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Optimising performance in steady state for a supermarket refrigeration system

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Abstract— **Using a supermarket refrigeration system as an illustrative example, the paper postulates that by appropriately utilising knowledge of plant operation, the plant wide performance can be optimised based on a small set of variables. Focusing on steady state operations, the total system performance is shown to predominantly be influenced by the suction pressure. Employing appropriate performance function leads to conclusions on the choice of set-point for the suction pressure that are contrary to the existing practice. Analysis of the resulting data leads to a simple method for finding optimal pressure set-point for given load situations.**

I. INTRODUCTION

In a competitive and global business environment plant-wide performance assessment and optimisation in the process industry have increasingly become important issues as they have direct impact on the operational costs, energy and environmental issues. Supermarket refrigeration systems are no exception: One of the larger operational costs of a supermarket is the refrigeration plant. In a supermarket, the refrigeration system accounts for 40% to 60% of annual electrical energy consumption, see [1]. Furthermore, there are substantial costs related to component replacement and unscheduled maintenance. In many industrial systems, it is customary to use over-dimensioned components that provide excess capacity in order to guarantee that the system functionality is provided under all conditions, which are in particular caused by non-optimal operational conditions. For instance, the compressor rack in supermarket systems is typically made of compressors that can provide up to 50% more capacity than the supermarket system is actually designed for. Non optimal operation not only affects the cooling efficiency and food quality but also have direct impact on the operational lifetime of the components. Proper optimisation tools/methods can be used to optimise the performance of an operating system. It can also assist the design engineering group to choose appropriate components of right dimensions/capacities at much more suitable costs in future plants. An appropriate performance function for plant-wide operation should include contributing terms that describe the quality of products, system efficiency, as well as the operating lifetime of the subsystems. In section II-A, a performance function fulfilling these requirements is proposed. Optimisation of refrigeration system has been attempted in other papers such as [2] where multi variable control is used to get at better performance of a vapour compression system. An energy optimal control approach for refrigeration system is introduced in [3] and in [4] an online steady state energy minimisation is presented, where the minimisation is relying on a model of the refrigeration system. In this paper, we utilise an appropriate performance function, introduced in [5], to assess the system performance. Since, supermarket refrigeration systems operate in steady state in the majority of their operating time, as many other plants in process industry, it is reasonable to separate the steady state condition from the transient one and then explore the ways to asses and optimise the performance. By employing appropriate performance function and choosing suction pressure as the dominating variable it is shown that the suggested operating set-points for the suction pressure differ significantly from the ones that can be obtained by using performance function that is used in common practice. Furthermore, the knowledge based on investigating the resulting performance under different load conditions is used to suggest a simple procedure for identifying the pressure set-point that leads to optimal operation in steady state conditions. In section II the problem is defined and the performance function is introduced as well as the optimisation problem. Thereafter, in section III the simulation setup is presented and simulation results are presented in IV. The method for set-point optimisation is then described in V and the paper ends with a conclusion.

II. PROBLEM STATEMENT

The supermarket refrigeration system operates in steady state in the majority of time and it is therefore of high importance to always use the optimal reference for the controllers. The compressor control loop is one of the important control loops because of the relatively high energy consumption of the compressors. The control task of the compressors is to maintain a desired suction pressure. However, choosing a proper suction pressure reference, in refrigeration system, is critical to provide a certain temperature level of refrigeration. To fully understand the problem an overview of a supermarket refrigeration system will be introduced hereafter. In Fig. 1, a simple diagram for a supermarket refrigeration system is presented. The compressors are connected in parallel with display cases and the condenser unit. The controller structure for the refrigeration systems is implemented in

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a distributed setup where each of the display cases has a controller that controls the temperature by manipulating the inlet of refrigerant into the evaporator of the display case. To ensure a sufficient temperature difference in all the display cases, a common evaporation temperature is achieved by controlling the compressors, to deliver a common suction pressure. The control of the compressor rack is discrete which means that the compressors can only be switched on or off. Excessive switching of the compressors is not desirable because it creates superfluous energy consumption and excessive wear on the compressors. The commonly used strategy is to choose the suction pressure reference as high as possible. The reason for choosing that strategy is that a higher suction pressure requires a lower compressor capacity. However, that strategy does not take the switching phenomenon into account.

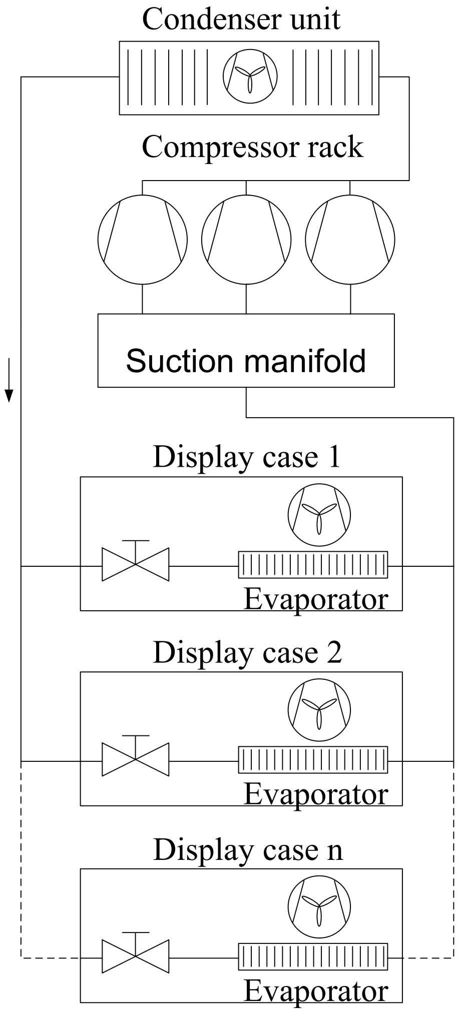

Fig. 1. Simplified supermarket refrigeration layout

A. Performance function

The quality of the solution for optimal performance is highly dependent on which performance criteria are included in the performance function. The relevant performance criteria for supermarket refrigeration systems are food quality, energy efficiency and reliability. Monitoring of the food quality is achieved by including the control errors of the temperature controllers and the suction pressure controller in the monitoring setup. The energy efficiency is monitored by using the coefficient of performance, COP, in the setup. The COP is defined as the delivered cooling power delivered divided by the electrical power consumed. The reliability of the plant is monitored by including the switch frequency of the compressors in the setup. Excessive switching of the compressors will generate excessive wear on the compressors and thereby increase the need for maintenance and decrease the lifetime of the compressors. The combined effect on the system is a lower operational reliability. Hence, minimisation of the switch frequency is desirable.

To ensure that the operation of the plant is optimal with respect to all three criteria the following performance function, which was introduced in [5], has been used in this work:

$$J(t) = \sum_{k=1}^{K} ||\mathbf{e}(k)||_Q^2 + \sum_{l=1}^{L} ||\frac{1}{COP(l)}||_R^2 + \sum_{m=1}^{M} ||f_{sw}(m)||_S^2 \tag{1}$$

The performance function (1) is a sum of quadratic terms where the notation is given by (2).

$$||\mathbf{e}||_Q^2 = \mathbf{e}^T Q \mathbf{e} \tag{2}$$

The first term in (1) is the control errors of K controllers. The second term is the inverted COP of L refrigeration cycles and the third term is the switch frequency of M compressors.

B. Normalisation

Since the main objective is to be able to employ the performance function in various supermarkets (with different subsystems of different sizes and dimensions), the performance function should be made of the scalable terms that can be easily adapted for a given supermarket. The scalability can be achieved through normalization of the terms in the performance function. For any given supermarket the corresponding performance function will then be established through the choice of appropriate weights that reflect the regional regulations on safety requirements as well as local operational expenses. In the following the normalisation procedure will be explained.

The error term is normalised using the knowledge that the temperature in a display case has a lower and an upper limit and the reference is chosen as the mean value of the temperature limits. The same argument is applied for the suction pressure error which also has an upper and a lower limit and the reference is then chosen as the mean value of the two limits.

$$\mathbf{e} = \left| \begin{matrix} \frac{2}{(T_{max,i}-T_{min,i})} \cdot (T_{\text{ref,i}} - T_{\text{air,i}}) \\ \frac{2}{(P_{suc,max}-P_{suc,min})} \cdot (P_{\text{sucref}} - P_{\text{suc}}) \end{matrix} \right| \tag{3}$$

The switch frequency term is normalized by dividing the measured frequency by the maximum allowable frequency of compressor switching in a compressor rack. This frequency is given by the compressor manufacture

$$f_{sw} = \frac{f_{meas}}{f_{max}} \tag{4}$$

As mentioned before the $\frac{1}{COP}$ is unit less and does therefore not need any normalisation. After normalisation each of the terms $\mathbf{e}$, $\frac{1}{COP}$ and f_{sw} will then be in the range between 0 and 1 and the weights will therefore represent the cost associated with each term. Each term in (1) contains a quadratic term which includes the weight matrices Q, R and S. These weights represent the costs, in terms of economic penalties or lost profits, which are associated with the performance of each subsystem.

Choosing Q, R and S will be done based on each of the terms impact on the price of running the refrigeration plant.

The weight Q, which is for the control errors, is based on the price that is associated with temperature requirements for the display cases in the supermarket. If the temperature gets too high the stored goods will have to be destroyed. In addition, if the failure is detected by the authorities the supermarket could be faced with a fine. The weight R, which is for the inverted COP, is based on the energy price since the inverted COP is effectively an efficiency of the refrigeration cycle. The weight R, which is for the switch frequency of the compressors, is based on the price of replacing and maintaining a compressor in the refrigeration system. The cost of maintaining and replacing a compressor contains many hidden costs, such as the price of the system being out of operation. Contributions like that renders significant freedom for manipulating the weight based on intuition. The simulation data presented in this paper is scaled. Thus, the absolute values of the performance function do not have any physical interpretation.

C. Optimisation formulation

In this section an optimisation problem for the considered system will be defined. As previously mentioned the supermarket refrigeration systems operate in steady state most of the time , i.e. at over 80% of the time. Therefore, it makes sense to first focus on optimising the system performance in steady state operation, henceforth denoted static performance optimisation. Depending on whether the focus is on static performance optimisation or on optimising the dynamic behaviour of the system, different set of parameters will be subject to optimisation. When the main objective is to optimise the static performance one should look for which subsystems have the highest impact on the total performance of the plant. For these systems the variables, which are used to address the conditions and objectives for the operation, are typically the set-points.

The performance function in (1) can be written in a more abstract way as:

$$J(\phi(t)) = \sum_{i=1}^{I=K+M+L} J_i(\phi(t)), \tag{5}$$

where $J_i(\phi(t))$ is the local performance function for the i^{th} subsystem that is dependent on the set $\phi(t)$ which is defined as:

$$\phi(t) = \left\{ Po_{ref}(t),\ \dot{Q}_{airload}(t) \right\}, \tag{6}$$

where Po_{ref}, denotes the suction pressure reference for the compressor rack controller which is a controllable variable, and the uncontrollable variable which is the heat loss to the surroundings and the main disturbance in the supermarket, is denoted by $\dot{Q}_{airload}$.

Set-point optimisation of the supermarket is defined as:

$$\min_{Po_{ref}} J(\phi(t)) \qquad \forall\, \dot{Q}_{airload} \tag{7}$$

The optimisation problem is to focus on finding the optimal value for $Po_{ref}(t)$ that minimises $J(\phi(t))$ for any given disturbance, $\dot{Q}_{airload}$. To solve the optimisation problem some primary simulations have been performed to get a deeper knowledge about the search space. The simulations have been carried out as follows:

To get an overview of the optimisation space, a series of simulations has been carried out. In the simulations, the suction pressure reference has been changed in steps from $1.0 \cdot 10^5$ $[Pa]$ to $2.5 \cdot 10^5$ $[Pa]$ with a step size of $0.1 \cdot 10^5 [Pa]$ or the equivalent of changing the evaporation temperature approximately $2°C$. For each of the steps in the suction pressure reference the disturbance, $\dot{Q}_{airload}$, and thereby also the load of the system has been changed by changing the ambient temperature of the display cases in steps from 18 $[°C]$ to 28 $[°C]$, with a step size of $0.5°C$. In these simulations, steady state values of various measurements have been used. Therefore changes, both in the suction pressure reference and ambient temperature, are step like. The dynamic behaviour has not been the focus.

III. SIMULATION SETUP

The simulation setup is based on a simplified model of a supermarket refrigeration system. The model contains two display cases, a compressor rack comprised of two compressors and a condensing unit. Each of the display cases are fitted with a PI controller that controls the air temperature in the display case. The compressor rack is fitted with a PI controller and a step controller that maintains the desired suction pressure, and thereby ensures a sufficient temperature difference to enable a heat transfer. The layout for a supermarket refrigeration system is shown in Fig. 1.

The control task of the display case is to ensure that the temperature is maintained at the desired level within the display case. This is normally done by controlling the opening degree of the inlet valve to the evaporator. The capacities of the compressors should ideally be chosen so that the common operation points of the refrigeration plant can be handled with a fixed number of compressors running. However, in practice the compressor rack will not fit the operation points exactly. Therefore, the compressors will have to switch to satisfy the refrigeration load. Thus, the choice of compressors is a compromise and is usually in favour of a certain operation point. Hence, switching of the compressors are unavoidable but should be kept at a

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minimum to avoid excessive wear on the compressors and superfluous energy consumption.

A. Modelling the refrigeration system

The model used for simulation in this paper is a slightly modified version of the supermarket refrigeration system model presented in [6]. The model has been changed so that the injection valve can be controlled continuously and thereby providing a model where the temperature in the display case can be controlled continuously.

The model features a refrigeration system with two display cases, a suction manifold, a compressor rack and a condenser. The temperature in each of the display cases is described by (8), where (9) describes heat flow from the surroundings and into the display case. The other terms in (8) are described in detail in [6]. The ambient temperature of the display case, T_{amb}, is assumed constant since it corresponds to the indoor temperature of the supermarket. To enable the possibility of a continuously controlled refrigerant flow the mass flow into the evaporator is modelled using (10).

$$\frac{\mathrm{d}T_{\mathrm{air,i}}}{\mathrm{d}t} = \frac{\dot{Q}_{\mathrm{goods-air,i}}(\cdot) + \dot{Q}_{\mathrm{load,i}}(\cdot) - \dot{Q}_{\mathrm{air-wall,i}}(\cdot)}{M_{\mathrm{air}} C_{\mathrm{p,air,i}}} \tag{8}$$

$$\dot{Q}_{\mathrm{load,i}} = UA_{\mathrm{amb}} \cdot (T_{\mathrm{amb}} - T_{\mathrm{air,i}}) \tag{9}$$

$$\frac{\mathrm{d}M_{r,i}}{\mathrm{d}t} = OD_i \cdot \alpha \cdot \sqrt{P_c - P_{suc}} - \frac{\dot{Q}_{e,i}}{\Delta h_{lg}} \tag{10}$$

$$\frac{\mathrm{d}P_{\mathrm{suc}}}{\mathrm{d}t} = \frac{\dot{m}_{\mathrm{in-suc}}(\cdot) - \dot{m}_{comp}}{V_{\mathrm{suc}}\ \nabla\rho_{\mathrm{suc}}(P_{\mathrm{suc}})} \tag{11}$$

In (10) the opening degree of the expansion valve is denoted by OD, P_c denotes the condensing pressure, $\dot{Q}_e$ denotes the heat removed by evaporation and the enthalpy difference across the two-phase region is denoted by Δh_{lg}. For details about the modelling of $\dot{Q}_e$ and Δh_{lg} see [6].

The suction pressure is the only common state for all of the display cases, the suction manifold and the compressor, and its dynamics can be described by (11). The refrigerant density is denoted by ρ_{suc} and $\nabla\rho_{\mathrm{suc}}$ denotes the pressure derivative of the refrigerant density.

The mass flow rate into the suction manifold, $\dot{m}_{\mathrm{in-suc}}$ is described by:

$$\dot{m}_{\mathrm{in-suc}}(M_{\mathrm{r,i}}, T_{\mathrm{wall,i}}, P_{\mathrm{suc}}) = \sum_{i=1}^{N} \frac{\dot{Q}_{\mathrm{e,i}}(\cdot)}{\Delta h_{\mathrm{lg}}(P_{\mathrm{suc}})} \tag{12}$$

The temperature, T_e, denotes the evaporation temperature. As explained in [6] Δh_{lg}, ρ_{suc} and $\nabla\rho_{\mathrm{suc}}$ are all refrigerant specific functions.

The compressor rack is described by (13).

$$\dot{m}_{comp} = \mathtt{Cap} \cdot \frac{1}{100} \cdot \eta_{vol,i} \cdot \dot{V}_{sl,i} \cdot \rho_{suc} \tag{13}$$

In (13) `Cap` denotes the running compressor capacity of the rack, the volumetric efficiency is denoted by η_{vol}, and the swept volume flow rate is denoted by $\dot{V}_{sl}$. The condenser model contains no dynamic, it only defines a static condensing pressure and a static sub-cooling, which suggests an assumption that the condenser is controlled well enough to keep a constant condensing pressure and a constant sub-cooling.

B. Controller setup

The control setup is comprised of a temperature controller for each of the display cases that manipulates the opening degree of the expansion valve, OD_i, and a suction pressure controller that manipulates the running compressor capacity in the compressor rack. The temperature controllers and the suction pressure controller are implemented as PI controllers. Emulation of the discrete behaviour of the compressor rack is achieved by defining the compressor rack as being comprised of two compressors. Generally the `Cap` in (13) has the following form:

$$\mathtt{Cap} = \sum_{i=1}^{i=N} \delta_i \mathtt{Cap}_i \tag{14}$$

with $\delta_i \in \{0, 1\}$ and $\sum_{i=1}^{N} \mathtt{Cap}_i = 100\%$. In our application $N = 2$, $\mathtt{Cap}_1 = 45\%$ and $\mathtt{Cap}_2 = 55\%$. To avoid excessive switching of the compressors a hysteresis band is applied around each compressor step. The layout of the compressor rack is based on a real supermarket system which has the same layout of the compressor rack.

IV. SIMULATION RESULTS

The simulation results presented in this section will be used as a basis for the analysis for the set-point optimisation presented in section V. On Fig. 2 the top plot shows the performance function and the remaining plots each of the terms from the performance function versus Po_{ref} at three different loads, Low, Medium and High, which in the simulation corresponds to a change in the ambient temperature of the display cases. As shown in Fig. 2, by increasing the load, the minimums are shifted to the right on the Po_{ref} axis. The inverted COP term is not changed in different loads. The performance function is highly correlated with the switch frequency and this term mostly shapes the behavior of the performance function.

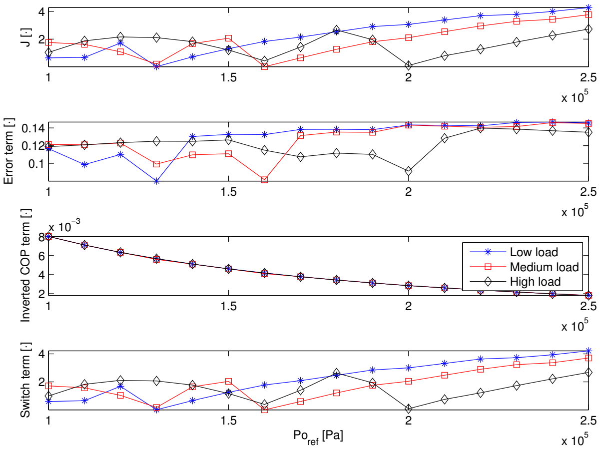

Fig. 2. Performance function and each of the terms plottet versus Po_{ref} at different load levels

Fig. 3 shows the performance function plotted versus Po_{ref} and the load, $\dot{Q}_{airload}$ and it can be seen that the reference for the suction pressure is dependent on the load, $\dot{Q}_{airload}$. Increasing load clearly calls for a higher suction pressure reference if optimal operation should be maintained. The same conclusion can be made by looking at Fig. 4 and Fig. 6. The contribution from the inverted COP term is shown in Fig. 5, which represents the curve form that will usually be used for optimising a refrigeration plant. Hence, using the performance function (1) as shown on Fig. 3 for choosing the optimal suction pressure will present a better set-point than solely basing the choice on the inverted COP.

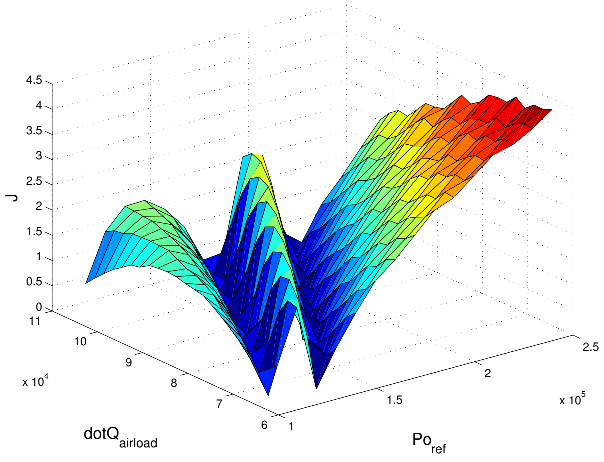

Fig. 3. Performance function versus Po_{ref} and $\dot{Q}_{airload}$

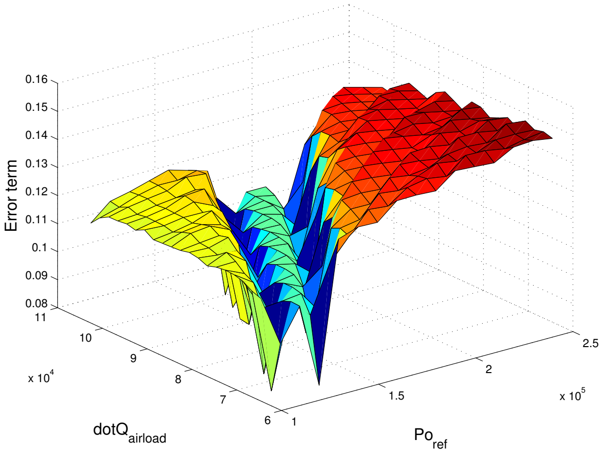

Fig. 4. Error term from the performance function versus Po_{ref} and $\dot{Q}_{airload}$

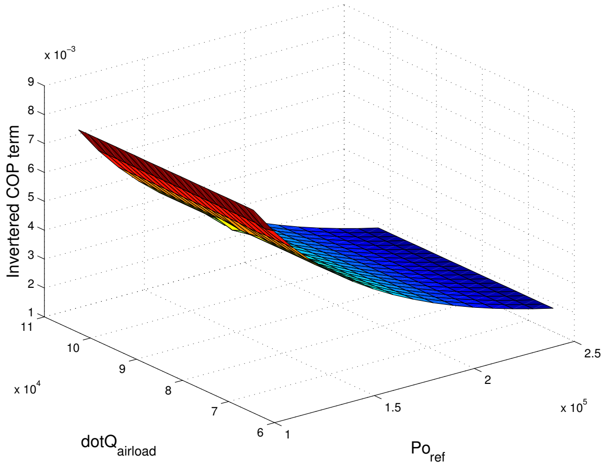

Fig. 5. Inverted COP term from the performance function versus Po_{ref} and $\dot{Q}_{airload}$

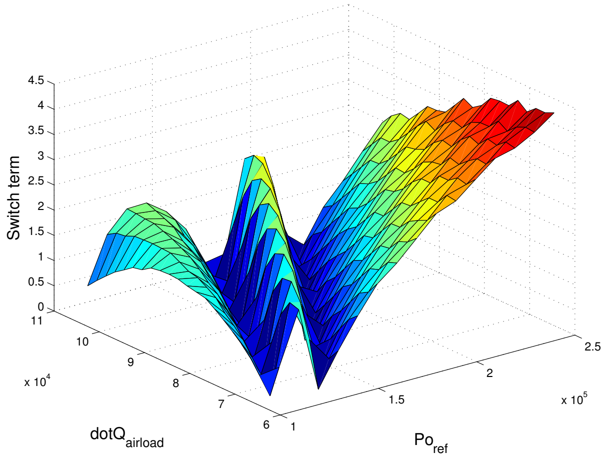

Fig. 6. Switch term from the performance function versus Po_{ref} and $\dot{Q}_{airload}$

V. SET-POINT OPTIMISATION

The set-point optimisation has to be based on the available information in the system. The optimisation method can not assume that there exists a sufficiently detailed model of any given refrigeration plant. Thus, it will not be possible to predict or estimate the performance for any given set-point. In addition, the method cannot use a benchmark data set, because it does not exist, and it is not feasible to assume the existence of such a data set for any given supermarket. However, it is feasible to online generate a limited data set.

Considering the above simulation results and problem statement, interpolation is chosen as a method to find the optimal set-pont.

A. Interpolation

Interpolation is a technique used to estimate unknown values that lie between known values, see chapter 6 in [7]. A linear interpolation of the following form is been used:

$$Po_{ref} = Po_{ref,a} + (Po_{ref,b} - Po_{ref,a}) \cdot \frac{\dot{Q}_{airload} - \dot{Q}_{airload,a}}{\dot{Q}_{airload,b} - \dot{Q}_{airload,a}} \quad (15)$$

More sophisticated interpolations are available and often applied to datasets with irregular spacing. However, in this case, the linear interpolation technique is used for set-point optimisation purpose because of the speed of the method, accurate response and the linear behaviour of the system performance with respect to the change on load and set-point pressure, see Fig. 7. Linear interpolation requires at least two sweeps of the suction pressure reference Po_{ref} at different values of the disturbance $\dot{Q}_{airload}$. According to the previous analyses, optimal set-points have been shifted to the right on the Po_{ref} axis, see Fig. 2 or 3. Analysis of Fig. 3 through 6, shows that the optimal point is changing linearly with respect to the change in the disturbance, $\dot{Q}_{airload}$. Therefore, by means of three or at least two optimal set-points, an optimal set-point line at different values of $\dot{Q}_{airload}$ can be interpolated 7. Therefore, the optimisation problem could be solved by determining the value of $\dot{Q}_{airload}$ at each instance and then set Po_{ref} to the corresponding value of $\dot{Q}_{airload}$ base on the knowledge gain by the two sweeps and the interpolation. Since the interpolation approach is based on the ability to do at least two sweeps at different values of $\dot{Q}_{airload}$, which is a disturbance, the method relies on that the disturbance changes over time and thereby renders sweeping at different load situations possible. The proposed algorithm can be described as follows:

1) For a given $\dot{Q}_{airload}$ sweep Po_{ref} and save the values of $J(t)$
2) Find the minimum value $J(t)$ and use the corresponding Po_{ref} as the optimal set-point for the given $\dot{Q}_{airload}$
3) When $\dot{Q}_{airload}$ changes significantly, repeat step 1 and 2 and establish the linear interpolation as suggested in (15).
4) Use the interpolated line to chose the optimal suction pressure reference, Po_{ref}, for future $\dot{Q}_{airload}$.

The load change between opening and closing hours of the supermarket system will be sufficient to provide a good interpolation results. However, extending the algorithm to update the interpolation when there has been a seasonal change might be a good idea. The proposed method will provide a close to optimal set-point based on the interpolation.

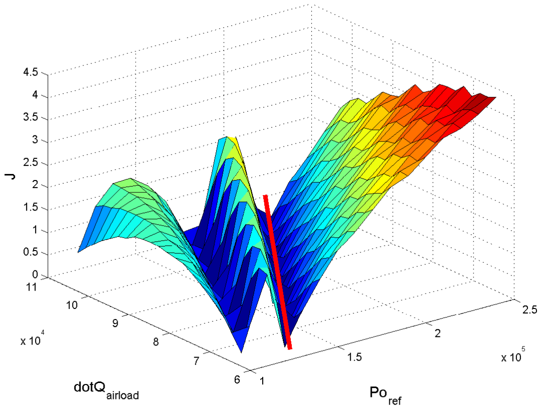

Fig. 7. Optimal interpolated line

VI. CONCLUSION

Optimising the global steady state performance of a supermarket refrigeration system has been the focus of this paper. This has been done by concentrating the optimisation effort on the choice of set-point for predominate controller for the plant, which is the compressor controller. The paper presents a method for handling the problem of choosing the optimal suction pressure reference with minimum knowledge of the refrigeration plant. The problem is solved by utilising the general knowledge gained by examining the simulation results based on model of a supermarket refrigeration system. The results clearly indicates that the optimal set-point is dependent on the load on the system, which is a disturbance in the system. The proposed method indicates that the set-point should be adjusted when the load changes significantly. The proposed method does not rely on the existence of a detailed model of the system or the availability of benchmark data.

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