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Adapted operating fault model for a heat pump life cycle's simulation by Petri net approach

Minh Toan VO^{*,1,2}, Emmanuel BOZONNET¹, Charles PELE²

¹ LaSIE UMR CNRS 7356, University of La Rochelle, 17042 la Rochelle, France

² CSTB - Scientific and Technical Center for Building, 77420 Champs-sur-Marne, France

* toan.vominh@cstb.fr

Abstract

In this study, a new methodology to evaluate the impact of heat pump's operating faults on its performance and the building energy consumption is proposed. In a first approach, a single operating fault - the evaporator fouling, is studied. In order to analyze all possible evolutions of the evaporator fouling at each time step, we use the Petri net approach. It describes any changes of the evaporator filter from the state without fault to a state with a specific fault level. Since it changes, the heat pump performance is re-assessed by an adapted vapor compression model. A building simulation model developed by CSTB is then used to simulate the annual energy consumption, which includes the evolution of evaporator fouling. It is illustrated by a case study - a residential house. At 20% of fault level, the compressor power increases by 5.5% and 7.3% respectively in heating and cooling mode. This leads, at the end of the first year of the building simulation, the increase of heating and cooling power by 1.1% and 0.66% respectively. The results highlight the possibility of this methodology for analyzing the impact of the operating fault on the heat pump performance and the building energy consumption.

Introduction to the heat pump operating faults

The heat pump plays an essential role in space heating and hot water in buildings in France, which account for 71.5% and 8.7% respectively of energy consumption in residential sector in 2010 (ADEME, 2012). It is a renewable energy solution providing the ecological, efficient and economical option.

However, there is always a difference between the heat pump coefficients of performance (COP): the nominal value announced by the constructors and the operating value measured on site. Monitoring 20 heat pump sites in the residential sector (6 to 15 kW heat pump), ADEME (2007) established an energy performance analysis to compare these two values. The average difference between them is at 19.8%. This difference is caused by three fault types: design faults, installation & maintenance faults and operating faults.

First, regarding the design faults and installation &

maintenance faults, Mondot and Benabdelmoumene (2008) did extensive research about faults containing system dimension faults, poor material choices, improper installation and misguided maintenance. This research evaluated statistically their impacts on heat pump performance. Also, Domanski et al. (2014) studied seven installation faults of a split residential heat pump. The results generally showed an increase in energy use by 30% due to improper installation practices. In order to prevent these faults, Afnor (2018) presented the heat pump European standard regarding the design, calculation, installation & maintenance guides. It would be helpful to avoid those faults in practices.

Therefore, a given heat pump is considered to be well-designed and well installed. In normal working conditions, if any particular piece of a heat pump is unable to operate because of the material failures (wear, breaking, and fatigue), an operating fault could happen. Concerning the operating faults, Hyvärinen and Kärki (1996) listed all possible faults, which can occur during the life cycle of a vapor compression heat pump. Their statistical analysis showed a big picture of the causes, the symptoms and the consequences of each operating fault.

Du et al. (2016) experimented with a split residential heat pump in the cooling mode under the controlled laboratory conditions. They used different types of expansion devices, compressors and refrigerants in order to evaluate some common faults, in which heat exchanger coil blockage, liquid line restriction and compressor/reversing valve leakage are the operating faults. An analysis of the results showed that the fault intensities, which are more than 15%, lead to a huge decrease in the COP value. The author also cited other publications as Kim et al. (2009) and Cho et al. (2014), which reported similar results. Besides, Yoon et al. (2011) analyzed these above operating faults on an 8.8 (kW), split residential heat pump in heating mode in the environmental chambers. Among them, evaporator fouling and condenser fouling caused the greatest performance degradation.

As the operating faults randomly appear during normal working conditions, fault modeling is not considered in the design process. There are very few pieces of research, analyzing the impacts of the operating

faults on the building energy consumption during the heat pump's life cycle. The current building simulation software (BES) does not take into account those operating faults. There is still a need for coupling a heat pump model integrating operating faults and a building simulation model. This coupling will accurately describe the heat pump operation and predict the system performance and also the building energy consumption for years.

In this article, we focus on the impact of evaporator fouling on the performance of a residential heat pump air/air in cooling mode. We proposed an adapted fault model in order to study this fault in-depth, to assess its impact. The life cycle of the heat pump, integrating the evaporator fouling in BES will be simulated under the Petri net. Finally, building energy consumption during one year will be analyzed.

Heat pump and Petri net Model

Evaporator fouling model

The operating faults of heat pump have been taken into consideration since a long time ago. There are four different heat pump models presented by Underwood (2016) in order to characterize the heat pump operation with faults. Among them, the steady-state vapor compression model and a fitted regression model are found mostly in the literature. The first approach uses the inputs that can be collected from the manufacturer's data while the second approach uses the experimental data. This, a fitted regression model applying the experimental results and for a specific machine, could give a good result for the simulation which uses the same experimental conditions. It is limited for other applications, that is the reason we chose a simplified steady-state vapor compression model, which can describe mathematical heat pump operation explicitly. It is less precise than a fitted regression model, but there is no need to specify an experimental device.

The following variables are assumed, or can be collected from the manufacturers' data, which can be found in the Fig.1.

- Q_{int} : The energy demand in the building
- $T_{\text{int}}, T_{\text{ext}}$: The air interior and air exterior temperature
- $\Delta T_{\text{EVa}}, \Delta T_{\text{CDa}}$: The air drop temperature (a) across the evaporator (EV) and the air rise temperature (a) across the condenser (CD)
- $\Delta T_{\text{EVr}}, \Delta T_{\text{CDar}}$: The pinch temperature - The temperature difference between the outlet air temperature (a) of the evaporator (EV) or condenser (CD), and the refrigerant temperature (r) respectively

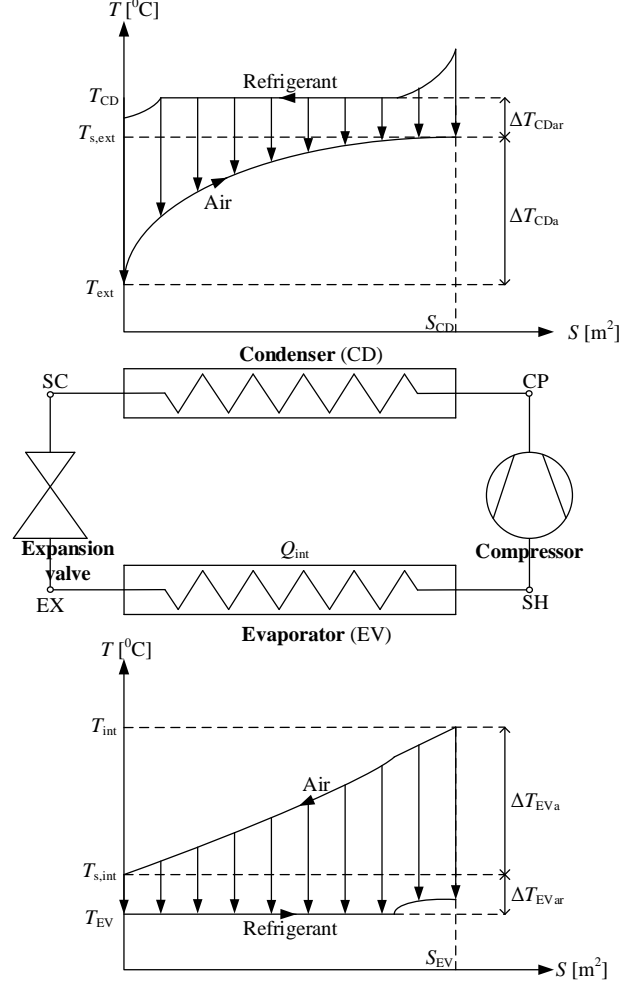


Figure 1: Theoretical temperature evolution of heat pump in the cooling mode (Bouteloup et al., 1997)

The evaporating and condensing temperatures in the cooling mode are calculated:

$$T_{\text{EV}} = T_{\text{int}} - (\Delta T_{\text{EVa}} + \Delta T_{\text{EVr}}) \quad (1)$$

$$T_{\text{CD}} = T_{\text{ext}} + (\Delta T_{\text{CD}} + \Delta T_{\text{CDar}}) \quad (2)$$

With these two evaporating T_{EV} and condensing temperatures T_{CD} , the refrigerant characteristics (temperature T , pressure p , enthalpy h , entropy s , vapor quality x) through four principal components are defined by following the refrigerant evolution in the enthalpy diagram.

$$T_{\text{SH}} = T_{\text{EV}} + \Delta T_{\text{SH}} \quad (3)$$

$$\eta_{\text{CPs}} = \frac{h_{\text{CPs}} - h_{\text{SH}}}{h_{\text{CP}} - h_{\text{SH}}} \quad (4)$$

$$T_{\text{SC}} = T_{\text{CD}} - \Delta T_{\text{SC}} \quad (5)$$

Compressor isentropic efficiency η_{CPs} varies with the compressor's type and size. A suggested value is proposed for the split residential heat pump $\eta_{\text{CPs}} = 0.8$ (Campbell, 1992). It applies to reciprocating, scroll

and rotary compressors which are the main types of compressor currently used in vapor compression heat pumps of small to medium capacity. The refrigerant mass flow rate q_{mr} and the compressor power W are calculated as follows.

- The mass flow rate of refrigerant:

$$q_{mr} = \frac{Q_{int}}{h_{SH} - h_{EX}} \quad (6)$$

- The compressor power:

$$W = q_{mr}(h_{CP} - h_{SH}) \quad (7)$$

- The coefficient of performance:

$$COP = \frac{Q_{int}}{W + W_{aux}} \quad (8)$$

Several factors will affect the efficiency of a heat pump, in which auxiliary equipment is one of the most critical factors. In this study, its power is estimated at approximately 10% of energy demand (Underwood, 2016).

During the evaporation, if the coil is frosted or dirty due to environmental dust, malfunctioning or burned out defrost component (heater, timer, motor), the evaporator is partially blocked, and only some air flow across the evaporator (Fig.2). The air flow will be decreased in the relation of the ratio of the fault-imposed air mass flow rate to the no-fault air mass flow rate, which is showed in the Eq.9. This ratio is presented as $1-F$, with F is a fault level.

$$\frac{q_v}{q_{v0}} = 1 - F \quad (9)$$

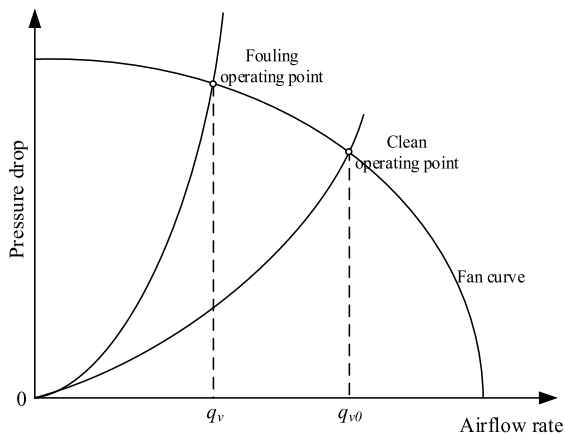


Figure 2: The impact of the evaporator fouling on the airflow

The evaporator power is also calculated from the air-side.

$$Q_{int} = Q_{EV} = \rho c_p q_v \Delta T_{EVa} \quad (10)$$

This equation does not take into account the condensation in the cooling mode. In case of evaporator fouling (the airflow q_v decreases), in the interest of maintaining the energy demand, Q_{int} , the temperature drop across the evaporator ΔT_{EVa} would be higher than the one without fault. According to the fault level and regarding the Eq.1, the evaporating temperature goes down. Following the calculation process from Eq.1 to Eq.8, the compressor power W and the COP value are re-assessed.

Comparison result between simulation and experiment

This proposed model is compared to the regression model developed by Cho et al. (2014). They studied nine different operating faults on a single-speed, split heat pump with a cooling capacity of 8.8 kW. The heat pump performance is characterized in the cooling mode under various single fault conditions, different fault levels and indoor and outdoor temperature conditions. Among six key performance parameters as the coefficient of performance (COP), total capacity, refrigerant-side capacity, sensible heat ratio, outdoor unit power, and total power, we chose a representative value of the COP to compare with. For the purpose of this study, we simulate the evaporator fouling under the same experimental conditions (the cooling capacity, and the interior and exterior temperature).

From the compared results, the maximum difference between the COP value from the simulation model and the experimental model is 2.4% under the condition of the interior and exterior air temperature of 21.1°C and 27.8°C respectively. It is showed in the Fig.3. As can be seen, an overall good agreement between those differences is observed, so that we could use this steady-state vapor compression model in order to simulate the performance of different kinds of the heat pump under different conditions with or without operating faults.

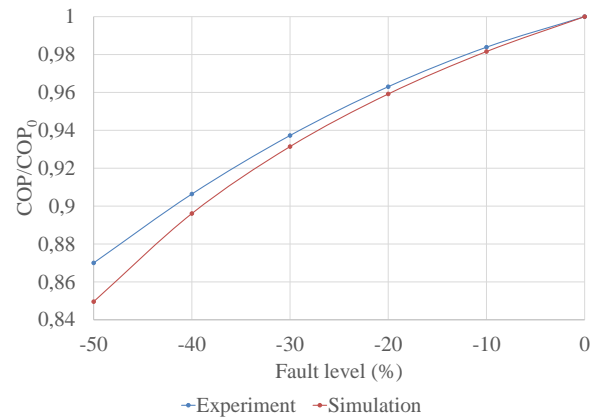


Figure 3: The COP evolution of a heat pump in cooling mode $T_{int} = 21.1^{\circ}C$ and $T_{ext} = 27.8^{\circ}C$

Integration of single fault model in the life cycle with Petri net model

Concerning the fault occurrence model, Noyes and Pérès (2007) did extensive research on fault modeling methods as the statistical methods and the dynamic stochastic methods. They analyzed the advantages and drawbacks of each method. Among them, the Petri net shows several advantages over others due to its flexibility and effectiveness. There are many applications of Petri net in many engineering fields as railway tracks (Andrews, 2013), bridges (Le and Andrews, 2016), wind turbines (Leigh and Dunnett, 2016), and building facades (Ferreira et al., 2018). Why do we not apply this Petri net approach to analyze the impact of the evaporator fouling on heat pump performance?

According to the proposed Petri net model from the previous research (Vo et al., 2018), which showed graphically all possible operating faults of a heat pump, we chose the evaporator fouling of a split residential heat pump air/air in this study. According to the field note from one technician from CETIAT regarding the evaporator fouling of a residential heat pump air/air, we could suppose that after 1000, 2000, 3000 hours operating of the heat pump, the evaporator is fouled at 5%, 10% and 20% respectively (Choup, personal communication, 2018). The evaporator fouling simulated by the Petri net model is illustrated in Fig.4. It shows a directed bipartite graph presented by the places and the transitions, which are linked by directed arcs.

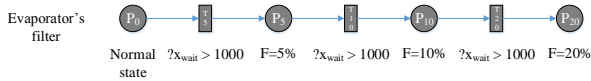


Figure 4: The evolution of an evaporator fouling of a heat pump without maintenance

- Place (P): This Petri net model composed four places P_0 to P_{20} , which represent one of the four states that characterize the degradation condition of the filter of an evaporator. The index of a place corresponds to the fault level. For example, the place P_0 represents the fault level $F = 0$, and so on.
 - Normal state means there is no fault on the evaporator filter
 - Fault level $F = 20\%$ state indicates that the ratio of the fault-imposed airflow rate to the no-fault airflow rate is 20%
- Transition (T): The transitions T_5 to T_{20} represent the required condition for the evaporator filter to progress to the next fault level state. The index of a transition corresponds to the fault level of next state. For example, the transition T_5 represents the conditions, which cause the

fault level $F = 5$, and so on. There is at least one condition for each transition:

- Predicates (?) describe a fired condition under the form of a mathematical formula, which can be true or false
- Assertions (!) update variables as transitions are drawn
- Directed arc (\longrightarrow) represents an input or output direction of a transition. By default, its capacity is one.
- Token (\bullet) located in the places represents the current component state

Concerning the fired process, a transition could be enabled if the number of tokens in input places is equal to the arc capacity. When fired, the tokens from the input places are taken and then distributed to output places. The component state is changed, or in other words, the dynamic behavior of the system is modeled.

Along the heat pump operation, Petri net describes a sequence of all possible evolutions of evaporator fouling. In the beginning, the heat pump works without fault, the filter of the evaporator is in excellent condition, and the token is in the place P_0E . If the token meets the fired condition (after 1000 hours of operation), the transition T_5E is fired, token moves to the place P_5E , and the filter is dirty at 5%. If there is no intervention from the user or technician, the heat pump will work with 5% of evaporator fouling fault. In order to keep the heat pump work at peak efficiency, it should be serviced regularly. The maintenance process is added into the Petri net, which is showed in the Fig.5.

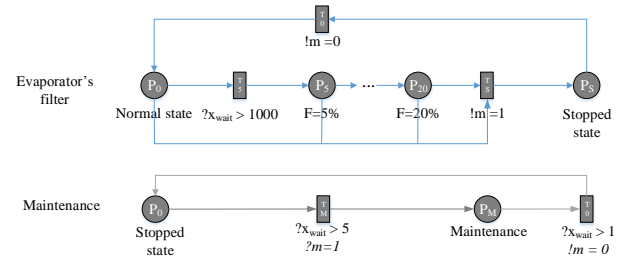


Figure 5: The evolution of an evaporator fouling of a heat pump with maintenance

Fig.5 describes the effect of the maintenance on the evolution of an evaporator fouling. Concerning the point of maintenance time, according to the maintenance contract (EES, 2017), the filter should be inspected and cleaned annually by the technician. If the user prefers doing the maintenance before the annual maintenance (transition T_5E), they will stop the system P_5E . For best results, the cleaning process is only executed after the unit has been off for at least five hours (transition T_{MM}) (Heat and Cool, 2015). When the transition T_{MM} is fired, the token moves

from the place P_0M to the place $P_M M$, which indicates the maintenance intervention. As mentioned before, there is no fault during the maintenance process. The maintenance is done correctly (transition T_0M), the token returns to the stopped state with the filter in good condition (place P_0M). A well maintained filter will ensure that the air moves freely and easily, or the heat exchanger performs well. The transition T_0E is therefore fired, the token returns to the normal state (place P_0E) before restarting its cycle.

Analysis of a heat pump operating fault

In this section, we analyze the impact of the evaporator fouling on heat pump performance. Following the result comparison from the prior section, we applied the steady-state vapor compression model under two priority nominal conditions of heating mode (interior temperature $T_{int}=20^0C$ and exterior temperature $T_{ext}=7^0C$) and cooling mode (interior temperature $T_{int}=27^0C$ and exterior temperature $T_{ext}=35^0C$) (CSTB, 2012).

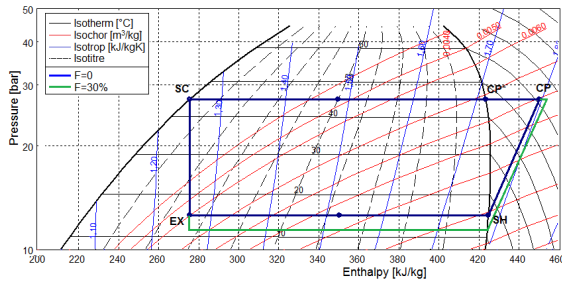


Figure 6: The enthalpy diagram of a heat pump air/air in cooling mode (interior temperature $T_{int}=27^0C$ and exterior temperature $T_{ext}=35^0C$) under the evaporator fouling

The enthalpy diagram of the refrigerant R410A in Fig.6 is used in order to show the heat transfer process occurring in a heat pump. In the normal working condition ($F = 0\%$), the heat transfer process follows the blue line. The saturated vapor enters the compressor suction (point SH in Fig.6). The vapor is compressed, following the isotropic line to the pressure corresponding to the condensing temperature (point CP in Fig.6). As mentioned in the previous part, compressor isentropic efficiency η_{CP_s} is 0.8, the compressor line is therefore modified to be toward the right-hand side of the isotropic line. Before any condensation occurs, the high-pressure vapor must be brought to a saturated condition (point CP^* in Fig.6). During the condensation, as heat is transferred from the refrigerant to the air, the refrigerant has been completely condensed (point SC in Fig.6). Then, the expansion valve reduces the refrigerant temperature and pressure to the evaporating temperature (point EX in Fig.6). The refrigerant quality has increased at the evaporator inlet. A mixture of saturated liquid and vapor goes through the evaporator. At the

moment this mixture is totally saturated, the cycle continues from the point SH in Fig.6.

If there is an evaporator fouling with $F = 30\%$ in the heat pump in cooling mode, the heat transfer process follows the green line. As we can see from the diagram, the compressor operates with more energy, which leads to a decrease in the EER of a heat pump. The simulation results of a heat pump performance under the impact of the evaporator fouling are showed in the Fig.7, with the fault level from 0 to 50%.

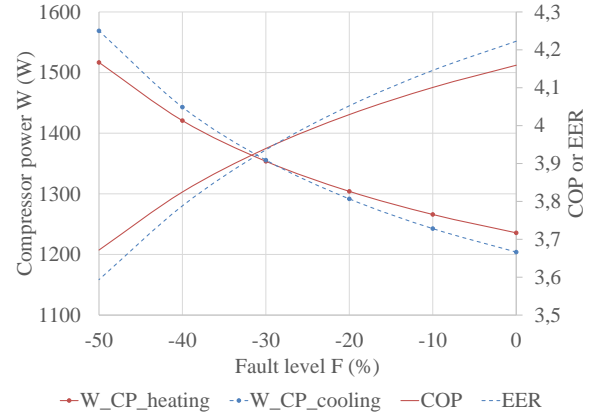


Figure 7: The impact of the evaporator fouling on the performance of a heat pump air/air in heating mode (interior temperature $T_{int}=20^0C$ and exterior temperature $T_{ext}=7^0C$) and in cooling mode (interior temperature $T_{int}=27^0C$ and exterior temperature $T_{ext}=35^0C$)

As can be seen from the Fig.7, the heat pump model quantified the impact of the filter on the heat pump performance through two values of the COP/EER and the compressor power W . In cooling mode, if the filter is fouled at 20%, the EER decreases 4% and the compressor power increases 7.3%. The dirtier the filter is, the greater the decrease in COP value and the greater the increase in compressor power.

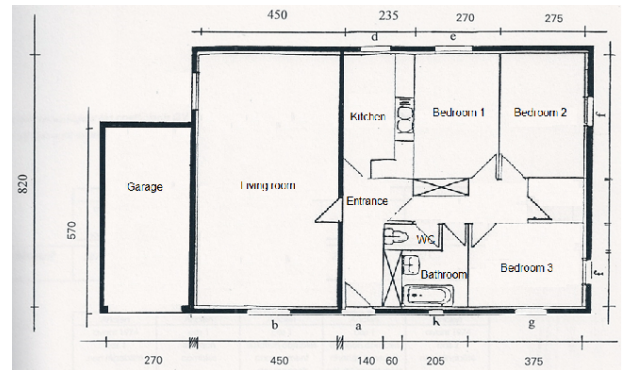


Figure 8: The tested residential building, MOZART

For the research needs, a typical French residential building MOZART (CSTB, 1995) was selected and modeled in a building simulation over the course of

one year, which is showed in the Fig.8. The house has eight windows. The thickness of the wall and ceiling is set to 20 (cm).

By using the coupling of 3 models from the steady-state vapor compression model, the Petri net and the building simulation COMETH, the impact of the evaporator fouling on the annual energy consumption in a building is simulated, which corresponds to the increase of fault level. The simulation results are showed in Fig.9.

Fig.9 shows the energy consumption during the first year simulation of the building under the impact of the evaporator fouling. The lower and middle diagram shows the heating and cooling energy in a building without operating fault, in every hour and every day respectively. The energy consumption is illustrated under the color variation from dark (more energy use) to light (less energy use) color. The upper one shows the power difference due to the evaporator fouling fault with the Petri net application. The evaporator fouling is considered as an operating fault if the fault level F is more than 10% (Bouteloup et al., 1997), which means we do not take into account the fault level $F = 5\%$, so the heat pump operates without fault until the point of time $t = 5490$ (hours) or until 17th August. Then, during the next 1000 operation hours, the heat pump will work with the fault level $F = 10\%$. At a point of time $t = 8192$ (hours) or on 08th December, the fault level of the evaporator filter increases to $F = 20\%$. At the end of the first year simulation, the energy consumption for heating and cooling increases by 1.14% and 0.66% respectively.

Conclusions

This research presents a methodology to study the influence of the operating faults, especially the evaporator fouling, on the performance of the split residential heat pump air/air and the energy consumption of the building under the Petri net approach. The simulations are based on a steady-state vapor compressor model by integrating the operating faults, the Petri net treating the evolution of the fault level, and the building annual simulation COMETH. The following conclusions can be drawn:

- The validation study of the heat pump model shows that we can apply the steady-state vapor compressor model to simulate a real operation of a heat pump in different conditions by integrating the operating faults.
- The impact of evaporator fouling on the performance of the heat pump was presented. In cooling mode, if the filter is fouled at 20%, the EER decreases 4% and the compressor power increases 7.3%. The dirtier the filter is, the greater the decrease in COP value and the greater the increase in compressor power.
- A Petri net model shows a general picture of the evaporator fouling's evolution throughout its

life cycle. It contains all possible evolutions of the evaporator fouling with or without the maintenance process. The graphic representation of Petri net describes the problem intuitively. The Petri net model provided consistent inputs to the building simulation and the overall building performance assessment.

- The coupling of 3 computed models (the steady-state vapor compression model, the Petri net and the building model) could evaluate and quantify the impact of the operating fault not only on the heat pump performance but also on the building energy consumption. At the end of the first year simulation, the energy consumption for heating and cooling increases by 1.14% and 0.66% respectively.

The primary goal of this article is to detail a new methodology to evaluate the impact of heat pump's operating faults on its performance and the building energy consumption. It is essential to mention the limitations of the current study, which should be addressed in future research. This study performed a simple operating fault as evaporator fouling. Further research should expand to study the other common operating faults of the heat pump. Moreover, it should focus on the ability of the new methodology in analyzing the impact of all operating faults together on the heat pump's performance and the energy building consumption.

Nomenclature

| | | |
|---------------|------------------------------------|----------|
| A | Area | m^2 |
| F | Fault level | % |
| Q | Heat transfer rate | W |
| T | Temperature | K |
| W | Compressor power | W |
| c_p | Specific heat at constant pressure | kJ/kgK |
| h | Enthalpy | kJ/kg |
| q_m | Mass flow rate | kg/s |
| q_v | Air flow | m^3/h |
| ρ | Density | kg/m^3 |
| η_{CP_s} | Compressor isentropic efficiency | |

Subscripts

| | | | |
|-----|----------------------|-----|---------------|
| a | air | i | inlet |
| aux | auxiliary components | ini | initial |
| CP | compressor | o | outlet |
| CD | condenser | r | refrigerant |
| EV | evaporator | SC | super cooling |
| EX | expansion valve | SH | super heating |

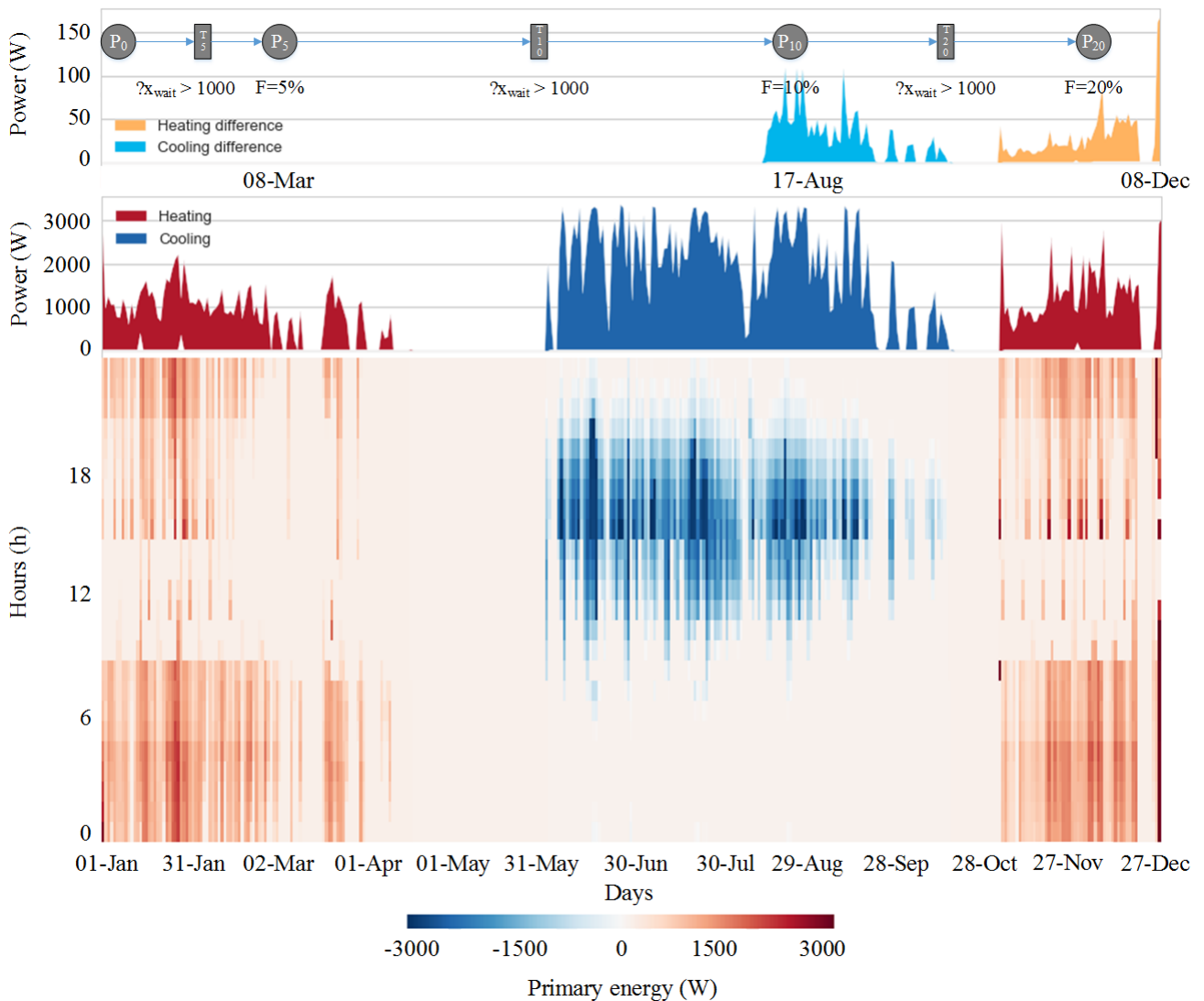


Figure 9: The impact of the evaporator fouling on the energy consumption of building

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