be considered as a global COP for the unit as from now on it supplies 2 demands: heating and cooling. Briefly, as shown on Figure 18, whereas during a summer day the compressors compress at a high-pressure level (HR2) to enable the transfer from the CO_2 to the ambient air, during a winter day the heat demand is such that the compressors will surely also compress to a high-pressure level (HR2 instead of HR1) to have a greater capacity for heat recovery. This is not true for all systems; HR1 and HR2 are not necessarily different but it will be supposed, and then it will be tested this theory to see if it is validated with on field-measurements.

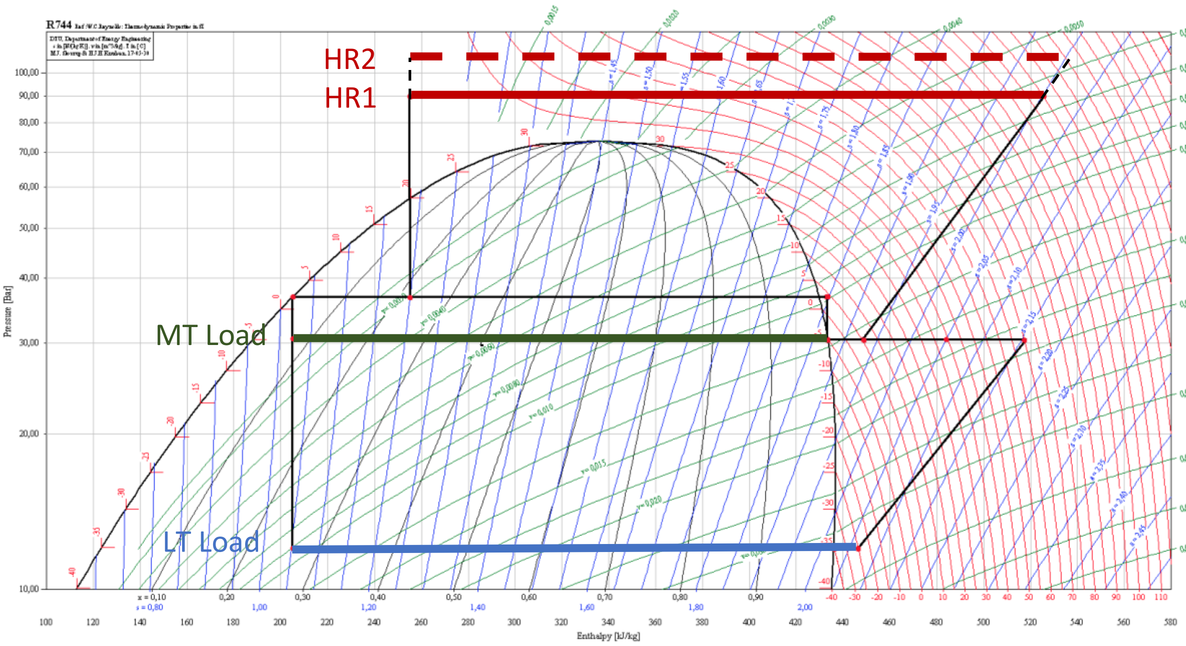


Figure 18: P,h diagram of the booster system configuration for 2 different GC temperatures

For the present study, it will be of great importance because therefore the system will "see" the same inputs applied to the gas cooler for a summer-day and a winter-day when there is heat recovery. It is then possible to regroup the tests of the two similar temperatures. In the Rema Kroppanmarka data, it can be seen which ambient temperature can be regrouped together by looking which ones have the same value for the gas cooler outlet temperature variable. The couples of T_{Sgc} and T_{amb} are plotted in Figure 19.

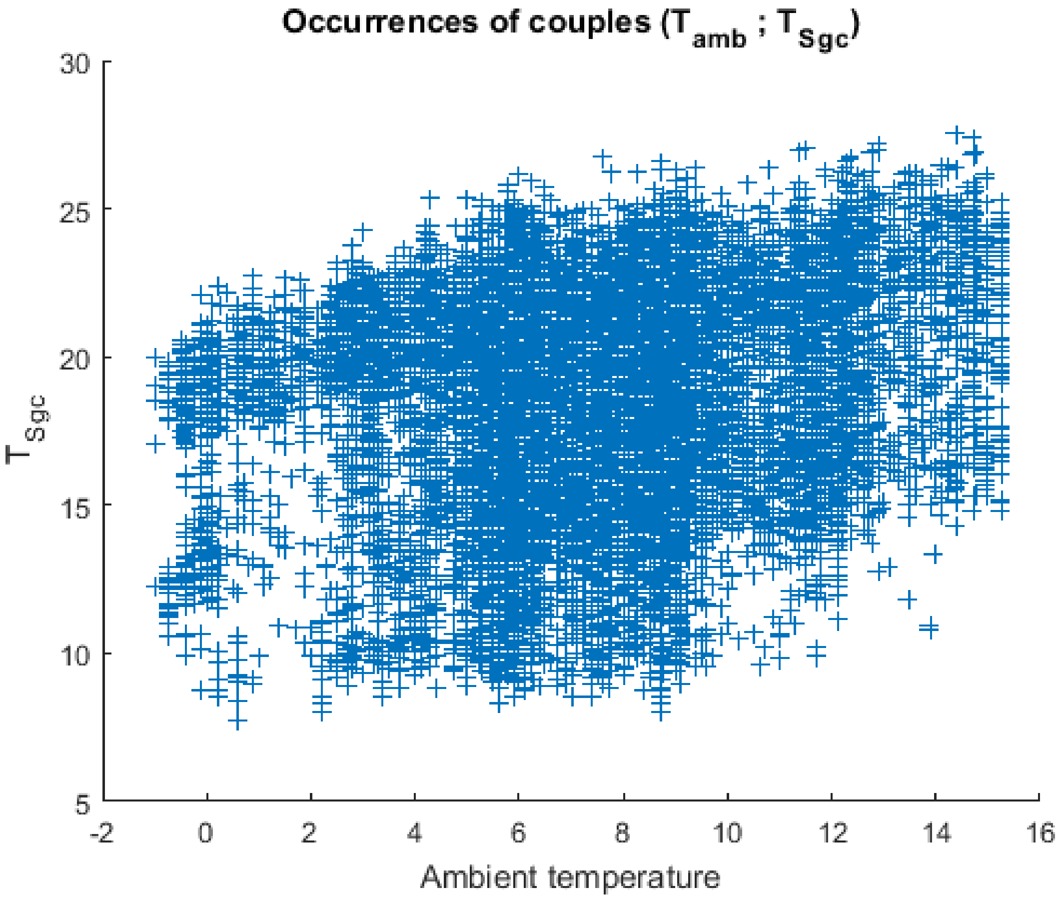


Figure 19: 2min occurrences of T_{Sgc} ,T_{amb} couples // Data: Rema Kroppanmarka April 2018

To have a better view, the occurrences are regrouped in the same way as shown previously (see Figure 20).

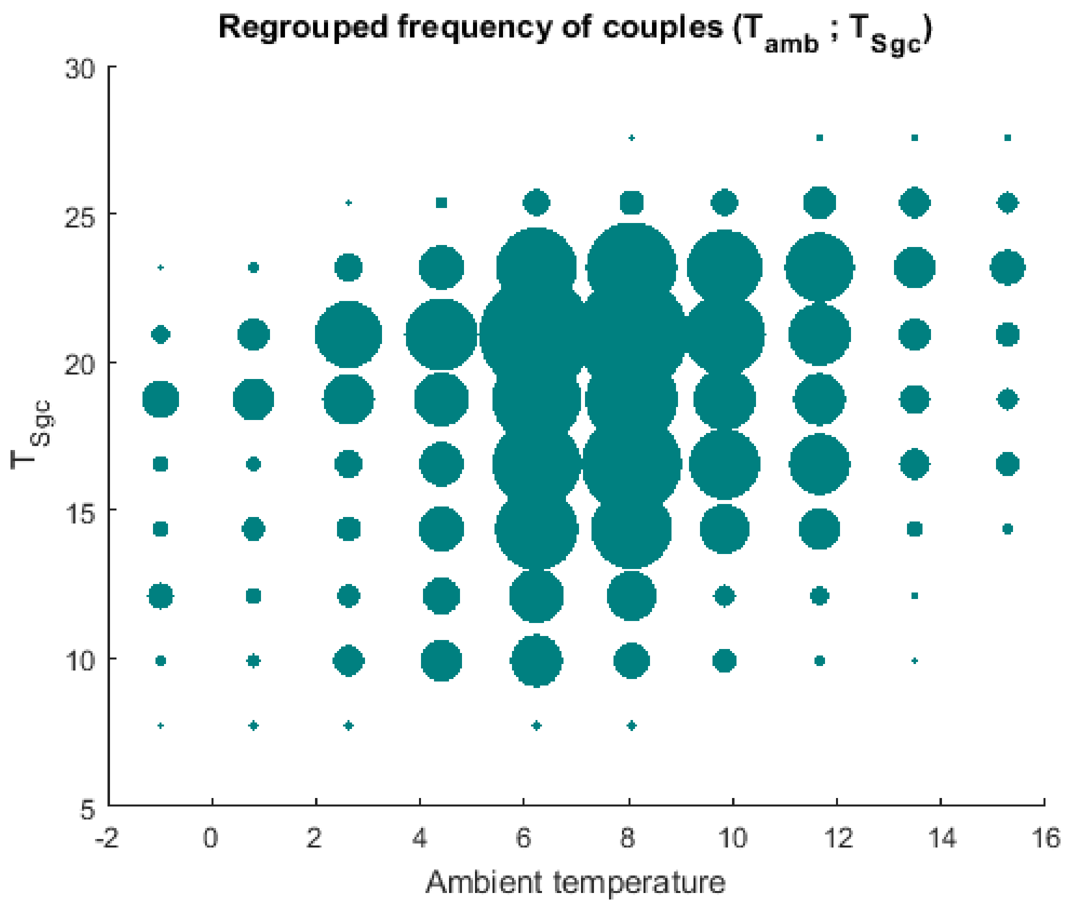


Figure 20: regrouped 2min occurrences of T_{Sgc} , T_{amb} couples // Data: Rema Kroppanmarka April 2018

It is actually possible to see that there is no real correlation between the ambient temperature and the temperature at the outlet of the gas cooler. In theory, it was a relevant idea, but the field measurements are not approving. It may be due to the heat storage.

The theory of similarities of winter with HR and summer conditions will finally not be taken into account in the rest of the study but it can be studied in a further work.

3) Calculation of the energy consumption in practice

An example of determination of a working point set will be driven here using the third method previously explained in the III) -2) -c) section. The similarities between summer and winter-HR conditions will be ignored. Unfortunately, the data over one year -as ideally needed for the LCCP- is not available so the energy consumption of only one month (April 2018) will be calculated. It nevertheless allows one to have an idea about how to proceed to the energy consumption calculation and it can be reproduced in a further work with a one year dataset to finally assess the LCCP.

a) Load determination

The 4 loads (MT, LT, AHU_CC, HeatReclaim) have to be determined. The MT load is assumed to have 2 different behaviors whether the shop is opened or closed. The LT load is assumed to be constant over the whole day. The heat reclaim is supposed to be only compound of the

AHU_HC. The AHU_CC (cooling of sales area's ambient air) and the AHU_HC (heating of sales area's ambient air) are both only depending on the ambient temperature.

Two MT Load values are kept for each period opened/closed. The LT Load is averaged in order to keep only one value. A 5 point integral subdivision is applied to the temperature dataset to keep 5 values for each period. Finally, as seen in III) -2) -c), the number of working points will be $n_{WP} = 2 \times 5 \times 2 = 20$.

i. MT Load determination

The MT Load is assumed to be constant on both periods opened/closed but at different values. On each period it is possible to apply a regular subdivision in order to choose a limited number of values for the MT Load. Hereby (Figure 21), a 5-point subdivision is applied and 2 values (the 2nd and the 3rd) are selected (Table 6) because of their prevalence above others in terms of time spent at this load value.

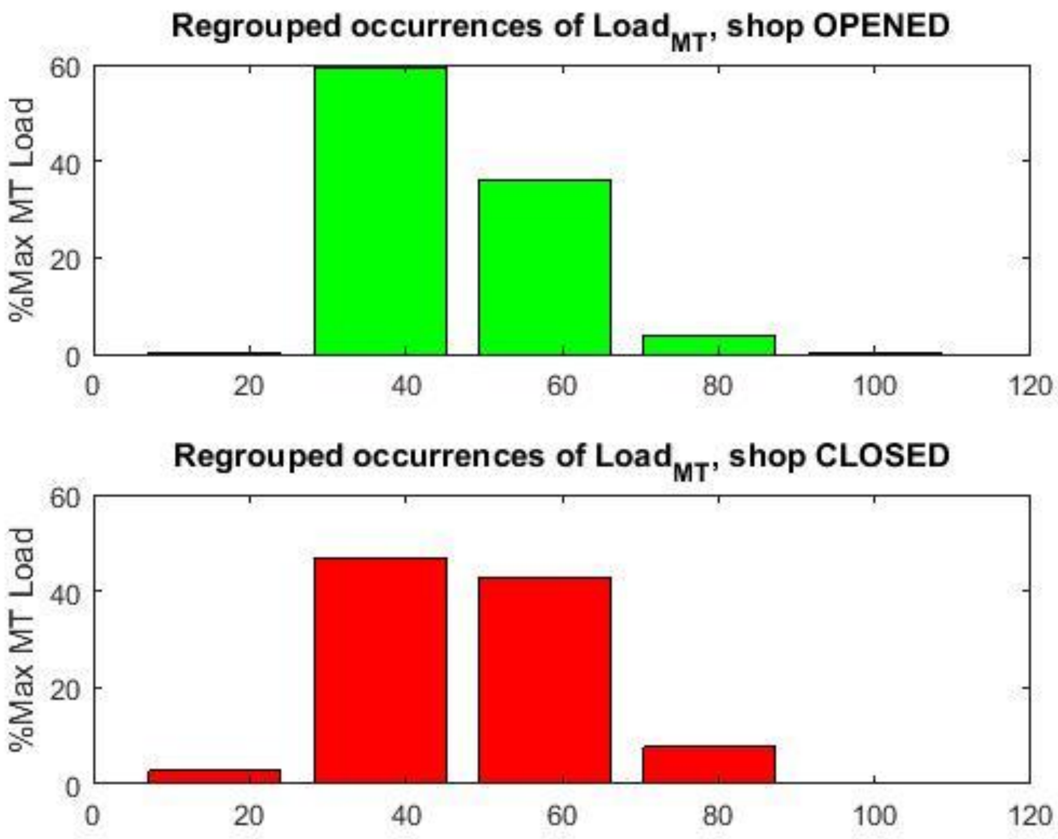


Figure 21: repartition of MT load // Data: Rema Kroppanmarka April 2018

Table 6: Selection of MT Load values

	L	%OPENED	%CLOSED
1	36.7	62	52
2	57.8	38	48

ii. *LT Load determination*

The LT Load is assumed to be completely constant. In order to keep only one value for it, it will be averaged. On the Figure 22, the hypothesis of a LT load being constant is validated.

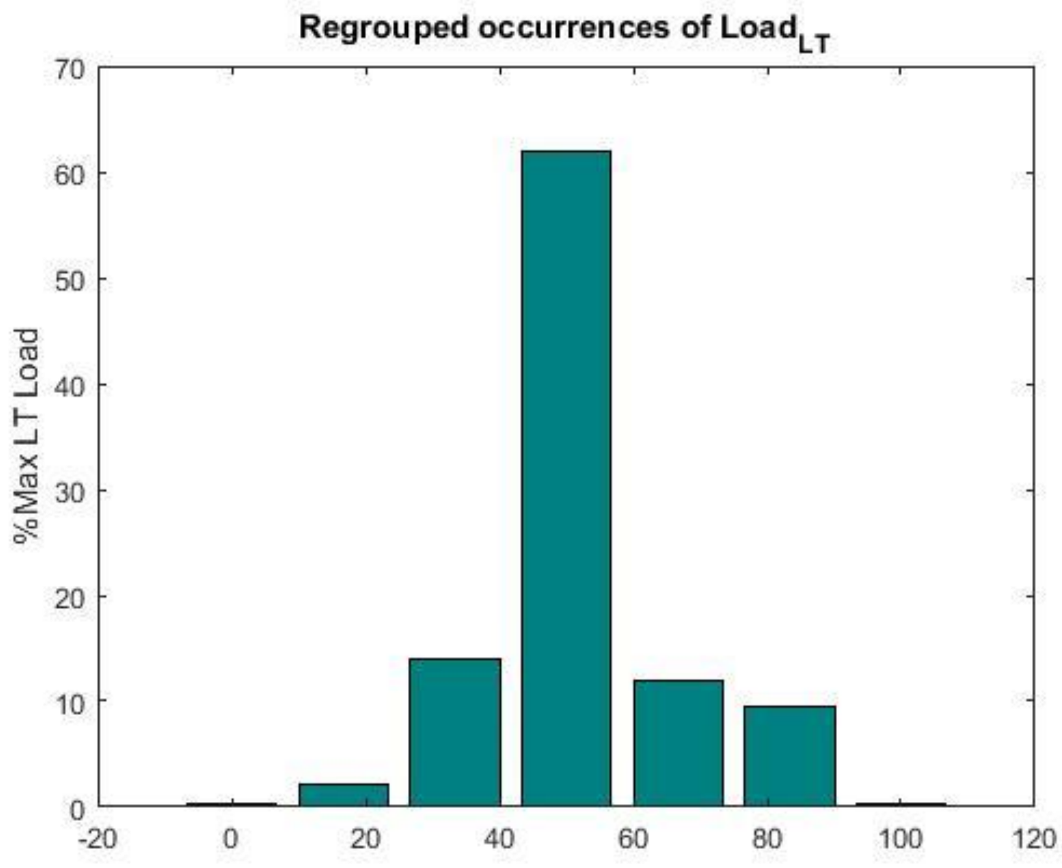


Figure 22: repartition of LT load// Data: Rema Kroppanmarka April 2018

When averaging under MATLAB, it is found a LT Load of 52%.

iii. *AHU_CC Load determination*

In order to determine the load demand for the cooling of sales areas, the occurrences of AHU_CC load values are averaged for each ambient temperature (Figure 23). The value -10% of the maximum load plotted on the graph below means that there is no occurrency approximated to this point of the subdivision.

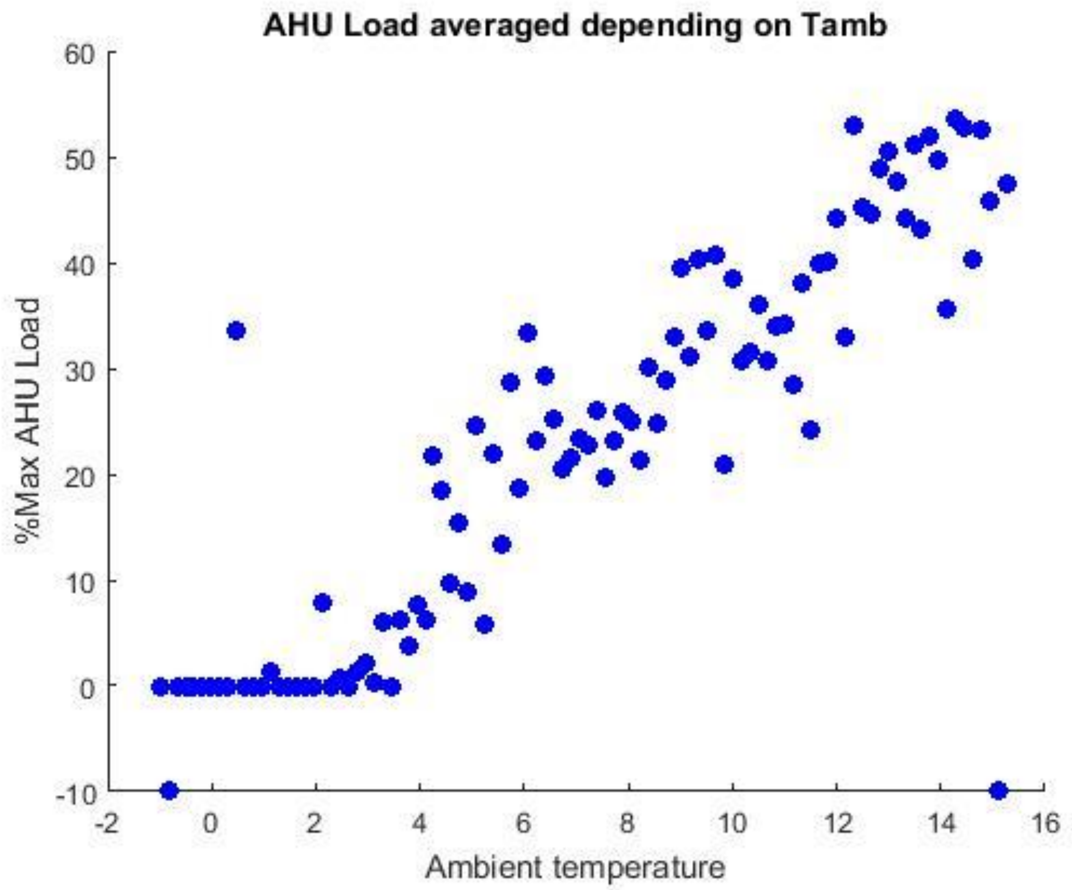


Figure 23:Averaged AHU_CC load values for each ambient temperature// Data: Rema Kroppanmarka April 2018

Then using EXCEL, it is done a linear regression in order to obtain Equation 8.

If Tamb >3 : AHULoad=3,6383*Tamb-3,1319 ; else AHULoad=0 (8)

iv. HeatReclaim Load determination

The same method as for the AHU_CC is proceeded on the AHU_HC value to obtain the HeatReclaim load. It is to say that the load values are averaged for each ambient temperature (Figure 24) and then it is done a linear regression to obtain a simple equation (Equation 9).

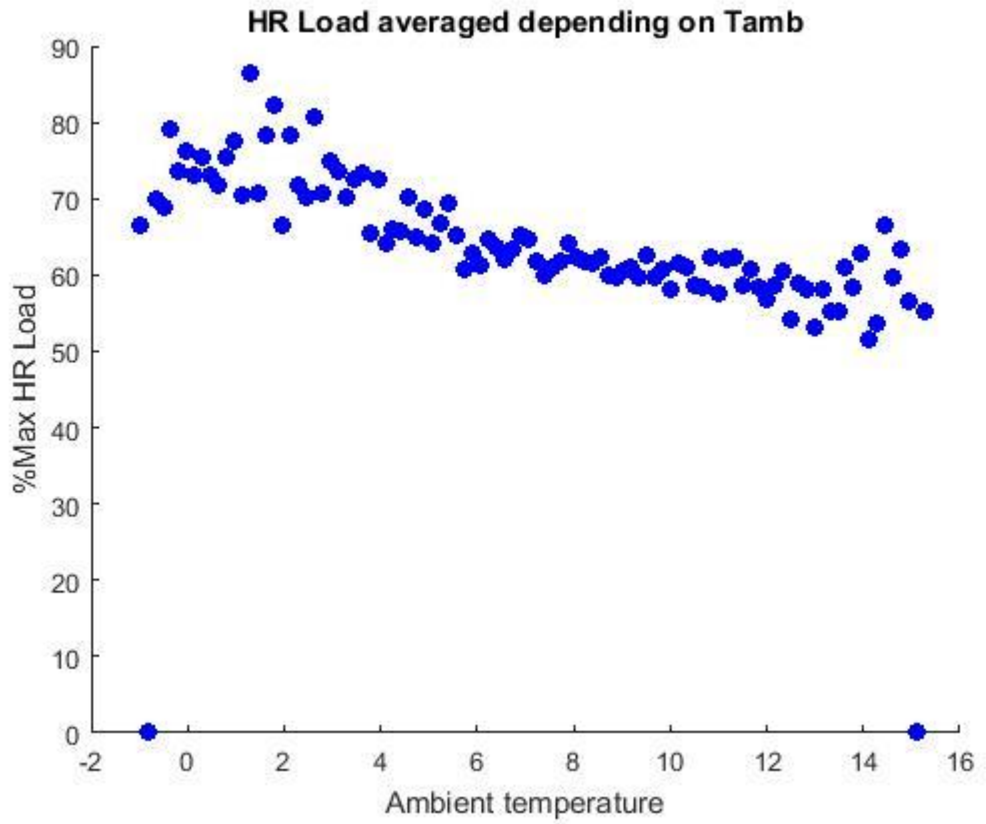


Figure 24: Averaged AHU_HC load values for each ambient temperature// Data: Rema Kroppanmarka April 2018

HeatReclaimLoad=-1,2709*Tamb+73,977 (9)

b) Ambient temperature subdivision

The ambient temperature dataset from whatever location can be chosen here in order to build the working point set that will give the energy consumption of the refrigeration system at this same location. For the exposed example, it will be used the temperature dataset at the reference supermarket, the Rema 1000 Kroppanmarka supermarket. It has been logged the ambient temperature around the shop by the sensors installed to control the facility.

A 5-points integral subdivision is made (Figure 25) using the method presented in III) -2) -d).

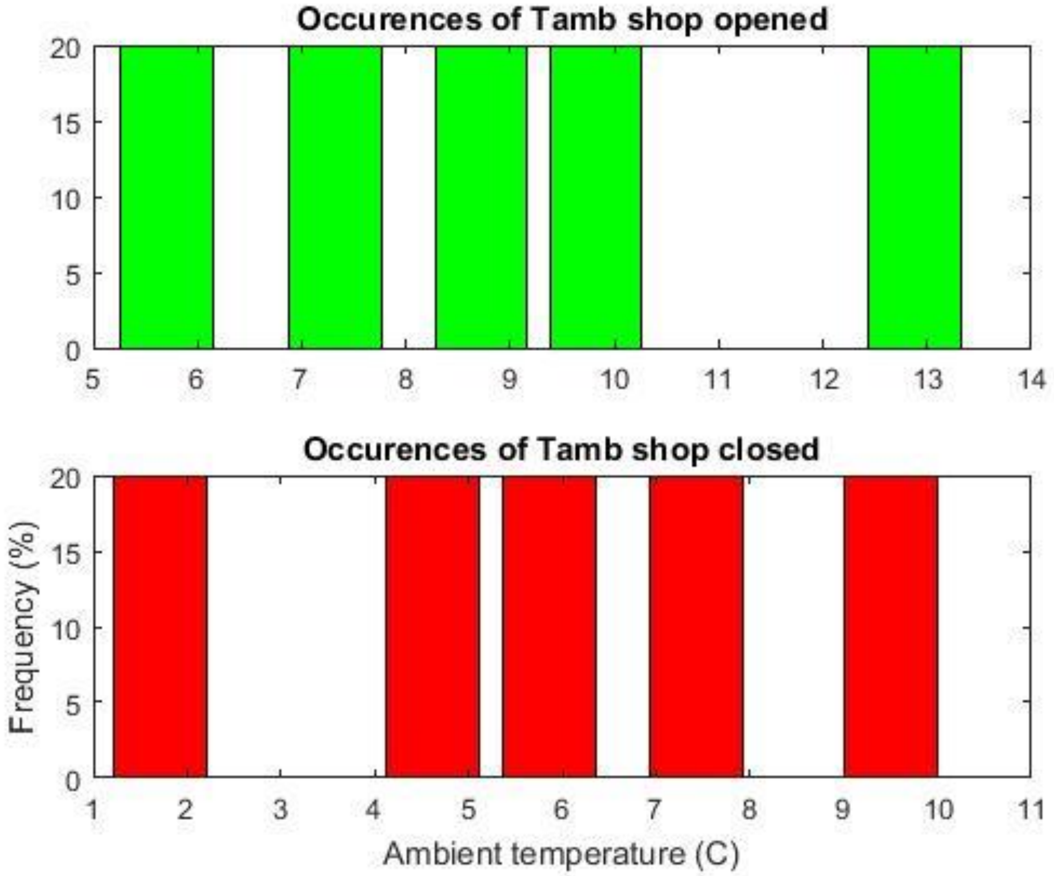


Figure 25: Regrouped occurences of Tamb using an integral subdivision for an opened and a closed shop// Data: Rema Kroppanmarka April 2018

It gives the ambient temperatures to test the prototype at. By construction, the time spent at each of the points of a period opened/closed is the same. The share between opened and closed is however different (67% opened and 33% closed).

c) Working point set construction

The working point set can be presented as a table. It is the best way to show the tests to the person running the experiments. For each test configuration it should be assessed the electric power of the prototype. The prototype is designed for a specific size of supermarket but the methodology has been proceeded with relative load so it is not a problem.

Although, the load values are for now expressed using the percentage of the maximum loads appearing on the dataset and it should be converted in absolute loads to apply it to the prototype. Normally, the dataset period is one year so that the maximums resulting for each of the loads can be considered as the maximum load demand that has to supply the refrigeration system in its whole life.

When designing the power of a refrigeration system it is usually taken the maximum load demand that can occur in the supermarket and then a coefficient is applied to finally have the maximum load that can actually achieve the refrigeration system. The coefficient is above 1 if it is wanted to have an overdesigned unit so that it will for sure be able to supply all demands but it worsens the performances. It will be below 1 to ensure good performances even if the load is not completely supplied sometimes. It is not a problem as the system has some inertia and the food can, in some extent, accept temperature peaks. The percentages of load demand must be divided by the design coefficient to now have it with reference the loads that can achieve the prototype. Finally, the absolute loads are calculated using the known maximum loads of the prototype. It is more intuitively explained with the following Equation 10.

$$AbsoluteLoad = \%MaxLoadAchievablePrototype \times MaxLoadAchievablePrototype = \frac{\%MaxLoadOccuring}{c_d} \times MaxLoadAchievablePrototype \quad (10)$$

Table 7: Working points that should be run on the tested refrigeration system

i	Weight (%)	Tamb (C)	MTload (%)	AHU (%)	HR (%)	LTload (%)
1	6.7	5.7	36.7 (62%)	18	67	52
2	6.7	5.7	57.8 (38%)	18	67	52
3	6.7	7.3	36.7 (62%)	23	65	52
4	6.7	7.3	57.8 (38%)	23	65	52
5	6.7	8.7	36.7 (62%)	29	63	52
6	6.7	8.7	57.8 (38%)	29	63	52
7	6.7	9.8	36.7 (62%)	33	62	52
8	6.7	9.8	57.8 (38%)	33	62	52
9	6.7	12.9	36.7 (62%)	44	58	52
10	6.7	12.9	57.8 (38%)	44	58	52
11	3.3	1.7	36.7 (52%)	0	72	52
12	3.3	1.7	57.8 (48%)	0	72	52
13	3.3	4.6	36.7 (52%)	14	68	52
14	3.3	4.6	57.8 (48%)	14	68	52
15	3.3	5.9	36.7 (52%)	18	66	52
16	3.3	5.9	57.8 (48%)	18	66	52
17	3.3	7.4	36.7 (52%)	24	65	52
18	3.3	7.4	57.8 (48%)	24	65	52
19	3.3	9.5	36.7 (52%)	31	62	52
20	3.3	9.5	57.8 (48%)	31	62	52

The energy consumption is calculated (Equation 11) using the weights $Weight_i$ of each working point (its time frequency), the instant electric power $ElectricPower_i$ and the total period duration τ_{tot} (ideally one year).

$$Energy\ consumption = \tau_{tot} \times \sum_i (ElectricPower_i \times Weight_i) \quad (11)$$

Conclusion

The challenge dealt in this report is to proceed to the evaluation of the environmental impacts of the SuperSmart Rack, a refrigeration system prototype running with CO_2 as only refrigerant.

It has been seen that the LCCP calculation methodology -made to assess the impacts on the greenhouse effect issue of a refrigeration system- is globally simple to follow but the challenge here is to deal with the calculation of the indirect emissions depending on the energy consumption. Indeed, the energy consumption of a prototype is impossible to get directly so it has been made some assumptions and approximations.

The dataset of a refrigeration system running on field at the Rema 1000 supermarket located at Kroppanmarka, Trondheim, Norway is used. The presented methodology helps one to build up a set of working points to test on the prototype, just starting from the weather database of a location.

Three different methods to assess the energy consumption of a prototype are detailed. The MT load is the one changing the most and each method has its own way to determine the MT load:

- The first method is based on the assumption that the MT (Medium temperature) load is depending on the hour of the day. It is quite accurate, but it leads to too many working points.
- The second consists in correlating the MT load and the ambient temperature at the location of the reference supermarket so that the accuracy and the number of working points are good but the location of the energy consumption calculation can only be the same as the reference supermarket's.
- The third is a greater approximation: only two values opened/closed shop are kept for the MT load; It gives a small working point set but less accuracy.

The working point selection is made by choosing visually the biggest circles on a plot. It is impossible to get the error when approximating this way. Further work should focus on implementing a mathematical method to select the points and evaluate the uncertainty associated to the approximation.

The StorView variables used for the air conditioning (heating and cooling of sales area ambient air) at the Rema 1000 Kroppanmarka supermarket are not sure to be what they are. The StoreView software is not completely transparent regarding the logged variables. Moreover, it is not taken into account the floor heating as the data is partially logged and what has been logged seems wrong. Either it can be discussed with the software developers the variables logged in StoreView or it can be taken another supermarket as reference.

The similarities that can theoretically occur between summer conditions and winter conditions with heat recovery have not been validated here. Further work in this line should deal with the validity of this approach.

Finally, the energy consumption calculation methodology has been presented and tried on a one-month dataset. It would be appreciated to validate the methodology applying it to a one-year dataset as required in the LCCP calculation methodology. It will then be possible to apply the methodology for different locations around the world, run the tests on the SuperSmart Rack, calculate the different LCCPs and finally compare with other conventional refrigeration systems.

Table of figures

Bibliography

(2016). Retrieved from energy.gov: https://www.energy.gov/sites/prod/files/2016/04/f30/32210a_Fricke_040616-1405.pdf

Beshr, M. (2015). *A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerants.*

Jorschick, H. (2014). *Measurement and Evaluation of Energy Integrated Supermarkets Concept.*

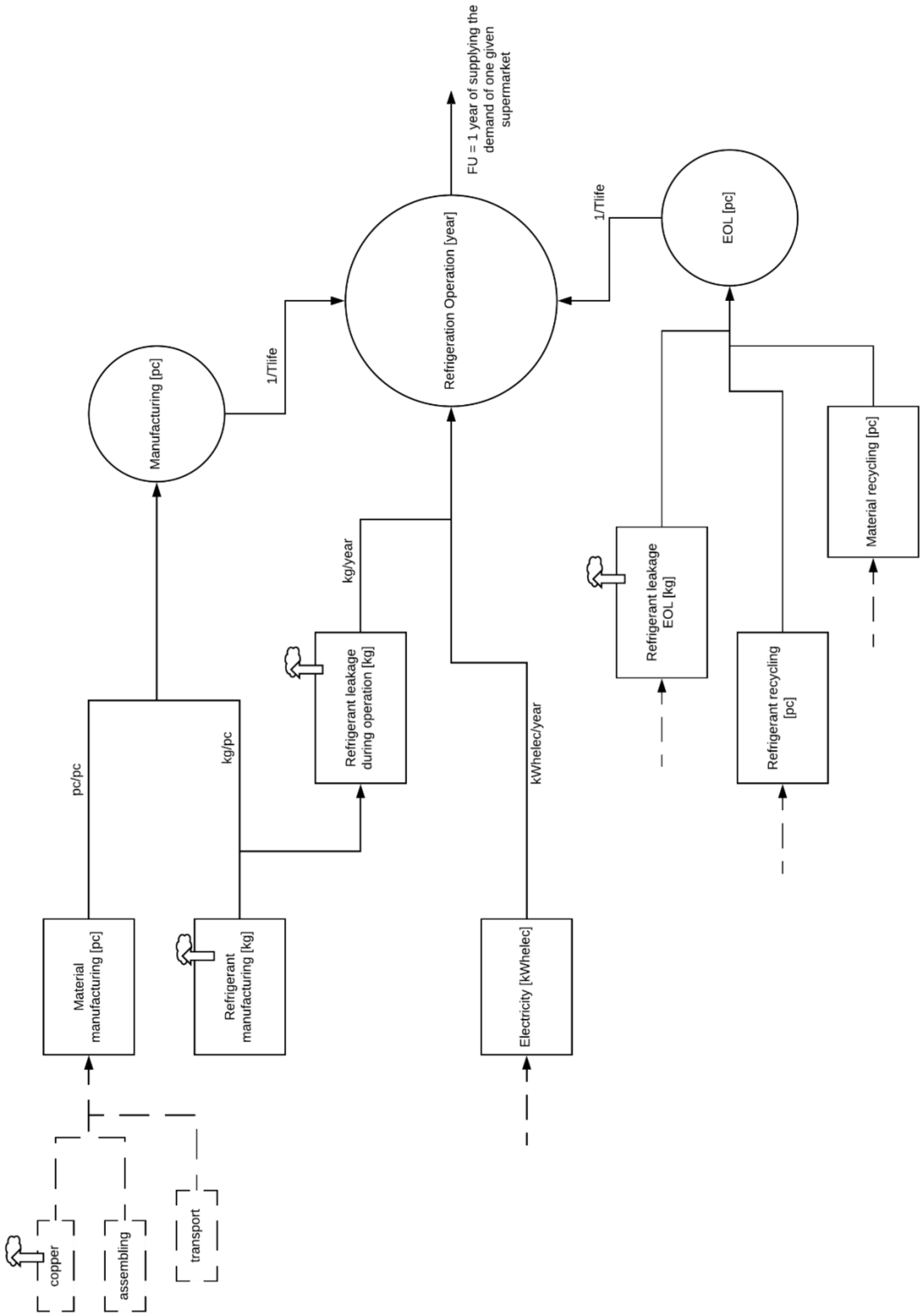
Lorentzen, G. (1994). *Revival of CO2 carbon dioxide as a refrigerant.*

Pardiñas, Á. Á. (2017). *performance test methodology for the LCCP determination of supermarket and other integrated systems.*

SINTEF. (2016). *How to build a new eco-friendly supermarket.*

Appendix

I. LCCP flowchart of a refrigeration system



II. Variables available in the StoreView of the Rema Kroppanmarka

Explicit name	StoreView package	StoreView name	Unit
Ambient temperature	1	AHUAI1eAmbientTemp	°C
Date	/		
MT Load	0	KjlemaskinCurrkWLoad	kW
LT Load	0	FrysemaskinCurrkWLoad	kW
AHU Load	1	EL_AHUCurrkWLoad	kW
HC	1	AHUHeatcoil	%
CC	1	AHUCooclcoil	%