



Resurseffektiva kyl- och värmepumpssystem

Smart Fault Detection and Diagnosis for heat pump systems

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June 2014

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Acknowledgements

This research is a part of a national research and development program in Sweden called “Effsysplus”. We would like to convey thanks to the Swedish Energy Agency and all the companies who financed this project.

Sammanfattning

Projektets mål var att:

1. Göra en omfattande databas över de vanligast förekommande felen under installation, drift och service av värmepumpsystem.
2. Skapa ett feldetekterings- och diagnossystem (FDD) för installation, drift samt service och underhåll.
3. Vara en lämplig kontaktlänk till internationella organisationer med liknande projekt t ex IEA QI/QM.

Värmepumptillverkare och försäkringsbolag är de bästa datakällorna för att finna de vanligaste och kostsammare felen som uppträtt i värmepumpsystem. Ungefär 68 000 fel som sänts in till olika tillverkare under garantitiden har analyserats. När garantitiden gått ut är det vanligen försäkringsbolagen som får felrapporterna från slutanvändarna. Därför har också 14 000 fel som insänts till ett av de största försäkringsbolagen tagits med och analyserats. Efter datareduktion har samtliga felrapporter från tillverkare och försäkringsbolag delats upp i fyra olika grupper: luft/luft-, luft/vatten-, vätska/vatten- (huvudsakligen jord och bergvärmepumpar) och frånluftsvärmepumpar. Felen som uppträtt i dessa fyra grupper har noga granskats separat. Många intervjuer har också gjorts för att kunna tolka de rapporterade felen. Det slutliga resultatet presenteras i denna rapport.

Det andra målet, FDD-systemet, innebar först en allsidig litteraturstudie för att finna de vanligaste metoderna för FDD i värmepump-, kyl-, luftkonditionerings-, och några andra systemtyper. Sammanfattningen av resultaten från denna litteraturstudie presenteras i denna rapport. Därefter har strategier för FDD under installations- och driftsfaserna diskuterats och dataprogram utvecklats för att visa exempel på FDD-mekanismer i ett värmepumpsystem. För att visa detta har vissa fel simulerats och dataprogram som använder olika metoder har använts för att detektera och diagnostisera felen.

Det tredje målet nåddes i och med att KTH har spelat en aktiv roll i Internationa Energy Agency (IEA) projekt Annex 36 kallat "Quality Installation, Quality Maintenance, QI/QM" där resultaten från den föreliggande studien presenterats. Resultatet finns också i annexets slutrapport och i slutpresentationen.

Summary

The project aims at:

1. Making a comprehensive database of the most common faults during the installation and operation and service processes.
2. Designing a fault detection and diagnosis system at commissioning, operation, and maintenance.
3. Providing an appropriate source for collaboration with international organizations with similar projects, e.g. IEA QI/QM.

Heat pump manufacturers (OEMs) and Insurance companies are the best sources to find out the most common and costliest faults already occurred in the heat pump systems. Approximately, 68000 of the fault reports which were sent to several OEMs during the warranty period are collected and processed. When the warranty period is passed, the insurance company is the one who usually receives the fault reports from the end-users. Therefore, in the present study, about 14000 faults reported to one of the largest insurance companies in Sweden are collected and processed. After the data reduction, all the fault reports from OEMs and the insurance company are split into four different categories: Air/Air, Air/Water, Brine/Water (mostly Ground Source Heat Pumps, GSHPs), and Exhaust air heat pump systems. The faults occurred in these types of heat pump systems are scrutinized separately. Furthermore, several interviews are made in order to interpret the faults reported to OEMs. The final results of this investigation are briefly presented in the report.

In order to achieve the second goal, designing the Fault Detection and Diagnosis (FDD) system, first a comprehensive literature review is carried out to find out the most common methods for FDD in heat pump and refrigeration systems, HVAC sector and some other sectors. The summary of results from this literature review is presented at this report. Second, the strategies for FDD at commissioning and operation phases are discussed and computer programs are developed to show the example of a FDD mechanism in a heat pump system. To demonstrate how a FDD system operates, some faults are simulated and the computer programs which are developed via using different methods are utilized to detect and diagnose the faults.

In order to achieve the third goal of the project, KTH played an active role in International Energy Agency (IEA) Annex 36 called “Quality Installation, Quality Maintenance” and the results from the present study is used within the annex activities. Furthermore, the results from the project were partly presented in the final report and final presentation of Annex 36.

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1. Introduction

In Sweden alone, it is estimated that over one million heat pumps have been installed. The market share of heat pumps for the current and newly built single family houses in Sweden is 50% and 90%, respectively (Forsen 2012). So any improvement in the performance of heat pump system can save a considerable amount of energy, and consequently reduce Green House Emissions to a large extent.

It is not uncommon for the heat pump systems to operate with much lower system efficiency than the typical efficiencies measured at standard conditions in manufacturers' laboratories. Sometimes, a trivial installation or control error can lead to the performance degradation of the whole system to a large extent.

Furthermore, there have been several heat pump failures reported to the insurance companies or heat pump manufacturers during the recent years. A considerable number of these failures are associated with confusion for the servicemen, long down-time for the system and unnecessary component replacement. These consequently might end up with some unnecessary costs for the end-customer, heat pump manufacturer, and insurance company which could have been avoided if smart procedures were used.

Therefore, a Smart Fault Detection and Diagnosis procedure (**SFDD**) is suggested as the solution to the problems mentioned. A SFDD system as the heart of a **smart heat pump** is able to minimize the installation and control errors, decrease the performance degradation during operation, avoid unnecessary visual inspections and components replacement, and reduce the maintenance cost and down-time of the system.

1.1 SFDD as the heart of a smart heat pump system

Before going through Smart Fault Detection and Diagnosis (SFDD) as a vital part of smart heat pump system, it is worth to describe a smart heat pump system.

As shown in Figure 1, the heat pump system can be viewed from four different boundary levels depending on where the system boundary is drawn (Lundqvist 2010):

1. The “heat pump unit” level, mostly comprising of an evaporator, a condenser, a compressor, an expansion valve and a working fluid,
2. The “heat pump system” level, including the heat source, liquid pumps or the auxiliary heater (if there is any),
3. The “building system” level, including the building characteristics and inhabitants, building thermal inertia, solar collector, etc.,
4. The “energy system” level, which not only includes the building system but also the primary energy supplied to the system to provide electricity, electric power transmission and distribution losses, etc.

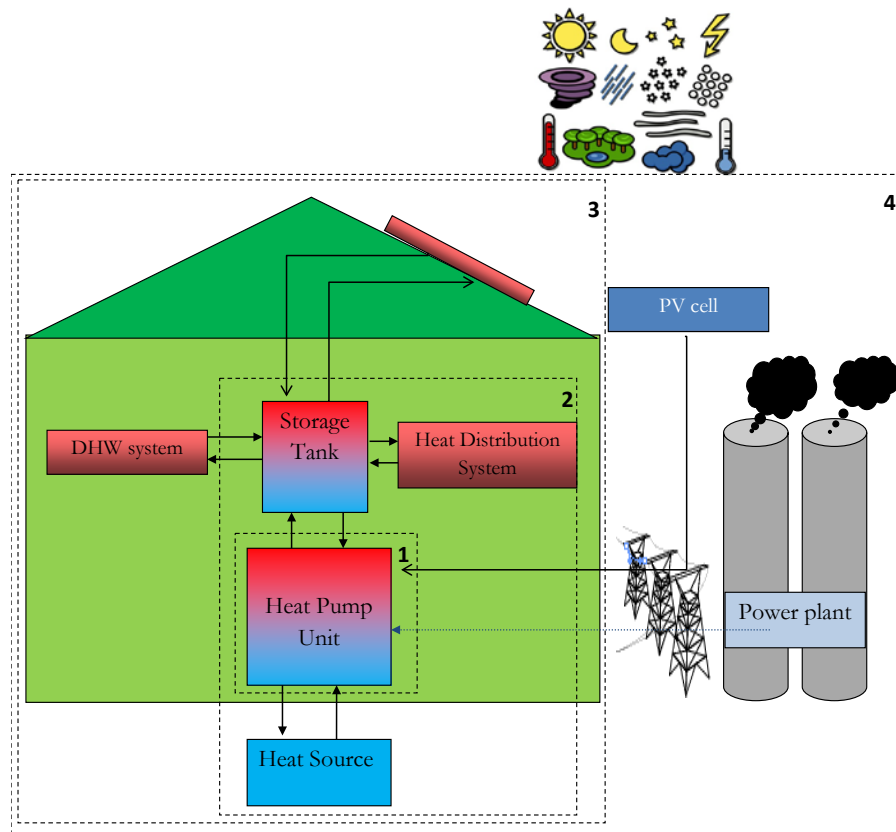


Figure 1. Smart heat pump system viewed from four different levels depending on where the system boundary is drawn.

The first boundary level only covers the “heat pump unit” which is defined as the system facilitating the thermodynamic cycle, i.e. the “heat pumping”, comprising of an evaporator, a condenser, a compressor, an expansion valve and a working fluid. For example, a smart heat pump on “heat pump unit level” can use a highly efficient compressor or it can detect and diagnose any fault on the unit level such as faulty compressor or frozen evaporator.

The second boundary level which is called “Heat Pump system” level includes several sub-systems such as the heat source (a liquid-filled borehole for example), the liquid pumps, the heat distribution system, the auxiliary heater, or storage tank. For example, a smart heat pump on the “system” level can change the pump or fan speed in the source or sink side to meet the heat demand; it can also use thermal storage mechanism to shift the heat production from day to night, etc.

The third boundary level, the “building system” level, covers the building system including the building inhabitants and building characteristics. In a smart heat pump on the building level, the control unit can be trained to take the inhabitants’ behavior and the thermal inertia of the building into account and change the control parameters continuously based on the dynamic behavior of the building and inhabitants. A smart

heat pump on the building level can predict the load profile based on the load history and weather forecast and use this prediction to produce or store the required heat in an efficient way. It can also communicate with the building inhabitants via smart phone or tablet apps in order to provide the comfort condition in an optimum way.

The fourth boundary level, the “energy system” level, has a wider perspective on the heat pump and takes the primary energy supplied to the system into account. The smart heat pump on the “energy system” level can be regarded as a part of a smart grid. Some EU directives, such as the RES directives, promote increasing the share of renewable energy sources in the electricity generation. This can lead to residual loads, caused by large amounts of highly volatile renewable electricity generation such as wind turbines or solar PV cells. Then, the smart heat pump can be utilized as a peak shaving mechanism or for storing the electric energy in the form of heat.

Finally, A SFDD system should act as the heart of smart heat pump system. it should be able to minimize the installation and control errors, couple or decouple the renewable energy sources, make load-shifting possible, detect the performance degradation during operation, avoid unnecessary visual inspections and components replacement, and reduce the maintenance cost and down-time of the system.

1.2 The project goal

The project aims at:

1. Making a comprehensive database of the most common faults during the installation and operation and service processes.
2. Designing a fault detection and diagnosis system at three different phases: commissioning, operation, and maintenance.
3. Providing an appropriate source for collaboration with international organizations with similar projects, i.e. IEA Annex 36: Quality Installation/Quality Maintenance.

This project can be considered as the first step which provides the knowledge basis for development of a Smart FDD system as the heart of future smart heat pumps.

1.3 The report structure

The report first gives an introduction about the SFDD as the heart of Smart Heat Pump system in the future. Then the methodology is briefly described. As the next step, a brief summary of the comprehensive literature study which was done during the project is given. The results' part of the report is followed by the summary of the most common and most expensive faults reported to some of the main heat pump manufacturers in Sweden and also the insurance company called Folksam. The last, but not the least, part of the results presents a brief summary about designing the SFDD system and the several computer programs which are developed as the examples of fault detection and diagnosis programs for heat pump systems. The report is finalized by the conclusion and the references.

2. Methodology

As the first step in the project, a comprehensive literature study has been done on fault detection and diagnosis in building energy systems, particularly in refrigeration and heat pump systems. Different methods for fault detection and diagnosis are categorized and advantages and disadvantages of different methods are discussed.



Figure 2. Different stages of the project

Figure 2 suggests a road map for the development of a SFDD mechanism for heat pump systems. To develop a SFDD mechanism, the first and most essential step is to find out the most common and costliest faults which usually occur in the heat pump systems. There is no previous study focusing on this essential step. So a comprehensive study is done to develop a database of the most common and costliest faults occurred in Swedish heat pump systems.

Heat pump manufacturers (OEMs) and Insurance companies are the best sources to find out the most common and costliest faults already occurred in the heat pump systems. Under warranty period, the customer service departments of OEMs receive a lot of feedback from the end-users in the form of phone calls, emails, etc. when the customer has any complaint or any fault or failure occurs in the system.

Approximately, 68000 of the fault reports which were sent to several OEMs during the warranty period are collected and processed. During the data processing, the unclear and uncompleted fault reports are excluded. Obviously, it is very important to know the faults in the most recent models of heat pumps. The old fault reports usually refer to the problems which are already known and solved during the recent years; so the faults which were reported before 2010 are also excluded from this study. Therefore, about 37000 faults reported to the OEMs, from the beginning of 2010 to the end of 2012 are analyzed and the results are presented in the next section.

When the warranty period is passed, the insurance company is the one who usually receives the fault reports from the end-users. Therefore, in the present study, about 14000 faults reported to one of the largest insurance companies in Sweden are collected and processed. In order to make the study more relevant, the faults from the

old systems are omitted and only the faults from the heat pumps which were sold after 2001 are considered (2001-2011). The file regarding the fault reports from 2007 was corrupted and could not be included in the statistic. After omitting the uncompleted or vague reports at the final stage of data processing, the number of fault reported to the insurance company is reduced to 8659.

After the data reduction, all the fault reports from OEMS and the insurance company are split into four different categories: Air/Air, Air/Water, Brine/Water (mostly Ground Source Heat Pumps, GSHPs), and Exhaust air heat pump systems. The faults occurred in these types of heat pump systems are scrutinized separately. Furthermore, several interviews are made in order to interpret the faults reported to OEMs. The final results of this comprehensive investigation are presented in the following sections.

The next step is development of a Smart Fault Detection system at different phases: commissioning phase and operation and maintenance phase. During the commissioning phase, the Smart Fault Detection system does the first system check a short time right after installation to ensure the manufacturer that the system is installed correctly and operates properly. At this phase, the Smart Fault Detection system finds the installation errors, incorrectly sized equipment, control errors, undercharge and overcharge conditions and so on. During normal operation phase, the Smart Fault Detection system detects any performance degradation or fault during the operation to avoid poor performance of the system due to minor problems, unnecessary visual inspections, or the faults which can lead to serious system failure.

When the performance degradation or fault is detected, the next step is to help the servicemen or operator to diagnose the fault. The computer programs are developed in this project to show some examples of how the SFDD system is able to give some hints to the servicemen where the faults come from and how to proceed in order to fix the problem.

3. Literature Review

Fault detection and diagnosis is an area of research that aims to automate the process of detecting faults and diagnosis the root causes in physical systems. Methods for fault detection and diagnosis were first developed for critical systems, such as nuclear power plants, for which early detection of malfunction is a primary interest but then it was applied also to other fields in order to guarantee better systems performances.

Table 1 presents a summary of the most important methods used in the literatures for fault detection and diagnosis. For further information about all the literatures, refer to (IEA Annex 36 report).

Furthermore, the project gives an overview on the previous studies related to Fault Detection and Diagnosis in Heating Ventilation and Air-conditioning (HVAC) sector. A brief summary of this overview is presented in Table 2. For further information, refer to Roccatello (2013).

In addition to the references already mentioned in the Table, Venkatasubramanian et al (2002) made three papers in series describing the methods for fault detection and diagnosis, grouped into three main categories: quantitative model-based methods, qualitative model-based methods, and process history based methods (Ibid). Likewise, in the work presented by Katipamula and Bramble (2005), the authors addressed the research and applications specific to the fields of HVAC & R and provided a brief discussion on the current state of diagnostics in buildings, discussing the future of automated diagnostics in buildings. Finally Isermann (2006) presented the most common methods for FDD comprehensively.

Rossi and Braun (1997) developed a method for fault detection and diagnosis for vapor compression air conditioners. The differences between measured states and predicted states obtained from models for normal performance, called residuals, are used as performance indices for fault detection and diagnosis. A diagnosis is performed by comparing the directional change of each residual with a generic set of rules unique to each fault. A similar work was conducted by Breuker and Braun (1998) for a rooftop air conditioning unit.

Li and Braun (2006) proposed a new method for FDD of vapor compression air-conditioners dealing with multiple simultaneous faults. The method is an improvement of the statistical rule-based technique developed previously. If the current operation points are not inside the normal operation, it will be classified as faulty. For the diagnosis, a mathematical methodology for decoupling is presented. Firstly air conditioner most common faults and their causes were listed; then a decoupling feature was detected for each of them. This feature is a parameter that can be either measured or derived from measurements.

Table 1. Different methods used for Fault Detection and Diagnosis

Methods	Characteristics	Advantages	Disadvantages
Limit Checking	<ul style="list-style-type: none"> - Rising alarms when Measured variables exceeds predefined thresholds. 	<ul style="list-style-type: none"> - Easy to develop and implement. Low computational effort. 	<ul style="list-style-type: none"> - Not very accurate since measurements are evaluated individually. Also not appropriate when there is a wide operating range.
Data-driven	<ul style="list-style-type: none"> - Not based on a prior knowledge of the system. - FDD is entirely based on processed data. - Can be classified into statistical and non statistical. 	<ul style="list-style-type: none"> - Do not require physical understanding of the system. - Useful in system where training data are easy to collect. - The computational effort required is generally manageable. 	<ul style="list-style-type: none"> - A large number of data is needed, representing normal and faulty conditions. - The derived models cannot be used to draw conclusions beyond the range of training data. - The models are specific to the system for which they are trained.
Analytical	<ul style="list-style-type: none"> - Generates features representing the status of the system using a detailed model based on physical laws. - FDD is performed by comparing, in a statistical sense, predicted features to actual measurements. 	<ul style="list-style-type: none"> - They are based on physical principles. - Model is developed for both normal and faulty operation. 	<ul style="list-style-type: none"> -Complex and time consuming to develop. - Computational intensive, therefore not suitable for on-line FDD. Models require inputs that can be difficult to obtain.
Knowledge Based	<ul style="list-style-type: none"> -Incorporate reasoning in diagnosing faults in a system. - Can be divided in Causal and Expert. -Suitable when a deep knowledge about the system is available. 	<ul style="list-style-type: none"> -Simple to develop and apply. - Useful when data about failure of the system is known. - Clean reasoning, therefore easy to verify. 	<ul style="list-style-type: none"> - Difficult to apply for complex systems. -They are specific to a system or a process. - Resolution is strongly dependent on knowledge and expertise of the developer.

Table 2. Fault Detection and Diagnosis in HVAC systems

Authors	Year	Method	Type
Y.Chen and L. Lan	2009	Principal component analysis (PCA)	Data-Driven
S.Wang and Q. Zhou	2010	Regression Model	Data-Driven
Navarro-Esbrí et al	2006	Multiple regression model	Data-Driven
Choi et al	2012	Regression Model	Data-Driven
Kim et al	2010	Multivariable polynomial regression (MRP)	Data-Driven
Peitsman and Bakker	1996	Black model based Artificial Neural Network	Data-Driven-ANN
Lee et al	1996	Black model based Artificial Neural Network	Data-Driven-ANN
Bailey	1998	Black model based Artificial Neural Network	Data-Driven-ANN
Morisot and Marchio	1999	Black model based Artificial Neural Network	Data-Driven-ANN
Zmeureanu	2002	Black model based Artificial Neural Network	Data-Driven-ANN
Reddy et al	2003	Black model based Artificial Neural Network	Data-Driven-ANN
Habbi et al	2009	Dynamic fuzzy logic	Data-Driven-Fuzzy logic
H. Han and J. Kang	2011	Machine learning techniques (support vector machine SVM) combined with multi-label approach, for FDD in multiple simultaneous faults (MSF)	Data-Driven
D. Zogg et al	2006	Black box model and clustering technique	Data-Driven
Par Carling	2002	Temperature efficiency as performance index	Analytical Methods
Li and Braun	2007	Mathematical methodology for decoupling	Analytical Methods
David Zogg	2002	Heat watch is based on steady state model	Analytical Methods
Rossi and Braun	1997	Steady-state model are statistical compared to on-line measurements	Knowledge based

Chen and Braun (2000) presented two easy to implement FDD method in rooftop air conditioner units: Sensitivity Ratio Method (consisting of a ratio of residuals, one being sensitive to a fault and the other one being insensitive) and the Simple Rule Base Method. The two methods were tested by laboratory experiment for different fault types and fault levels and found to have good performance and low computational effort.

Yoon et al. (2010) evaluated an air to air heat pump equipped with a thermostatic expansion valve (TXV) tested in climate chambers during steady-state no-fault and imposed-fault operation. Different faults were imposed and observations were made during heating and cooling mode. They identified sensitive and insensitive features related to each fault under the heating or cooling mode. Furthermore, Yoon et al. (2008) presented a methodology for developing a steady-state detector for a vapor compression system based on a moving window and using standard deviations of seven measurement selected as features, using the recursive version of the variance and standard deviation.

Moreover, Zogg et al. (2006) developed a tool for fault diagnosis particularly for heat pumps. A method based on black box model and clustering technique was proposed. Clustering method is applied for fault classification. Clusters representing all different faults are built. The properties of each one, such as centers and standard deviations are obtained from parameters identified during the training phase. During the operation, a membership grade of the parameters to the fault cluster is calculated, thus this fault occurring in the system can be identified.

Table 3 presents a summary of literatures regarding fault detection and diagnosis developed in some other sectors. For example, Li and Lei (2012) presented a fault detection and diagnosis for an aircraft engine with a fuzzy interference conformed by 9 feature parameters to detect 21 faults. Kulkarni et al. (2012) used a combination of analytical and fuzzy logic approach to detect and diagnose faults in hydraulic systems. Residuals generated by non-linear observer are evaluated using fuzzy logic. The fault severity of the system is evaluated based on the membership functions and rule base developed by the fuzzy logic system. A different research was conducted by Isermann and Clever (2008) related to FDD for a diesel engine with a parameter estimation and parity equation model based.

Table 3. Fault Detection and Diagnosis in various systems

Authors	Year	Description
V. Venkatasubramanian et al	2002	A review of the quantitative model-based methods for fault detection and diagnosis
V. Venkatasubramanian et al	2002	A review of the qualitative methods for fault detection and diagnosis
V. Venkatasubramanian et al	2002	A review of the process history methods for fault detection and diagnosis
T. Rossi and J, E. Braun	1997	FDD for vapor compression AC. Statistical rule based method as a diagnosis classifier.
H. Li and J, E. Braun	2006	FDD of vapor compression with multiple simultaneous faults with decoupling mathematical methodology for diagnosis.
M. Breuker and J, E. Braun	1998	FDD for vapor compression rooftop AC. Statistical rule based method as a diagnosis classifier.
B. Chen and J, E. Braun	2000	FDD for vapor compression rooftop AC. Sensitivity and rule based methods studied.
S. Katipamula and M, R. Bramble	2005	Overview of different studies for model based FDD in building systems.
David Zogg	2002	Faults are classified from the parameters from a grey-box model, using statistical techniques, fuzzy logic and neural network theory.
David Zogg et al	2006	Black box and clustering techniques for heat pump fault classification with fault imposed.
Rolf Isermann	2006	Several methods for fault detection and diagnosis.
W, V. Payne et al	2010	Evaluation of air to air heat pump with single fault imposed.
W, V. Payne et al	2008	Design of steady state detector for heat pump.
F. Gustafsson et al	2013	Optimization of thresholds.
Silvio Siman	2000	Model Based fault diagnosis in dynamic system using identification techniques
S. Clever and R. Isermann	2008	Fault detection for diesel engine, model based with parameter estimation and parity equations.
. L. J, deMiguela	2005	Fuzzy logic for fault diagnosis in a DC motor.
Rolf Isermann	2005	Model-based review for FDD.

M. Kulkarni et al	2009	FDD for hydraulic system with fuzzy logic approach.
C. Li and Y. Lei	2012	FDD for aircraft engine with fuzzy inference system as classifier.
M. Muenchhof and R.Isermann	2005	Comparison of residual reaction in different methods for a Hydraulic Servo-Axi

Finally, the relevant patents in this field are studied, as presented briefly in Table 4. The inventions include the methods to determine refrigerant leakage detection, compressor fault detection, expansion valve, etc.

Table 4. A brief overview on the patents related to Fault Detection and Diagnosis

Patent	Description
US006658373B2 Todd M. Rossi et al (2003)	The method consists of the measurements of five to nine parameters for vapor compression refrigeration systems and then calculating system performance variables based on the system parameters. Once the performance variables of the system are determined, the invention provides a fault detection mechanism to assist a serviceman in diagnosis.
US20040159114A1 Walter Demuth et al (2004)	The invention relates to a method of refrigerant level monitoring in a refrigerant circuit of an air-conditioning or heat pump system. The method includes standstill level monitoring with the compressor switched off and/or in-operation level monitoring with the compressor switched on.
US20020139128A1 Takahisa Suzuki et al (2002)	A vapor compression refrigeration apparatus is provided, in which refrigerant leakage is detected at an early stage. A temperature difference related to the theoretical heat dissipation of the condenser is compared with the actual temperature difference in heat dissipation (temperature difference between the condensation temperature and the outside air temperature) of the condenser to determine whether there is a refrigerant leakage.
WO2005059446A2 Thomas Dobmeier (2005)	The invention provides a way to detect loss of refrigerant charge and expansion valve malfunctioning. A superheat (SH) value in a refrigerant system is compared to an expected superheat level. If the actual SH exceeds a pre-determined value, this is an indication of refrigerant charge loss or malfunctioning expansion device.

US20080077260A1 Michael Ramey et al (2008)	A method determines whether a refrigeration related system is operating at normal condition by comparing reference data derived from ideal or normal conditions within the system. Data regarding the actual operating parameters of the system is provided via a set of microsystems sensors disposed throughout the refrigeration or cooling system. The parameters obtained with the sensors are compared to predefined threshold from the P-h curve.
EP0033781B1 Mueller, Dale A et al (1984)	The invention provides an improved and reliable compressor fault detection system for a reversible refrigeration apparatus or heat pump. The invention provides a means of detection when a compressor has started and is correctly compressing and a means of detection when the compressor has stopped from a running condition; the two means may be used separately, together and/or in conjunction with other control apparatus.

4. A comprehensive study on the important faults in heat pump system during the warranty period

Approximately, 68000 fault reports which were sent to several heat pump manufacturers during the warranty period are collected and processed. Some of these reports were real fault in the system and some of them were some complaints, for example about the noise in the system. About 8600 fault reports are not clear enough to be analyzed; about 4300 fault reports do not mention the type of the heat pump which makes it hard to interpret; so these unclear and uncompleted fault reports are excluded from the study. It is very important to know the faults in the most recent models of heat pumps. The old fault reports usually refer to the problems which are already known and solved during the recent years; so approximately 18000 faults which were reported before 2010 are also excluded from this study. Therefore, about 37000 faults reported to the Heat Pump Manufacturers, called OEMs, from the beginning of 2010 to the end of 2012 are analyzed and the results are presented in the following section.

Table 5. Number of faults reported to OEMs analyzed in the present study

Total number of fault reports received	Number of fault reports with missing key info	Number of fault occurred before 2010	Total number of faults analyzed in this study
67952	12984	17895	37037

While the number of Brine to water heat pumps i.e. Ground Source Heat Pumps (GSHPs) which are sold in Sweden between 2010 and 2012 are considerably higher than the Air/Air or Air/Water heat pumps, the number of fault reports in the present study is the highest for the Air/Water heat pumps. It should be mentioned that the number of fault reports studied in the present paper cannot give any indication about the quality of different types of heat pumps. Due to the fact that the present study does not cover all the faults reported to the heat pump manufacturers in Sweden, it is not possible to say in general which type of heat pump has the highest or lowest number of faults.

4.1. Air/Air Heat Pump system

Only in Sweden, over one hundred thousand air/air heat pumps are sold during 2010-2011 (two years). This type of heat pump is also very common in North America due to the large number of buildings which are renovated where the old gas furnace is replaced by an air/air heat pump. Since air/air HPs just use the outside air as the heat source and do not need any heating water distribution system, they are cheaper and

easy to install, and popular, particularly in the mild climates for both heating and cooling applications.

Figure 3 shows the number distribution of air to air heat pump system faults. The most common faults reported to HP manufacturers are faulty fan (26 %), control/electronics (25 %), and faulty temperature sensors (16 %). Fans were very frequently reported as the faulty component in OEMs fault database though the cost for repair or replacement was relatively low (362 € on average).

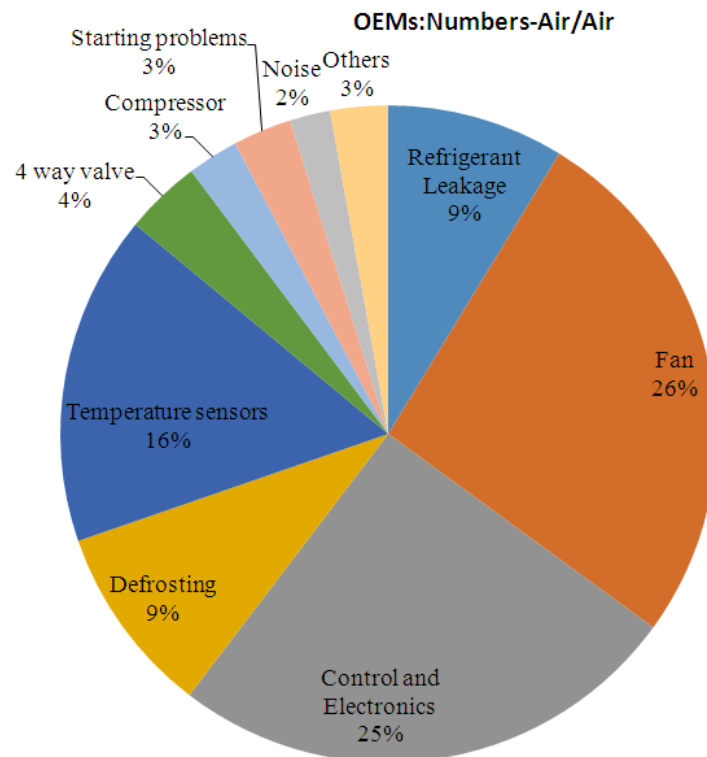


Figure 3. Air/Air heat pumps: the share of different faults from the total number of faults reported to HP manufacturers

Usually, noise is one of the main issues regarding the indoor fan. Regarding the outdoor fan, usually ice formed on the evaporator leads to the fan damage; a malfunctioned control unit or sensor may lead to inappropriate defrosting and the ice formed on the evaporator can break the outdoor fan. The control/electronics faults mainly correspond to a faulty PCB (Printed Circuit Board) and control card.

The temperature sensors are usually used to measure indoor, outdoor, or air temperature for defrosting control. Usually, the temperature sensors which are exposed to the outside air are more likely to become faulty. The air moisture can enter and freeze in the temperature sensor and result in the sensor damage. The rapid temperature change during defrosting can be another reason for the temperature

sensor's failure. Furthermore, bad wiring can also be another reason for some of these faulty temperature sensors.

Figure 4 shows the cost distribution of faults reported to OEMs. Control/electronics, refrigerant leakage and faulty fan imposed the highest total costs among the different faults reported to OEMs. Surprisingly, as shown in Figure 4, according to OEMs fault database, temperature sensors imposed higher costs than the compressors during the last three years (2010-2012).

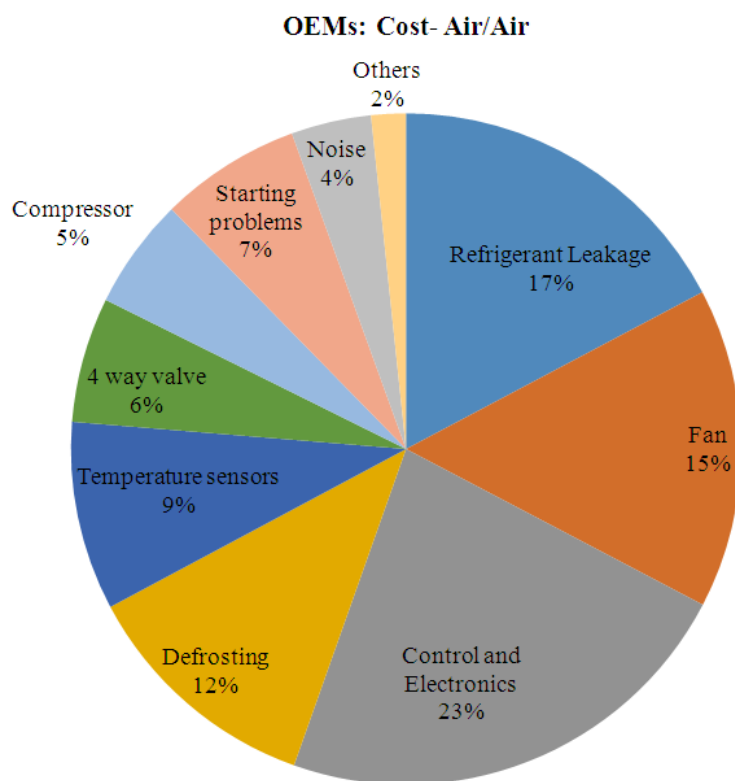


Figure 4. Air/Air heat pumps: the share of different faults from the total cost of faults reported to HP manufacturers

Defrosting, start-up problems and noise are symptoms which were wrongly reported by servicemen as the cause of heat pump fault/failure. Defrosting problems can be caused by a faulty temperature sensor, 4 way valves, or control unit. Start-up problems are the general symptom meaning that the heat pump systems could not be started after installation. This type of problem which leads to replacement of the HP unit by a new one should be obviously investigated more in detail to find what the causes were. The fault reported as "noise" can be caused by a compressor which is mounted improperly, by an air filter which is blocked, by a fan which hits the ice formed on the evaporator, by a whistling valve which cannot be closed completely, or by wear in the motor. Sometimes, the normal sound from the unit, for example in defrosting periods, is reported as fault by the people who are very sensitive to the noise.

It is worth to mention again that the faults shown in Figure 3 and Figure 4 are the faults reported to the OEMs, not necessarily the root cause or the real fault. As mentioned before, some of them such as defrosting problem, starting problem, or noise are only symptoms; the root cause is located somewhere else. Some components which were introduced by servicemen as the fault such as fan or compressor can be either the root cause or only a victim of another fault in the system. Some of the faults reported by the servicemen such as defrosting problem, faulty 4 way valve, temperature sensor, or control/electronics are highly inter-connected and they cannot be completely separated or distinguished from each other.

4.2. Air/water Heat Pump system

In Sweden, over 20000 Air/Water heat pumps were sold during 2010-2012 (three years). Figure 5 and Figure 6 present the number and cost distribution of faults occurred in Air/Water heat pump systems respectively. As shown in Figure 5 and Figure 6, pressure switches (pressostats), control/electronics, temperature sensors, and compressors are the most common and costliest faults in Air/Water HPs reported to OEMs between 2010-2012.

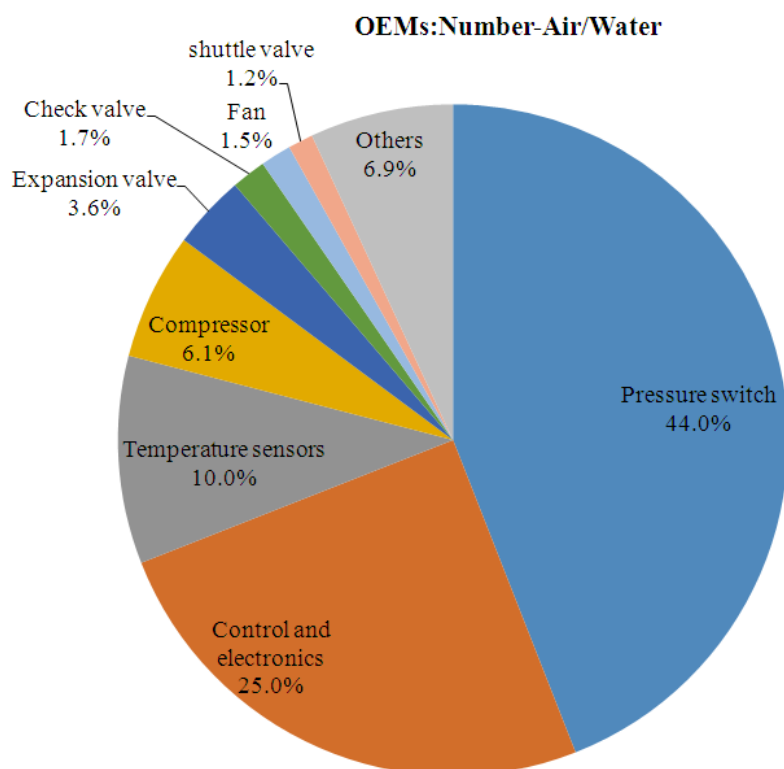


Figure 5. Air/Water heat pumps: the share of different faults from the total number of faults reported to HP manufacturers

OEM:Cost-Air/Water

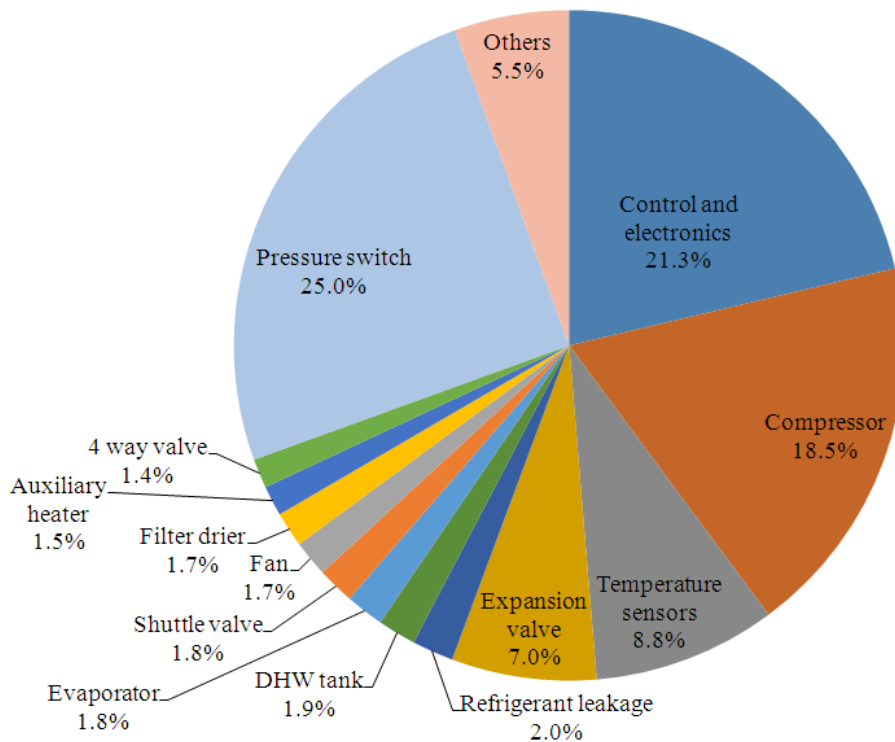


Figure 6. Air/water heat pumps: the share of different faults from the total cost of faults reported to HP manufacturers

As shown in Figure 5 and Figure 6, 44% of the faults number and 25 % of the faults cost is devoted to pressostats (pressure switches). There are two pressure switches, one at low and one at high pressure sides of HP unit, located before and after the compressor. Some of them are the cheap low-quality switches which are vulnerable or very sensitive to the dusts in the air; so they can alarm for example about too low pressure whereas too low pressure does not exist in the reality. An improper defrosting can lead to too low evaporation pressure and consequently the pressure switch at the low pressure side can react to too low pressure. Furthermore, some other faults such as faulty compressor can result in too high pressure and this involves the pressure switch at high pressure side. Moreover, high vibration at the discharge line right after the compressor may also lead to the fault in high pressure switch (Weber 2013). So in many cases, pressure switches are not the cause of fault report; but they only react to too high or too low pressures caused by other faults in the system.

Control/electronics faults include any fault related to control unit, PCB, display, soft starter, overcurrent and motor protection relay, contactor, short circuits, etc. The faults in temperature sensors were already discussed in 4.1. In addition to the sensors mentioned before, in the air/water HP systems, there is a temperature sensor measuring the supply or return temperature from the heating distribution system

(radiator or floor heating) which can become faulty. Regarding fault in expansion valve, generally when a thermostatic expansion valve is used in the HP unit, the thermostatic expansion valve can be wrongly adjusted which can lead to too low superheat temperature and “hunting” can occur in the HP unit and make the HP unit unstable.

4.3. Brine/Water heat pump system

Brine/Water heat pumps i.e. ground source heat pumps are the most common type of heat pump installed in Sweden. There are more than 400000 Brine/Water heat pumps installed in Sweden. During 2010-2012, more than 80000 Brine/Water heat pumps were sold in the country. Figure 7 and Figure 8 present the number and cost distribution of faults occurred in Brine/Water heat pump systems, i.e. GSHP systems respectively. As shown in Figure 7 and Figure 8, Control/Electronics, liquid pumps, and shuttle valves are the most common and the most expensive faults occurred in Brine/water HPs during the last three years (2010-2012).

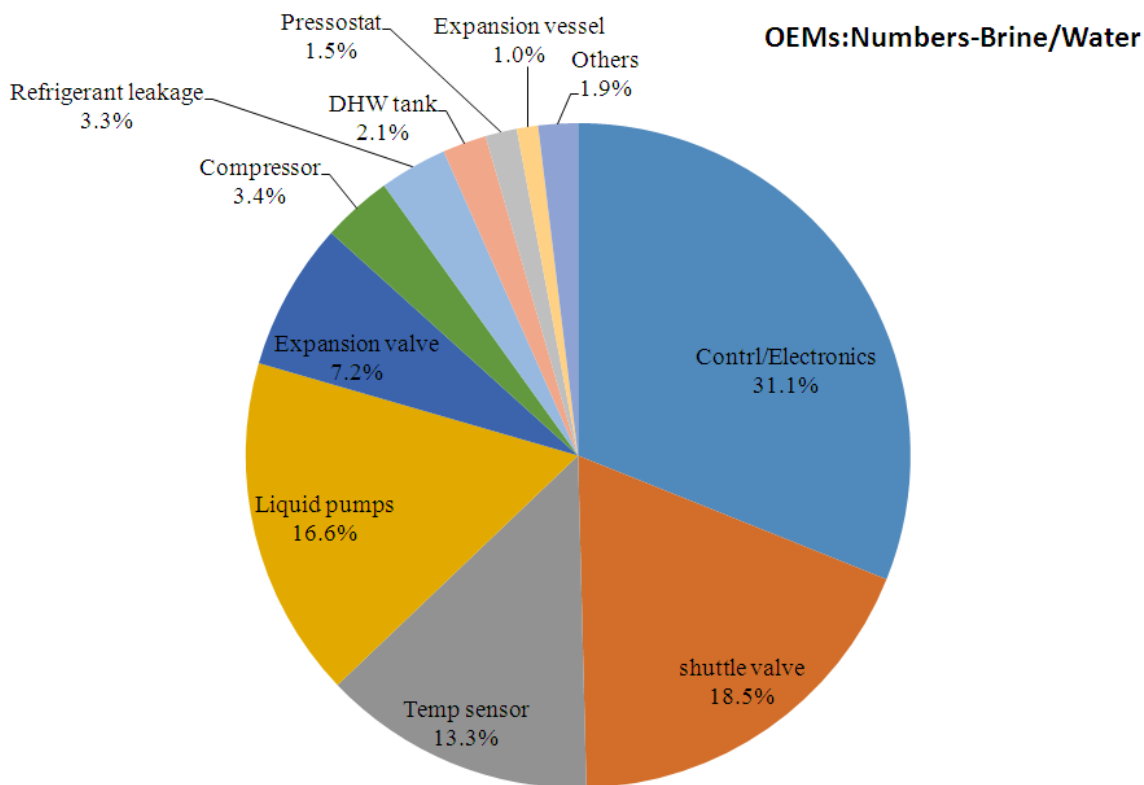


Figure 7. Brine/Water heat pumps: the share of different faults from the total number of faults reported to HP manufacturers

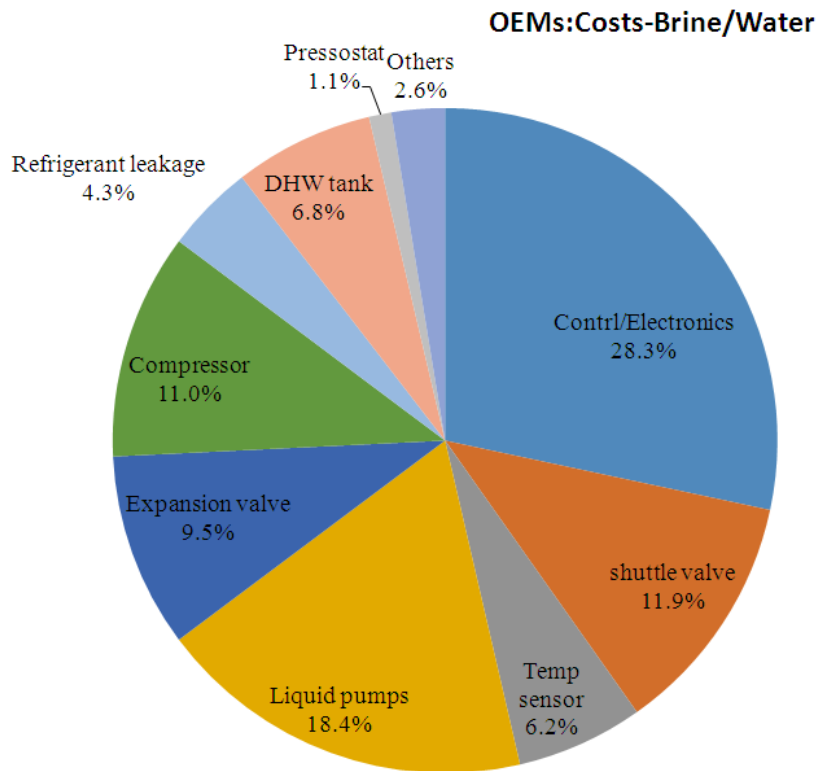


Figure 8. Brine/water heat pumps: the share of different faults from the total cost of faults reported to HP manufacturers

Control/Electronics include any fault related to control unit, electrical faults (such as short circuit, etc.), PCB, display, soft starter, overcurrent and motor protection relay, mobile application, online services, etc. The shuttle valve which is the three-way valve switching between space heating and DHW lines is the second most common fault reported to OEMs. Dirt and particles in the heating water, particularly in the old systems, are very common root cause of the faults in shuttle valves.

In the Brine/water HP systems, the brine pumps beside the pumps in the heating distribution system can cause system failure. This makes the liquid pump as the second costliest faults, with about 18 % share of total costs reported to OEMs. Some of the brine pumps have failed to operate due to the frost or/and leakage in the brine loop; some of the brine pumps had problem at startup and some of them alarmed about fault whereas there was not any real fault in the pump.

Furthermore, expansion valves and temperature sensors are among the most common and costliest faults reported to OEMs. The problems in expansion valves can be due to wrong adjustment or noise. Beside the other common temperature sensors in a heat pump, in the brine/water heat pump systems, there are usually two temperature sensors before and after the ground heat exchanger, close to the evaporator. The moisture entering the sensors can damage them and cause faults in the systems.

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4.4. Exhaust air/Water heat pump system

During 2010-2012 approximately 30000 Exhaust air/Water heat pump systems were sold in Sweden. Figure 9 and Figure 10 present the number and cost distribution of faults occurred in Exhaust air heat pump systems, respectively. As shown in Figure 9, Control/Electronics, Shunt valve/motor, and temperature sensors are the most frequent faults reported to the OEMs. Furthermore, Control/Electronics, refrigerant leakage, and DHW tanks are the costliest faults reported to the OEMs during the last three years (2010-2012).

Shunt valve which is both frequent and expensive fault in the exhaust air heat pump is a motorized valve that continuously regulates the heat supply between the heat pump and the auxiliary heater. As shown in Figure 9, refrigerant leakage is not very frequent fault (3.6 % of the faults number); but the cost imposed by the fault is so high that makes the leakage the second most expensive fault reported to the OEMs. Similarly, leakage in DHW tank which is very expensive fault occurs so rarely that it cannot be seen in the figure of faults number (Figure 9). The faults called “pipes or couplings”, shown in Figure 9 and Figure 10, are usually due to the leakage in the pipes and couplings which can be in the heating distribution system or between the tank and heat pump unit. Control/Electronics include any fault related to control unit, electrical faults (such as short circuit, etc.), PCB, display, motor protection relay, etc.; however, it excludes the faults in shunt motor/valve.

Compressor faults have a relatively large share in both number and cost of the faults. Noise is one of the most common causes of the fault reports in exhaust air heat pumps. Sometimes, blockage in the air filter leads to too low air flow in the evaporator and consequently too low evaporation temperature and pressure. This can put the operating point out of operating envelope of compressor and consequently can damage the compressor if the compressor does not have any proper protection. Similar to outside air source heat pumps, faulty fan is common in exhaust air heat pumps. This can stem from noise or improper control of fans which are usually variable speed ones.

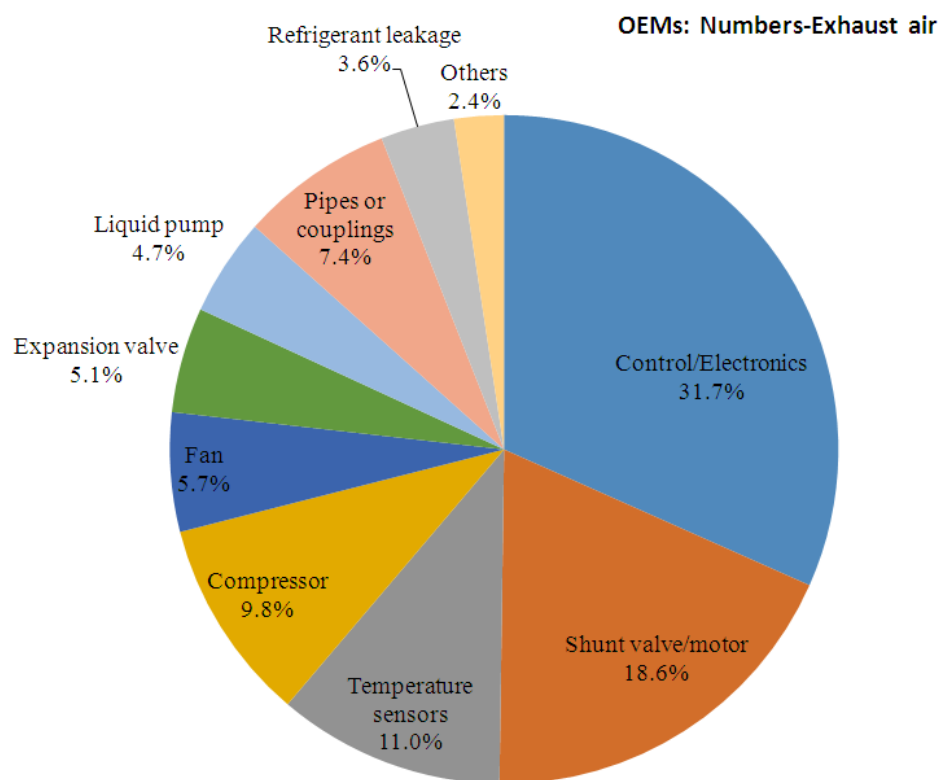


Figure 9. Exhaust air/Water heat pumps: the share of different faults from the total number of faults reported to HP manufacturers

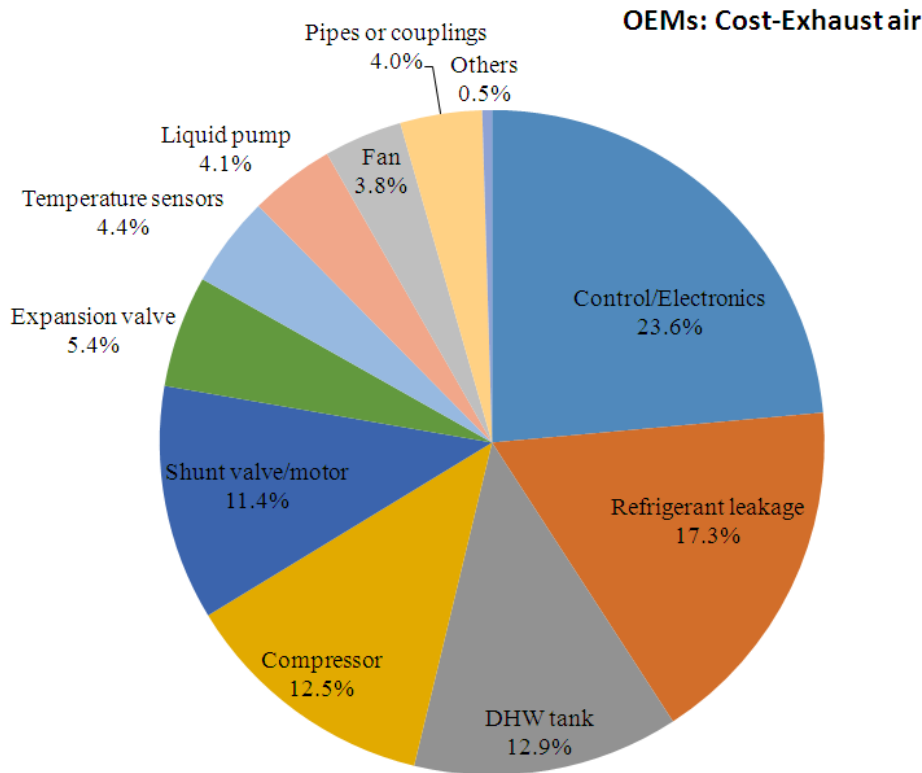


Figure 10. Exhaust air/water heat pumps: the share of different faults from the total cost of faults reported to HP manufacturers

4.5. Results summary

Table 6 presents a summary of the most common faults and the faults with the highest total costs which are reported to the heat pump manufacturers from 2010 to the end of 2012 (three years).

The results presented in this study show that faults in Control and Electronics are among the most common and costliest faults in all types of heat pumps. Faults in Control and Electronics include any fault related to control unit, electrical faults (such as short circuit, etc.), PCB, display, soft starter, overcurrent and motor protection relay, etc. To conclude, in order to reduce the number and cost of the faults in the heat pump systems, it is essential to pay a special attention to the control and electronics in heat pump system.

Table 6. A summary of the most common and costliest faults in different types of heat pump system- according to the reports to HP Manufacturers during 2010-2012

Type of Heat Pump	Air/Air HP	Air/Water HP	Brine/Water HP	Exhaust air HP
The Most common faults	Fan (26%)	Pressure switch (44%)	Control and Electronics (31%)	Control and Electronics (32%)
	Control and Electronics (25%)	Control and Electronics (25%)	Shuttle valve (19%)	Shunt valve/motor (19%)
	Temperature sensors (16%)	Temperature sensors (10%)	Liquid pumps (17%)	Temperature sensors (11%)
The costliest faults	Control and Electronics (23%)	Pressure switch (25%)	Control and Electronics (28%)	Control and Electronics (24%)
	Refrigerant leakage (17%)	Control and Electronics (21%)	Liquid pumps (18%)	Refrigerant leakage (17%)
	Fan (15%)	Compressor (19%)	Shuttle valve (12%)	Domestic Hot Water tank (13%)

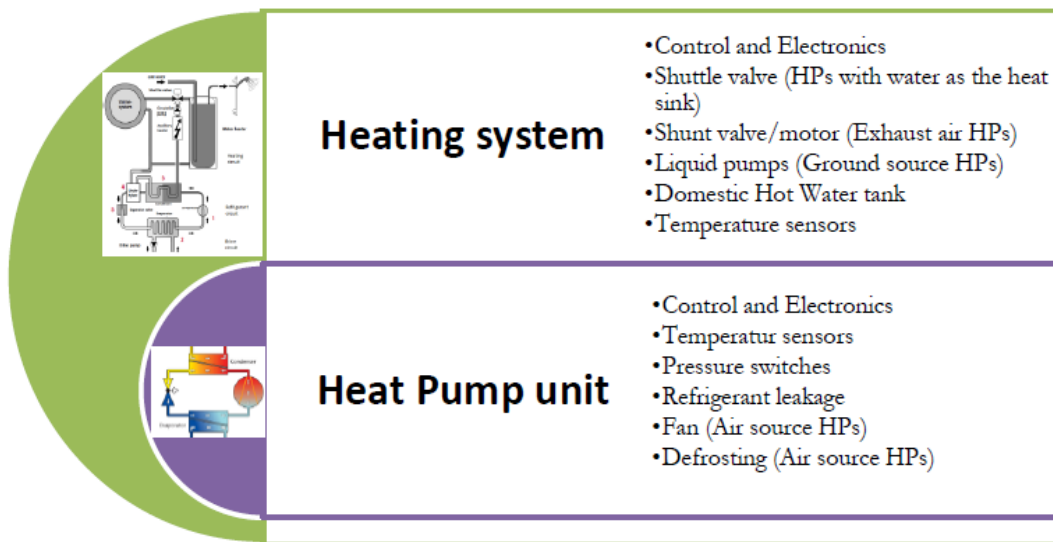


Figure 11. Important faults reported to OEMs at two different boundary levels: heat pump unit and heating system levels

As shown in Figure 11, some of the faults such as faulty pressure switches or fans are only related to the heat pump unit, i.e. the thermodynamic cycle which facilitates the heat pumping cycle. A lot of the frequent and expensive faults are related to the faulty components in the heating systems. For example, about one fifth of the fault numbers in Ground Source Heat Pumps (GSHPs) are related to the faulty shuttle valve, a simple three way valve which switches between the space heating and domestic hot water application. Some other faults such as faults in control and Electronics or temperature sensors can be related either to the heat pump unit or the heating system. For example,

if the faulty temperature sensor is the one which measures the ambient temperature in order to control the supply temperature of the heating water, the system control will not operate properly and a system failure or significant performance degradation can occur.

The faults reported to the heat pump manufacturers are usually those occurring within the warranty period; e.g., when the heat pump is less than 3-5 years old. Most of these faults occur when the heat pump age is less than a few years (usually less than 3 or 5 years). So the characteristics of these faults can be different from the faults reported out of warranty period such as the faults related to the components ageing or the faults stemming from the performance degradation over a long time.

Some of these fault reports are not real faults in the system but only complaints from the end-users for example about the noise in the fan. On the other hand, there can be some serious performance degradations in the heating systems which were not reported to the HP manufacturers. Usually, the performance degradation in the system is not found until it leads to the system failure.

5. A comprehensive study on the important faults in heat pump system after the warranty period

When the warranty period is passed, the insurance company is the one who usually receives the fault reports from the end-users. Therefore, in the present study, about 14000 faults reported to one of the largest insurance companies in Sweden are collected and processed. In order to make the study more relevant, the faults from the old systems are omitted and only the faults from the heat pumps which were sold after 2001 are considered (2001-2011). The file regarding the fault reports from 2007 was corrupted and could not be included in the statistic. After omitting the uncompleted or vague reports at the final stage of data processing, the number of fault reported to the insurance company is reduced to 8659.

After the data reduction, all the fault reports from the insurance company are split into four different categories: Air/Air, Air/Water, Brine/Water (mostly Ground Source Heat Pumps, GSHPs), and Exhaust air heat pump systems. The faults occurred in these types of heat pump systems are scrutinized separately. Furthermore, several interviews are made in order to interpret the faults reported to the insurance company. The final results of this comprehensive investigation are briefly presented in the following section.

5.1. Air/Air heat pump system

Figure 12 and Figure 13 shows the number and cost distribution of faults occurred in air to air heat pumps which were reported to the insurance company. As shown in the figures, compressor, control and electronics, and fan are the most frequent and the costliest faults in Air/Air HPs reported to the insurance companies. As shown in Figure 12 and Figure 13, 30% of the fault numbers and almost half of the faults' costs (46.5%) are reported as compressor faults. After compressors, control/electronic devices and fans have the highest number of faults and also the highest total costs among the faults reported to the IC between 2001 and 2011. Control/electronics faults include any fault reported as control unit, PCB, actuator, short circuit, etc.

It is worth to mention that the faults shown in Figure 12 and Figure 13 are the faults reported to the Insurance Company (IC), not essentially the root cause or the real fault occurred in the machine. Some components which were introduced by servicemen as the fault such as fan, compressor, or evaporator can be either the root cause or only a victim of another fault in the system. Some of the faults reported by the servicemen such defrosting problem, faulty 4 way valve, sensors, or control/electronics as are highly inter-connected and they cannot be completely separated from each other; refrigerant leakage and evaporator are also another example of the faults in the system which are too inter-connected to separate.

The IC-Number Air/Air-

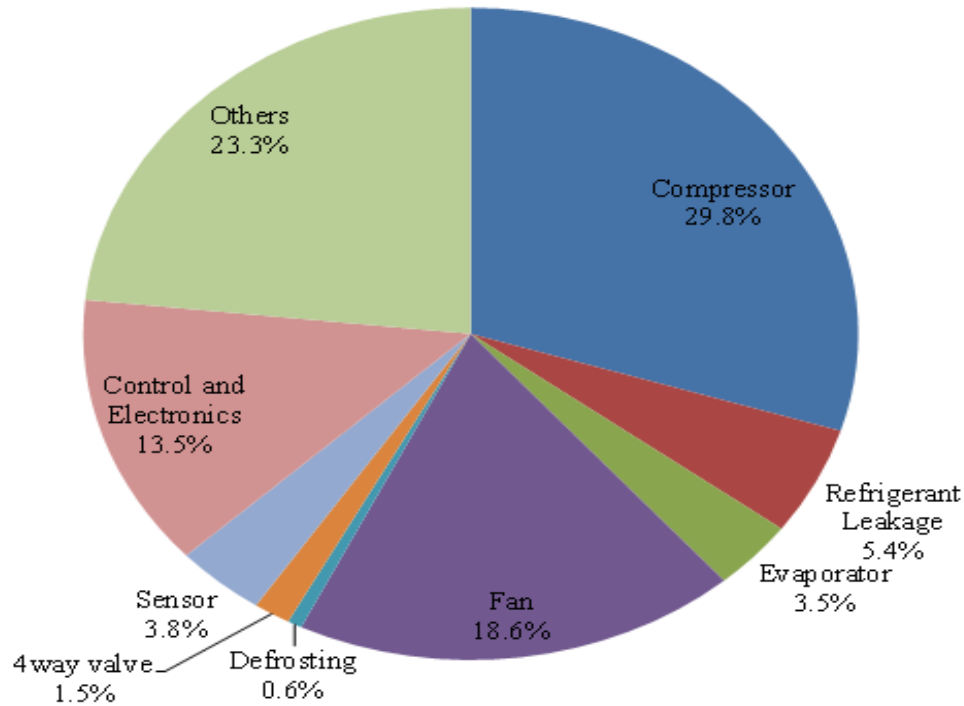


Figure 12. Air/Air HP: the number of faults reported to the insurance company

The IC-COST-Air/Air

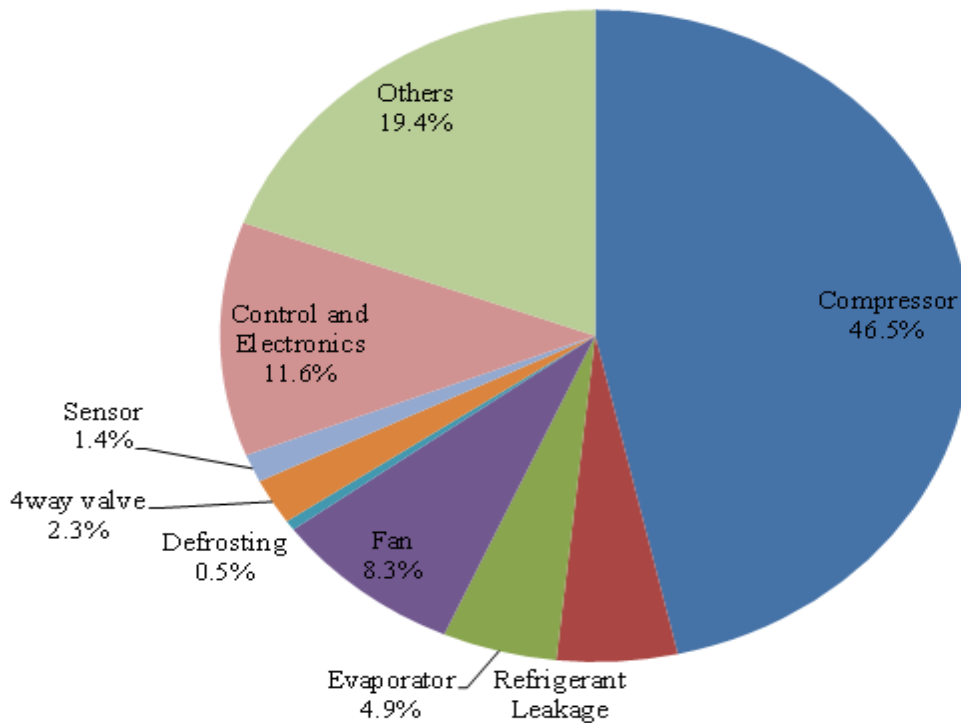


Figure 13. Air/Air HP: the cost of faults reported to the insurance company

5.2. Air/water heat pump system

Figure 14 and Figure 15 show the number and cost distribution of faults occurred in air to water heat pumps which were reported to the Insurance Company (IC). As shown in the figures, compressor fault is both costliest and most common fault reported to the IC. After compressors, evaporator, refrigerant leakage, and control/electronic devices have the highest total costs among the faults reported to the IC between 2001 and 2011. Regarding the number of faults reported to IC, control/electronics and fans are the most common faults after the compressor. Control/electronics faults include any fault reported as control unit, PCB, actuator, display, shunt, etc.

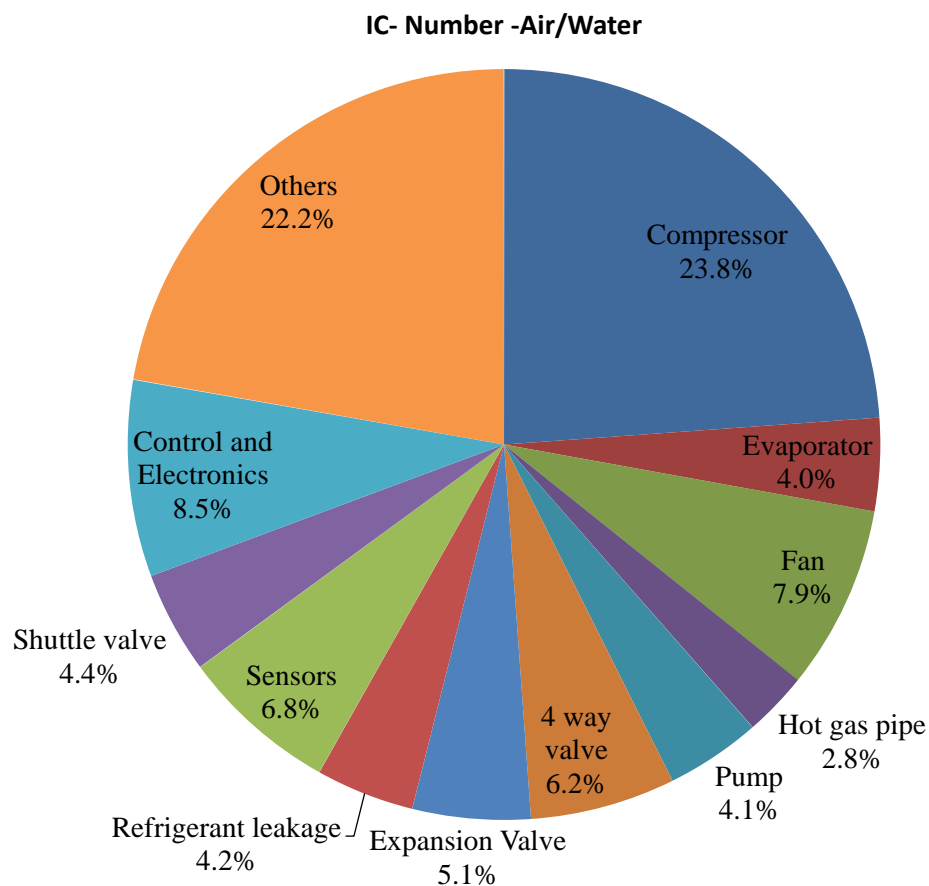


Figure 14. Air/Water heat pumps: the share of different faults from the total number of faults reported to the insurance company

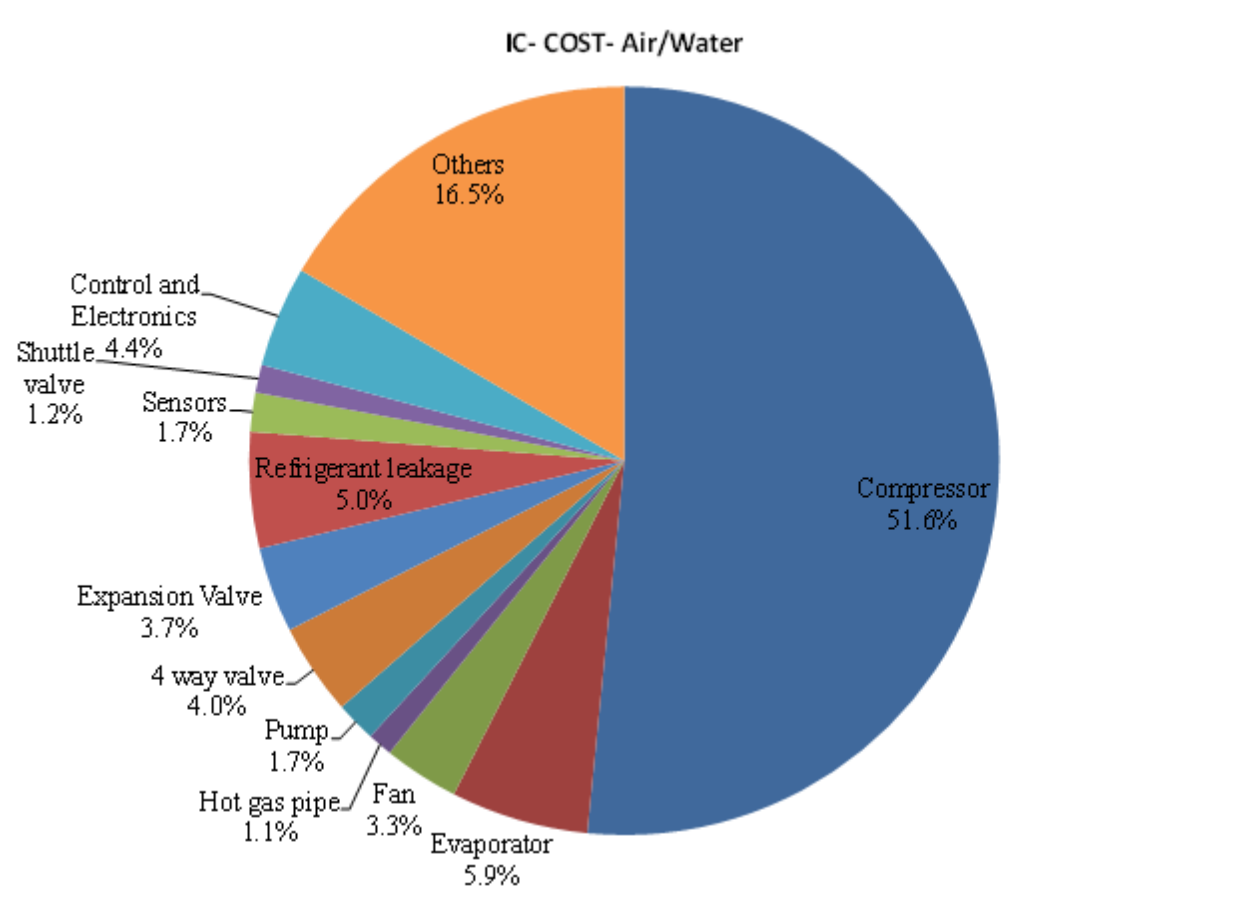


Figure 15. Air/water heat pumps: the share of different faults from the total cost of faults reported to the insurance company

5.3. Brine/water heat pump system

Brine to water heat pumps are the most common type of heat pump installed in Sweden (SVEP 2013). As shown in Figure 16 and Figure 17, shuttle valve and compressor are the most common and costliest faults reported to IC, respectively. Furthermore, the faults related to control/electronics have a large share in both number and cost of faults reported to the IC between 2001 and 2011. Control/electronics faults include any fault reported as control unit, PCB, actuator, display, shunt, etc.

IC-Number-Brine/Water

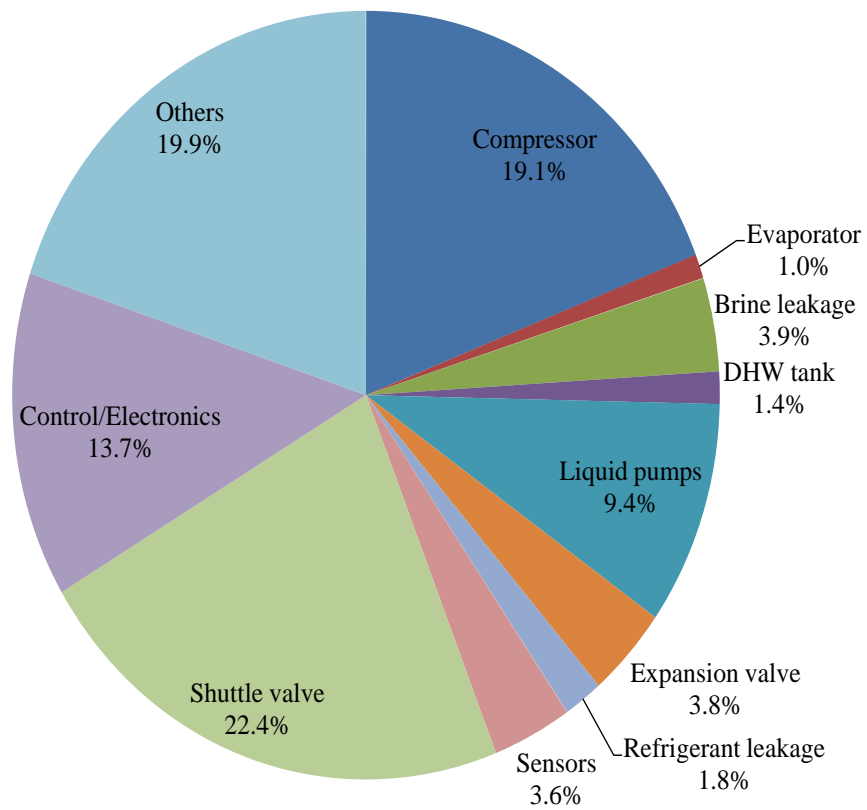


Figure 16. Brine/Water heat pumps: the share of different faults from the total number of faults reported to the insurance company

IC-Cost-Brine/Water

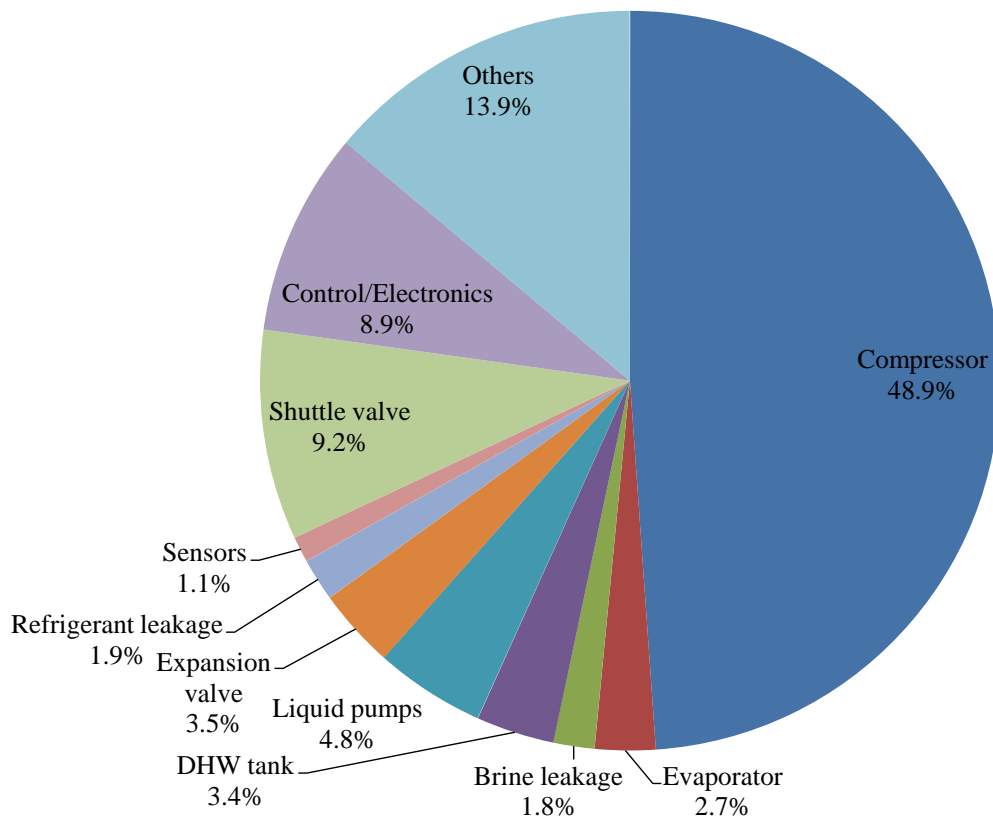


Figure 17. . Brine/water heat pumps: the share of different faults from the total cost of faults reported to insurance company

5.4. Exhaust air/water heat pump system

Regarding Exhaust air/water heat pump systems, as shown in Figure 18 and Figure 19, compressors, evaporators, and Control/Electronics are the most common and costliest faults reported to IC. Compressors are involved in about 40% of the faults reported to the IC. According to the faults reported to the IC, Evaporator is the second most expensive fault occurred from 2001 to 2011. Control/electronics faults include any fault reported as control unit, PCB, display, actuator, etc. excluding the faults called “shunt motor” or “shunt valve”. Shunt motor/valve faults are reported very frequently in the exhaust air heat pumps; So due to their importance, they are put in a different category with the same name, as it can be seen in Figure 18 and Figure 19.

The IC-Number-Exhasut Air

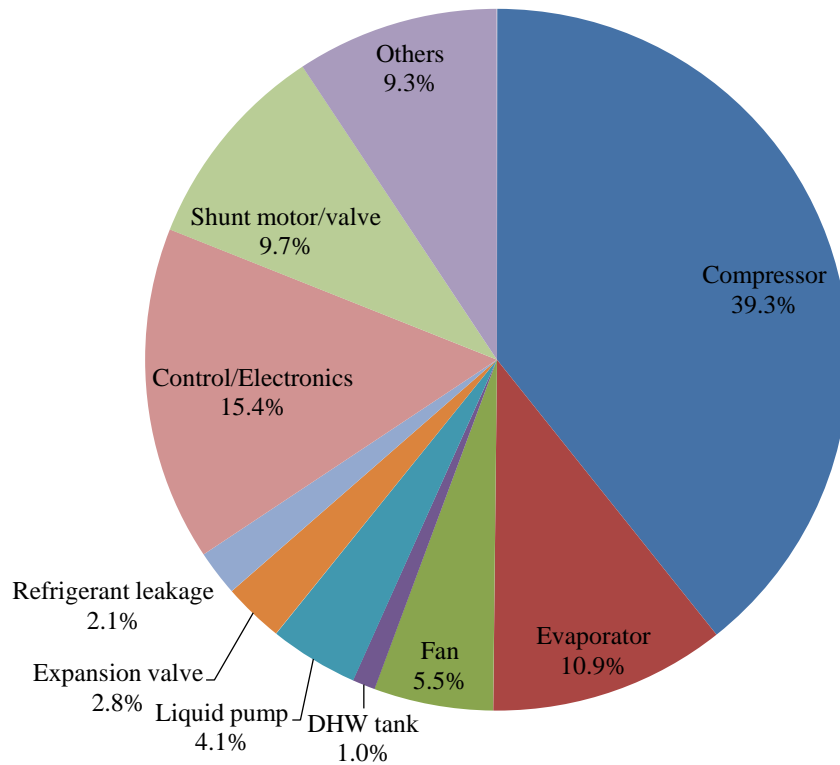


Figure 18. Exhaust air/Water heat pumps: the share of different faults from the total number of faults reported to the insurance company

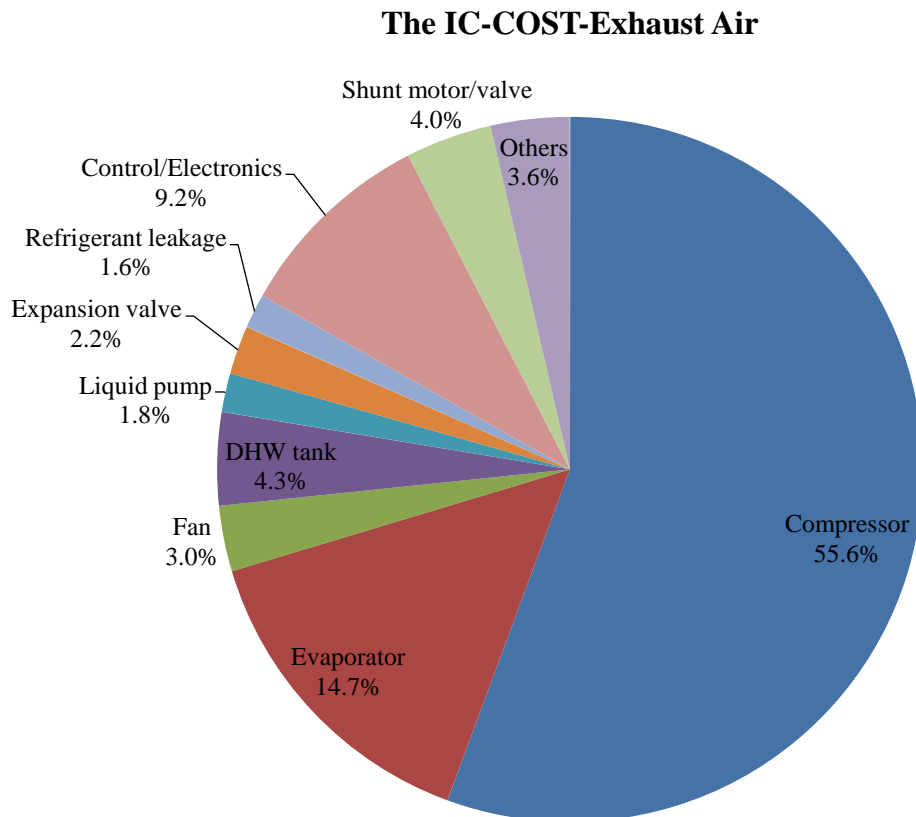


Figure 19. Exhaust air/water heat pumps: the share of different faults from the total cost of faults reported to the insurance company

5.5. Results summary

Table 7 presents a summary of the most common faults and the faults with the highest total costs which are reported to the insurance company from 2001 to 2011, excluding 2007. As presented in Table 7, the compressor is the costliest fault reported for all types of heat pump systems. Furthermore, compressor is the most common fault reported to Folksam for all types of heat pumps except for Ground Source Heat Pumps (GSHPs). For GSHPs, the shuttle valve is the most common fault reported to the IC.

It is worth to mention that the quality and clarity of the reports from the servicemen after the warranty period is not satisfactory enough to draw a solid conclusion regarding the most common faults in heat pump systems. The process of handling a fault occurred in heat pump system is not structured and leaves a lot of space for the servicemen to maneuver. Furthermore, a considerable number of faults reported by servicemen look

incomplete and non-informative; so it is suggested that the whole process of fault reporting should be restructured to improve the quality and clarity of the faults.

Table 7. A summary of the most common and costliest faults in different types of heat pump system- according to the reports to one of the main Swedish insurance companies during 2001-2011

Type of Heat Pump	Air/Air HP	Air/Water HP	Brine/Water HP	Exhaust air HP
The Most common faults	Compressor (30%)	Compressor (24%)	Shuttle valve (22%)	Compressor (40%)
	Fan (19%)	Control and Electronics (8%)	Compressor (19%)	Control and Electronics (15%)
	Control and Electronics (13%)	Fan (8%)	Control and Electronics (14%)	Evaporator (11%)
The costliest faults	Compressor (46%)	Compressor (52%)	Compressor (49%)	Compressor (56%)
	Control and Electronics (12%)	Evaporator (6%)	Shuttle valve (9%)	Evaporator (15%)
	Fan (8%)	Refrigerant leakage (5%)	Control and Electronics (9%)	Control and Electronics (9%)

6. Designing the Smart Fault Detection and Diagnosis system

Smart Fault Detection and Diagnosis unit should support the heat pump systems at different phases: commissioning, operation, and maintenance phases. These phases are treated as following:

6.1. Commissioning phase

During the commissioning phase, the Smart Fault Detection and Diagnosis (SFDD) system does the first system check a short time right after installation to ensure the manufacturer that the system is installed correctly and operates properly. At this phase, the SFDD system finds the common installation errors, incorrectly sized equipment, control errors, undercharge and overcharge conditions, and faulty components at both heat pump unit and heat pump system levels.

In order to detect the faults at this phase, the Key Performance Indicators (KPIs) for commissioning phase must be defined and collected in a commissioning management database of the SFDD toolbox. The installer should go through the commissioning management box and check that all the KPIs are within a reasonable range. The SFDD system for a specific heat pump unit is already trained in the laboratory and it knows what the reasonable range is for each KPI.

For instance, SFDD checks that the heat pump unit is dimensioned properly as the building heating system. Madani (2012) recommends that the on/off controlled Ground source heat pumps to be dimensioned to cover more than 70% of peak heat demand of the building. So the SFDD toolbox is able to get some basic information about the building such as exterior wall and roof material, floor area, glazing to wall area ratio, ventilation and infiltration rates, etc.; then the toolbox estimates the heat demand of the building at different ambient temperatures. The toolbox can also estimate the heat capacity of the heat pump unit at different ambient temperatures based on lab experiments¹. Therefore, the balance point temperature² can be estimated by the SFDD toolbox and under-dimensioned or over-dimensioned heat pumps can be detected.

Furthermore, proper dimensioning of system components can also be checked with SFDD. For example, undersized heat exchanger can be detected when the overall heat transfer coefficient of the heat exchanger (the UA value) is considered as one of the KPIs at the commissioning phase.

¹ The ground source heat pump has almost the same heat capacity at different ambient temperatures assuming a constant source temperature over the year; however, when the ambient air is used as the heat source of the heat pump, the heat capacity of the heat pump and ambient temperature are proportional.

² The balance point temperature is the ambient temperature at which the heat pump has the same heat capacity as the heat demand of the building.

The amount of refrigerant charge is another important parameter which should be traced at the initial phases in order to detect under- or over-charged systems. Sub-cooling temperature is a well-known indicator of the refrigerant charge in the system which can be used as a KPI at the commissioning phase.

The results from the study on the faults in Swedish heat pumps, as presented in chapter 4 & 5 show that some of the valves such as shuttle valve or shunt valve can be one of the most common and costliest faults in ground source and exhaust air heat pumps respectively. So the SFDD at the commissioning phase should check the quality and performance of these valves in the systems.

The faults related to Control and Electronics are one of the most common and costliest faults occurred in Swedish heat pump systems so special consideration should be granted to control and electronics when SFDD is designed. Regarding the capacity control issues, most of the heat pump systems in Sweden use compressor cycling (on/off control) as the capacity control method. A small share of the heat pumps use variable speed compressor though the share of variable capacity heat pump systems is increasing gradually.

The on/off controlled heat pump systems usually use hysteresis (either constant or floating) or Degree-Minute methods to control either supply or return temperature of the heating system based on the heating curve (Madani et al. 2013). For example, in Degree-minute method, the difference between the actual supply temperature and the required supply temperature is multiplied by the time it takes to calculate a parameter called “degree-minute”. The calculated degree-minute is summed over time and then used to control both heat pump and electrical auxiliary heater in the system. For example, the heat pump is turned on when the sum is lower than -60 Degree-Minutes or the electrical auxiliary heater is turned on when the sum is lower than -600 Degree-Minutes. The important issue in controlling the on/off controlled heat pump is how to set these control parameters based on the thermal inertia in the building, the thermal inertia in the heating distribution system, the ambient temperature, the heat load behavior, etc.

In the traditional way to control the on/off controlled heat pumps, installers set the control parameters mentioned before in the control unit of the heat pump and then leave the system until a serious fault occurs. However, SFDD at the commissioning phase should learn from the heating system and the building what the most appropriate control parameters are and what the best heating curve is to be set in the control unit. In later stages, the control parameters should change dynamically by SFDD based on different inputs such as time, building system characteristics and ambient temperature.

Although most of heat pumps in Sweden are on/off controlled, there is a growing market for variable capacity heat pump systems, the heat pumps equipped with inverter-driven compressors. The SFDD for variable capacity heat pump system must check the variable speed compressor to ensure that the compressor operates mostly at the speed which is close to the optimum speed (usually 3000-3600 RPM). For example, when a certain output temperature from the heat pump is required, naturally there are many ways to meet the demand: operating at high speed for a relatively short time, operating at low speed for relatively long time, etc. In this case, SFDD at the commissioning

phase learns from the system, building, and users aiming at finding the optimum frequency which meets the demand and at the same time yields a high system COP. Of course, the exception is very cold and relatively warm days when the compressor has to operate at the speed close to minimum and maximum speed, respectively.

Finally, there is a significant challenge to be faced when SFDD at commissioning phase is designed: how long the commissioning phase should take? For how long the inspection should go on to check if a proper installation was made and the system operates at an optimum condition? Of course, the answer depends on the type, size and conditions of heat pump, installation, etc. However, it would be appropriate to choose a smart commissioning strategy: SFDD in general records the data continuously and keeps the data for a certain time, for example the last 24 hours. The installers should be assigned to do at least two obligatory inspections via SFDD, one right after the installation and one within 24 hours after the installation; it is recommended to have minimum 12 hours between the first and second inspection; then based on the outcomes from these two inspections via SFDD, it can be decided if there is any need to make corrections or modification in the system and if the SFDD should record the data for a longer time for further investigation or not.

In the case of need for further investigation, the installer should log into the commissioning management database in the SFDD toolbox within 24 hours after the last inspection to make further investigation or take the essential steps to fix the possible problem. The process should go on until the SFDD shows a green light as an indication of a healthy condition.



Figure 20. SFDD Commissioning management system decides how long the inspection should continue based on the results from the former inspections

6.2. Operation and maintenance phase

After reviewing the different methods for fault detection and diagnosis at chapter 3, it can be concluded that a knowledge-based method is one of the best methods to detect and diagnose the faults in heat pumps particularly when several models had been already developed. The development process is as following:

1. The models of heat pump unit components such as compressor, evaporator, condenser and expansion valve are developed and validated against the experimental results.
2. The Key Performance Indicators (KPIs) at both unit and system levels are determined. The models developed at the first stages are used to calculate some of the KPIs based on the online measurements in heat pumps.
3. The models developed at the previous stages are used to emulate the possible faults and analyze the effect of different faults on the measured parameters and consequently on KPIs and: how the different parameters are affected by the fault (the trend), how intense is the effect, etc.
4. The parametric studies in the previous stage lead to categorization of different faults; there are some common symptoms between different faults but also some distinguished symptoms for every fault which can be used as the key input in order to detect and diagnose the fault.
5. All the findings so far are used in order to develop a computer program which is able to detect and diagnose the faults based on the trends and behavior of different KPIs and their categories. The program is used in SFDD operation and maintenance management system which helps the servicemen to detect the real cause of the fault and avoid unnecessary component replacement.

Regarding modeling the heat pump system and its components, several models had been developed during the previous Effsys projects. For example, Madani et al. 2011 developed a generic model of the Ground Source Heat Pump system including building, building inhabitants, the heat source, climate, and some other factors. The models can be widely used to emulate different faulty conditions. Furthermore, Corberan et al. at UPV, Spain³ developed user-friendly software called IMST-ART which can also be used to find the effect of different faults on KPIs. In the present study, some examples of Swedish heat pumps are modeled following the model development by Madani (2012) and the IMST-art software.

The Key Performance Indicators (KPIs) are the key parameters which are calculated based on the measurements continuously being done on the heat pump systems. The heat pumps built nowadays are already equipped with sensors which measure several temperatures and pressures at different points in heat pumps. Therefore, there are a lot of measured data already available for many HP installations. However, there is a little understanding about the meaning of these measured data and the massive

³ <http://www.imst-art.com/>

measurement points make it very hard to evaluate what is really happening in the system.

KPIs in SFDD system act as the interpreter of the measured data. SFDD receives all the measured temperatures, pressures, electrical powers etc. and converts these massive data to only a few Key Performance Indicators related to different parts of the systems. These KPIs will be used at the later stages to detect and diagnose the faults. Table 8 gives some examples of measured parameters and KPIs related to them.

Table 8. The example of measured parameters and Key Performance Indicators

Example of the parameters measured	Example of KPIs
Evaporation and condensation pressures	Compressor volumetric and isentropic efficiencies
Refrigerant suction and discharge temperatures	Temperature difference in the coil (defrosting issue)
Heat source inlet and outlet temperatures	Thermal effectiveness of heat exchangers
Heat sink inlet and outlet temperatures	Instantaneous and integrated COP
Ambient temperature	Superheat and subcooling temperatures
Input power	Compressor operating envelope

6.2.1. Simulation of faults

In this section, some examples are presented to show how the faults can be simulated by the models and the parametric study and trend analysis can be implemented. Eight simple faults in a Ground Source Heat Pumps (GSHPs) are simulated as presented in Table 9.

Table 9. The fault examples and the methods for faults' simulation

Fault	Simulation Method
F1: Water underflow (heat sink side)	Water flow rate at condenser side is reduced by 10, 20, and 50 %.
F2: Brine underflow (GSHP system)	Brine flow rate at the evaporator side is reduced by 10, 20, and 50 %.
F3: Refrigerant undercharge	Refrigerant charge is decreased by 10, 20, and 50 %.
F4: Refrigerant overcharge	Refrigerant charge is increased by 10, 20, and 50 %.
F5: malfunctioning or under-sized Expansion valve (too high superheat)	The superheat temperature is increased by 10, 20, and 50 %.
F6: Condenser heat transfer fouling	Condenser heat transfer area is reduced by 10, 20, and 50 %.
F7: Evaporator heat transfer fouling	Evaporator heat transfer area is reduced by 10, 20, and 50 %.
F8: Operating out of compressor envelope	varying the condensation and evaporation pressures

Regarding the parametric studies and trend analysis, Table 10 shows an example of the results. The number of plus or minus signs indicate the intensity of the change in each parameter caused by the faults.

Table 10. an example of results from trend analysis done for the faults already described in Table 9

Faults\ parameters	P_{cond} (kPa)	P_{evap} (kPa)	$T_{superheat}$ (K)	$T_{subcool}$ (K)	\dot{Q}_1 (kW)	\dot{Q}_2 (kW)	\dot{E} (kW)	UA_{cond} $(\frac{kW}{K})$	UA_{evap} $(\frac{kW}{K})$	$HTC_{cond.ref}$ $(\frac{kW}{m^2.K})$	$HTC_{evap.ref}$ $(\frac{kW}{m^2.K})$	$HTC_{cond.w}$ $(\frac{kW}{m^2.K})$	$HTC_{evap.br}$ $(\frac{kW}{m^2.K})$
F1	++	=	=	++	+	=	+	-	=	--	=	--	=
F2	-	--	=	-	-	-	-	--	--	-	--	-	--
F3	-	=	=	--	-	=	-	=-	=	=	=	=-	=
F4	+	=	=	++	+	=	+	=+	=	=	=	=+	=
F5	=	-	++	=-	=	=	=+	-	-	-	-	=	=
F6	++	=	=	++	+	=	+	-	=	=+	=	+	=
F7	=	--	=	=	-	-	-	=	-	=	=+	=	=+

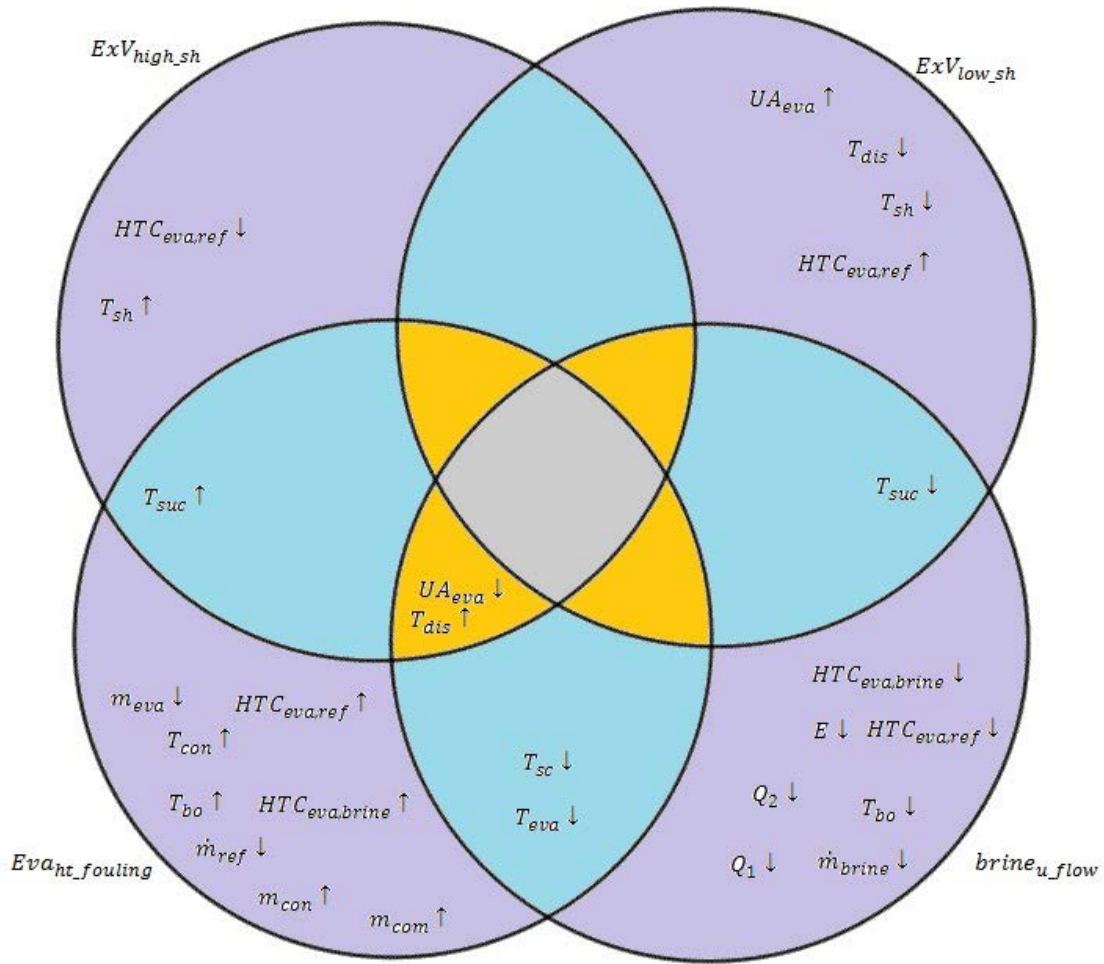


Figure 21. Venn diagram for expansion valve malfunctioning, evaporator fouling and brine underflow: an example of the results from trend analysis

6.2.2. Computer programming

In this section, several algorithms are developed in order to develop the fault detection and diagnosis in the heat pump unit. The algorithms must serve as a simple and practical guide and need to be improved when more faults are included and higher accuracy is needed.

The first two algorithms developed in this study are the examples of data-driven FDD algorithm. First algorithm checks the operating point to be within the operating envelope of compressor. Since the compressor is the most expensive part of the heat pump, it is important to protect it and avoid operating out of its envelope. The second data-driven

algorithm developed in this study is called “Temperature Quickscan”. The evaporation and condensation temperatures can be obtained through the pressure measurements. Furthermore, some other temperatures such as water inlet and outlet temperatures or brine inlet and outlet temperatures (in case of GSHPs) can be also measured easily in the system. Then the “Temperature Quickscan” algorithm can be used as a very simple way to check if there is a fault which can be easily detected and what the possible causes of faults can be. The compute programs for these two data-driven algorithms can be found in Vecchio (2014).

Another FDD method presented in this study is a knowledge-based method called “Sensitivity Ratio Method”, first developed by Chen and Braun (2000). Obviously, this algorithm developed via this method has a higher resolution in detection and diagnosing the faults compared to “Temperature Quickscan” since large number of parameters and models are included in the algorithm. The models developed at the early stage of the project are used within this method in order to calculate the KPIs which cannot be obtained by direct measurements.

The basic idea of the Sensitivity Ratio method is to use an unique pair of measurements for each fault type where one is fault sensitive and the other is not (Chen and Braun 2000). Fault sensitive ratios are calculated as the ratio of the residual of insensitive measurement to the residual of the sensitive measurement. The residual of a given measurement is defined as the difference between the measured parameter and the parameter predicted by the model for fault free steady state operation. When a fault occurs, the sensitivity ratio of the fault decreases. As soon as the value is below the pre-set threshold, the FDD mechanism warns for the fault (Ibid).

For instance, four sensitivity ratio which evaluate the faults for the condenser, expansion valve, evaporator, compressor, refrigerant, water and brine leakage can be defined as following:

$$R_{con} = \frac{|r_{Teval}|}{|r_{Tcon}|} \quad \text{Equation 1}$$

$$R_{sc} = \frac{|r_{Teval}|}{|r_{Tsc}|} \quad \text{Equation 2}$$

$$R_{eva} = \frac{|r_{Tcon}|}{|r_{Teval}|} \quad \text{Equation 3}$$

$$R_{sh} = \frac{|r_{Tcon}|}{|r_{Tsh}|} \quad \text{Equation 4}$$

The algorithm is developed using these ratios. An example of the computer program is given below:

```

if R_con<1
  if R_sc<1
    if r_Two > Tol
      m_1=msgbox('Water underflow','Fault Detection');
      if r_HTC_con_water > Tol_heat
        w_1=warndlg('Check condenser blockage',...
          'Fault Detection');
      elseif r_m_dot_water < -Tol_flow
        w_1=warndlg('Check water underflow, blocked filters, circulating pump',...
          'Fault Detection');
      else
        w_1=warndlg('Check refrigerant over charge',...
          'Fault Detection');
      end
    elseif r_Tbo < -Tol
      w_2=warndlg('Check evaporator blokage','Fault Detection');
    else
      w_2=warndlg('Check refrigerant under charge at early stages',...
        'Fault Detection');
    end
  end
elseif R_sh<1
  m_2=msgbox('Expansion valve malfunction','Fault Detection');
  if r_Tdis > Tol
    w_3=warndlg('Too high superheat','Fault Detection');
    if r_Tsc < -Tol
      w_4=warndlg('Refriderant under charge','Fault Detection');
    end
  else
    w_5=warndlg('Too low superheat, check for "Hunting"',...
      'Fault Detection');
  end
elseif R_eva<1
  if r_Tbo< -Tol
    w_6=warndlg('Brine underflow, pipe frozing, pump malfunction',...
      'Fault Detection');
  else
    w_7=warndlg('check evaporator blockage','Fault Detection');
  end
else
  m_3=msgbox('Verify compressor operating envelop');
end

```


Let's take an example to show how the FDD can operate under faulty conditions when either Temperature Quickscan or Sensitivity Ratio method is used. As an input, the water mass flow rate is decreased by 50% to see how the FDD reacts to the artificial faulty condition. Figure 22 and Figure 23 shows the warning message obtained after running both algorithms. As shown in Figure 22, when Temperature Quickscan method is used, the message includes several possible faults: water underflow, condenser blockage, or over-charged system. However, the Sensitivity Ratio method limited the message only to water underflow and a few possible causes.

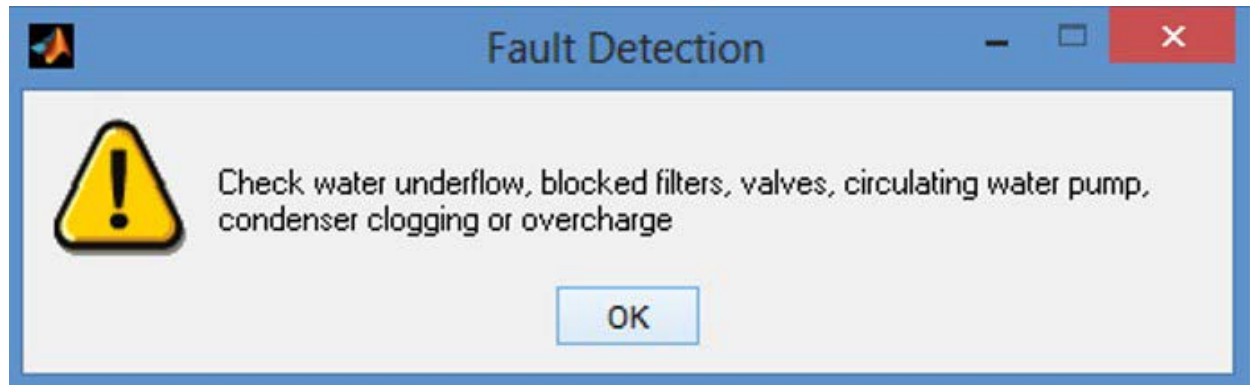


Figure 22. Warning message given by the computer program when Temperature QuickScan method is used.



Figure 23. Warning message given by the computer program when Sensitivity Ratio method is used.

The last FDD method presented in this study uses fuzzy logic approach. The fuzzy logic processes inaccurate information using if-then rules and membership functions allowing a qualitative description of numerical values. For example, by combining the results from Table 10 with theoretical and experimental results, several rules can be developed in order to describe a fault. When all the rules are defined, the next step is the fuzzification via membership function to provide a quantitative value to a qualitative description. A membership function is a curve that defines how each point in the input

space is mapped to a membership value (or degree of membership) between 0 and 1 (Sivanandam et al. 2007). The simplest shapes of the curve are triangular and trapezoidal (Figure 24); however more complex membership functions can be developed according to each system.

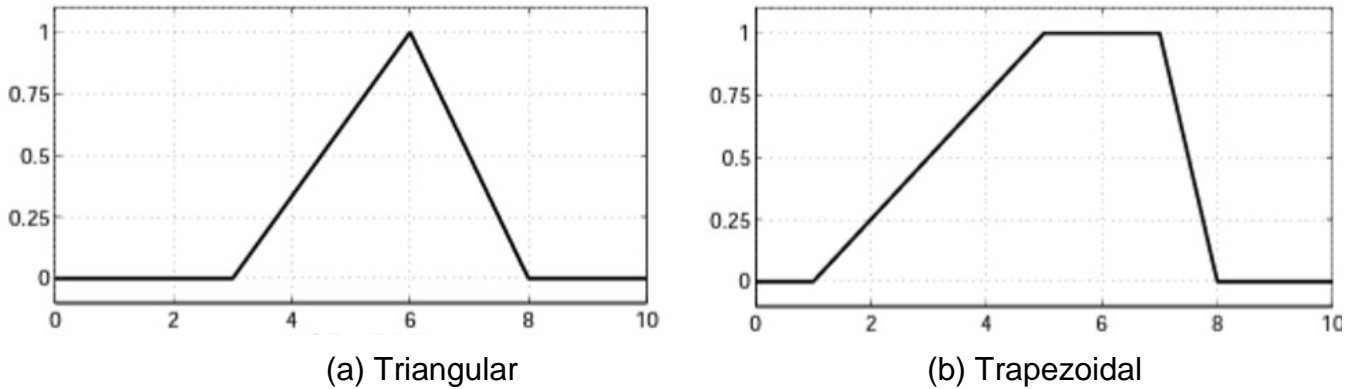


Figure 24. Simplest membership function shapes (Sivanandam et al. 2007)

Consequently, for those cases in which a rule has more than one premises or antecedent, a fuzzy operator needs to be used to resolve the antecedent to a single number between 0 and 1. For fault detection and diagnosis, this is the defuzzification step and this output value will give a numerical probability of occurrence of a fault in the scale [0-1], comparing the output single numerical value for each rule, the most likely fault in the system will be known.

7. Conclusions

This project aims at providing a knowledge basis for development of a Smart Fault Detection and Diagnosis in heat pump systems. A comprehensive literature review is carried out to find out the different methods which are already applied for FDD in heat pump and refrigeration systems, HVAC sector and some other sectors. The advantages and disadvantages of the methods are discussed and summarized.

The project suggested a “smart” FDD mechanism for heat pump system which should act as the heart of “Smart” heat pump system; so the features of a smart heat pump system are discussed at different boundary levels.

A comprehensive study is done on the faults reported to both OEMs and a main insurance company in Sweden. The results show that faults in Control and Electronics are among the most common and costliest faults in all types of heat pumps. Faults in Control and Electronics include any fault related to control unit, electrical faults (such as short circuit, etc.), PCB, display, soft starter, overcurrent and motor protection relay, etc. To conclude, in order to reduce the number and cost of the faults in the heat pump systems, it is essential to pay a special attention to the control and electronics in heat pump system.

Some of the faults such as faulty pressure switches or fans are only related to the heat pump unit, i.e. the thermodynamic cycle which facilitates the heat pumping cycle. A lot of the frequent and expensive faults are related to the faulty components in the heating systems. For example, according to the faults reported to OEMs, about one fifth of the fault numbers in Ground Source Heat Pumps (GSHPs) are related to the faulty shuttle valve, a simple three way valve which switches between the space heating and domestic hot water application. Some other faults such as faults in control and Electronics or temperature sensors can be related either to the heat pump unit or the heating system. For example, if the faulty temperature sensor is the one which measures the ambient temperature in order to control the supply temperature of the heating water, the system control will not operate properly and a system failure or significant performance degradation can occur.

Some of these fault reports are not real faults in the system but only complaints from the end-users for example about the noise in the fan. On the other hand, there can be some serious performance degradations in the heating systems which were not reported to the HP manufacturers. Usually, the performance degradation in the system is not found until it leads to the system failure.

Finally, it is worth to mention that the number and cost of faults in heat pumps is not high when it is compared to the market value of the heat pumps. The results of the project (see the appendix) show that the cost of faults in heat pumps is estimated to be around 0.1 % of the market value of heat pump systems. Generally, heat pump technology provides an efficient and sustainable solution for heating and cooling of the

buildings. When the heat pump operates in a healthy condition, there is great opportunity to save a large amount of energy and cut the global CO₂ emissions. However, there is still a huge potential for improvement of heat pump efficiency and reliability (e.g., reduction of number and cost of system faults). A lot of faults can be avoided by doing some minor changes in the whole system. For example, using higher quality pressure switches, shuttle valve, or temperature sensors does not add so much to the cost of the system but it reduces the number of faults considerably.

In addition to the faults analysis, different methods and strategies for FDD at commissioning and operation phases are discussed and computer programs are developed to show the example of a FDD mechanism in a heat pump system. To demonstrate how a FDD system operates, some simple faults are simulated and the trend for different parameters including the measured ones and Key Performance Indicators is analyzed at simulated faulty conditions.

Consequently, a few algorithms are developed to detect and diagnose faults in the heat pump unit. The first two algorithms developed in this study are the examples of data-driven FDD algorithm. The third FDD algorithm presented in this study uses a knowledge-based method called "Sensitivity Ratio Method". The last algorithm uses a fuzzy logic method to detect and diagnose the faults.

As the final conclusion, a product for Smart Fault Detection and Diagnosis can be developed by the heat pump manufacturers using the knowledge provided by this study and several other studies. This study shows that it is feasible and realistic to develop such a product to be integrated to heat pump system in order to reduce the maintenance cost, help the servicemen, and minimize the number of faults and performance degradation in heat pump systems.

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