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Plant-wide dynamic and static optimisation of supermarket refrigeration systems: a review report of International Journal of Refrigeration

By

I NYOMAN SUAMIR, ST, MSc, PhD

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2023

CONTENTS

1. CORRESPONDENCES

Gmail **I Nyoman Suamir <inyoman.suamir@gmail.com>**

Reviewer Invitation for JIJR-D-12-00247

1 message

Felix Ziegler <felix.ziegler@tu-berlin.de> Mon, Nov 19, 2012 at 1:11 AM
To: Inyoman.Suamir@brunel.ac.uk, Inyoman.Suamir@gmail.com

Ms. Ref. No.: JIJR-D-12-00247
Title: Plant-wide Dynamic and Static Optimisation of Supermarket Refrigeration Systems
International Journal of Refrigeration

Dear Mr. I Nyoman Suamir,

Given your expertise in this area, I would appreciate your comments on the above paper. I have included the abstract of the manuscript below to provide you with an overview.

If you accept this invitation, your comments will be due by 09 Dec 2012. If you are unable to act as a reviewer at this time, I would greatly appreciate your suggestions for alternate reviewers.

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ABSTRACT:
Optimising the operation of a supermarket refrigeration system under both dynamic as well as steady state conditions is addressed in this paper. For this purpose an appropriate performance function that

encompasses food quality, system efficiency and also component reliability is established. Depending on whether the focus is on optimising the system performance under steady state or dynamic conditions different set of parameters will be subject to optimisation. 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. The dynamic optimisation requires use of dedicated excitation signals. A method for designing such signals under realistic operational conditions is been suggested. A derivative free optimisation technique based on invasive weed optimisation (IWO) has been utilised to optimize the parameters of the controllers in the system. Simulation results have been used to substantiate the suggested methodology.

I Nyoman Suamir <inyoman.suamir@gmail.com>

Thank you for agreeing to review

3 messages

Felix Ziegler <felix.ziegler@tu-berlin.de> Tue, Nov 20, 2012 at 12:55 AM
To: Inyoman.Suamir@brunel.ac.uk, Inyoman.Suamir@gmail.com

Ms. Ref. No.: JIJR-D-12-00247
Title: Plant-wide Dynamic and Static Optimisation of Supermarket Refrigeration Systems
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Thank you for agreeing to review manuscript number JIJR-D-12-00247 for International Journal of Refrigeration.

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Thank you in advance for your timely cooperation and for your contribution to the success of International Journal of Refrigeration.

Yours sincerely,

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Felix Ziegler (Regional Editor for Europe)
International Journal of Refrigeration

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I Nyoman Suamir <inyoman.suamir@gmail.com> Mon, Dec 10, 2012 at 6:46 AM
To: Felix Ziegler <felix.ziegler@tu-berlin.de>

Dear Felix Ziegler,

Just to let you know. I can't make the review in time due to personal reasons,
I need 5 more days until 14 December 2012.
Hopefully, this will be possible.

I do apologise for the delay.

Best regards
Suamir

[Quoted text hidden]

Ziegler, Felix, Prof. Dr. <felix.ziegler@tu-berlin.de> Mon, Dec 10, 2012 at 2:44 PM
To: I Nyoman Suamir <inyoman.suamir@gmail.com>

Dear colleague,

thank you very much; no problem.

Maybe you will receive automated mailings – just disregard them.

Sincerely

Felix Ziegler

Prof. Dr.-Ing. Felix Ziegler

Technische Universität Berlin

Sekr. KT2

Institut für Energietechnik

Marchstraße 18

Tel +49 (0) 30 314 - 22387

Fax +49 (0) 30 314 - 22253

[Quoted text hidden]

Gmail **I Nyoman Suamir <inyoman.suamir@gmail.com>**

Thank you for the review of JIJR-D-12-00247

1 message

Felix Ziegler <felix.ziegler@tu-berlin.de> Tue, Dec 18, 2012 at 2:53 AM
To: inyoman.suamir@gmail.com, suamir_nyoman@yahoo.com

Ms. Ref. No.: JIJR-D-12-00247
Title: Plant-wide Dynamic and Static Optimisation of Supermarket Refrigeration Systems
International Journal of Refrigeration

Dear Dr. I Nyoman Suamir,

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Thank you again for sharing your time and expertise.

Yours sincerely,

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2. REVIEW COMMENTS

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JIJR-D-12-00247
"Plant-wide Dynamic and Static Optimisation of Supermarket Refrigeration Systems"
Original Submission

I Nyoman Suamir, PhD (Reviewer 1)

Reviewer Recommendation Term:	Major Revision
Overall Reviewer Manuscript Rating:	65

Manuscript Rating Question(s):	Scale	Rating
Please rate on a scale of 1-3 whether the Highlights are a meaningful and accurate representation of the article. 1 = Meaningful; 2 = Not Meaningful; 3 = Not Provided. For more information, see www.elsevier.com/highlights.	[1-3]	1

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0 __1 __2 x__3 __4 __

The conclusions were supported by the data.

0 __1 x__2 __3 __4 __

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Please note that your recommendation and reviewer report are expected to cover the Highlights and Graphical Abstract if submitted with the manuscript.

Please give a frank account of the strengths and weaknesses of the article:
The strength: the subject of the investigation is worthy for supermarket refrigeration applications to improve food quality, energy efficiency and component reliability. This is one of sustainability technology in the supermarket applications.
The weakness:
The control strategy taken does not reflect common practices used for supermarket refrigeration system.
The optimisation model has not been validated
The analyses are not supported with proper data.
The artical is very difficult to follow due to misuse of tenses,words and inefective sentences.

Comments to Author:

Comments on Manuscript Number: JIJR-D-12-00247

The paper provides quite interesting theoretical insight into the performance optimisation of supermarket refrigeration plant but it is somewhat difficult to follow for the reasons outlined below. I would recommend that the comments are taken into account and the paper is then modified accordingly:

1. General (positions: spread throughout the paper): Avoid using "future tense" and phrase "should be" for the works that have been done. Use "past tense" to describe previous or published works.
2. Page 1, Abstract, sentence 3, line 30: " Depending on whether the focus is optimising the system performance under steady state or dynamic conditions different set of parameters will be subject to optimisation". This sentence is confusing. Rephrase it and avoid using "future tense".
3. Page 3, Nomenclature: Include units on the relevant parameters. Line 34: typo "tranfer" should be "transfer", Line 50: typo "Desity" should be "Density"
4. Page 4, lines 39-42: "For instance, the compressor rack … up to 50% more capacity than the supermarket system is actually designed for". A reference is needed.
5. Page 5, line 50: typo "optmiser" should be " optimiser". Line 54: " … is base on …" should be " … was based on …."
6. Page 6, line 11: typo " ensures" should be " ensure". Line 13: "A supermarket refrigeration systems …." should be "Supermarket refrigeration systems …".
7. Page 6, lines 30-44: "In section 4.1 …. is employed" This description is not required.
8. Page 7, line 9: typo " priori" should be " prior"
9. Page 8, line 30: " The considered refrigeration system dealt with in this paper is …" should be "The refrigeration system considered in this paper is …", line 32: typo "skectch" should be "sketch", "on Fig.2" should be "in Fig.2".
10. Page 8, lines 36-42: "Each of the display cases is fitted with an air temperature controller which adjusts the temperature by manipulating the opening degree of the inlet valve to the evaporator". Does the inlet valve mean an expansion valve? If so, please provide comments why air temperature is used to control the opening degree of the expansion valve. Commonly the valve is regulated by temperature of evaporator outlet and evaporating pressure because the purpose of regulating the opening of the valve is to maintain the set degree of superheat at the outlet of the evaporator not to control the air temperature in the cabinet. Typo "cases" should be "case"
11. Page 8, lines 54-11 page 10: " The inlet valves have been modified to enabled the possibility of continuous control … continuously." Rephrase this sentence. It is confusing.
12. Page 9, the title of Figure 2 should be "Schematic diagram of the supermarket refrigeration system"
13. Page 10, explain the use of UA term in the eq.(2). What does the heat transfer area "A" refer to? Explain also how to determine Tair in the cabinet. Provide a reference for the eq.(2).
14. Page 10, eq.(3): the term "ODi . α . (Pe-Psuc)0.5" is not a mass flow rate as the other terms in the equation. Please double-check the equation.
15. Page 11, lines 32-36: "The control structure is comprised of PI controller for each of the display cases, which controles the air temperature by manipulating the opening degree of the expansion valve, ODi." In practice the air temperature of the cabinet is controlled by regulating solenoid valves upstream of the expansion valves or switching the compressors On/Off. Please explain the use of expansion valve to control the cabinet air temperature.
16. Page 12, line 42: "cooling power" should be "cooling load", line 44: "… the switch frequency of the compressors …" should be "… the switching frequency of the compressors …"
17. Page 12, lines 53-55: "Collecting all of the three performance criteria in one performance function to provide overview was introduced in Green et al. (2010)," better to say "Combining all of the three performance criteria in one performance function was overviewed in Green et al. (2010),"
18. Page 16, lines 33-37: "As supermarket refrigeration systems operate in steady state conditions most of the time (i.e. over 80% of the time) …" Is this "over 80%" your estimation or based on published source? Please provide a reference.
19. Page 16, line 43: "For these systems, the conditions and objectives of the operation, are predominantly realized through the choice of appropriate set-points" What do these systems refer to? Is it the refrigeration system described in Fig.2? Please explain clearly.
20. Page 17, lines 47-51: "In the simulations, the suction pressure reference has been changed in steps from 1.0 * 105 [Pa] to 2.5 * 105 [Pa] with a step size of 0.1 * 105[Pa] or the equivalent of changing the evaporation temperature approximately 2◦C." Please add an explanation, how to determine this pressure-range and its evaporation temperature equivalence?
21. Page 18, Fig.3: the 4 graphs in this figure should be numbered with a, b, c and d then described by using the figure number e.g.: Fig.3a, Fig.3b, etc.

22. Page 19, paragraph 1, lines 9-23: this paragraph is very difficult to understand. Please add more explanation and rephrase the existing sentences.
23. Page 21, line 41: typo "interpolated 8." should be "interpolated"
24. Page 21, the last paragraph: Would it be possible to determine the range of optimal suction pressure set point at the given load? Let say at 18oC. This will help the readers to clearly understand the proposed control optimisation.
25. Page 22, Section 4.3: In practice, it is not very common to control the suction pressure set point based on the cabinet load. The suction pressure is usually set up based on the product temperature requirement (or air on/off temperature of the evaporator). How do you justify the control strategy using estimated load instead of product temperature requirements?
26. Page 30, line 9: typo "extrema" should be "extreme value"
27. Page 30, line 49: "Meaning that they rely on …" it is better to use "These mean that they rely on …"
28. Page 31, lines 29-42:"In the next generation of …" this description is not very relevant to the paper.
29. Page 32, paragraph 3: typo "on Fig." should be "in Fig."
30. Page 35, line 9: typo "sstem" should be "system"

Review Attachment(s):

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3. PUBLISHED ARTICLE

INTERNATIONAL JOURNAL OF REFRIGERATION 38 (2014) 106–117

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Plant-wide dynamic and static optimisation of supermarket refrigeration systems

Torben Green [a,*], *Roozbeh Izadi-Zamanabadi* [a,d], *Roozbeh Razavi-Far* [a,b], *Henrik Niemann* [c]

[a] *Danfoss Refrigeration & Air Conditioning, Nordborgvej 81, 6430 Nordborg, Denmark*
[b] *Department of Control Engineering and System Analysis, Université Libre de Bruxelles (ULB), 50 Av. F.D. Roosevelt, CP 165/55, B-1050 Brussels, Belgium*
[c] *DTU ELEKTRO, Department of Electrical Engineering, Technical University of Denmark, Elektrovej, 2800 Lyngby, Denmark*
[d] *Department of Electronic Systems, Frederik Bajers vej 7, 9220 Aalborg, Denmark*

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ABSTRACT

Optimising the operation of a supermarket refrigeration system under dynamic as well as steady state conditions is addressed in this paper. For this purpose an appropriate performance function that encompasses food quality, system efficiency, and also component reliability is established. The choice of setup parameters, which are necessary for system performance optimisation, depends on whether the system operates under steady state or dynamic conditions. While operating under steady state conditions, the total system performance is shown to predominantly be influenced by the suction pressure. The dynamic optimisation requires use of dedicated excitation signals. A method for designing such signals under realistic operational conditions is proposed. A derivative free optimisation technique based on Invasive Weed Optimisation (IWO) is utilised to optimise the parameters of the controllers in the system. Simulation results is used to substantiate the suggested methodology.

Optimisation dynamique et statique au niveau de l'ensemble du système frigorifique dans des supermarchés

Mots clés : Contrôle ; Systèmes frigorifiques ; Suivi actif du système ; Evaluation de la performance ; Optimisation de la performance

1. Introduction

In a competitive and global business environment plant-wise 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

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[*] *Corresponding author*. Tel.: +4 5 7488 1415; fax: + 45 7488 3849.

E-mail addresses: torben.green@danfoss.com, torben.green@gmail.com (T. Green), roozbeh@danfoss.com, riz@es.aau.dk (R. Izadi-Zamanabadi), roozbeh.razavi-far@ulb.ac.be (R. Razavi-Far), hhn@elektro.dtu.dk (H. Niemann).

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Nomenclature

J	Performance function
Γ	Contribution from neighbouring subsystems
y	Output from subsystem
y_{ref}	Reference signal
η	Excitation signal
φ	Parameter set
u	Control signal
e	Control error
T[K]	Temperature, subscript describes the context
$\dot{Q}$ [$J\cdot s^{-1}$]	Heat transfer, subscript describes the context
M[kg]	Mass, subscript describes the medium
$C_{p,air}$ [$J\cdot kg^{-1}\cdot K^{-1}$]	Specific heat capacity of air
UA [$J\cdot s^{-1}\cdot K^{-1}$]	Overall heat transfer coefficient
OD	Opening degree of the inlet valve
α	Cross sectional area
P_c [Pa]	Condensing pressure
P_{suc} [Pa]	Suction pressure
Δh_{hlg} [$J\cdot kg^{-1}$]	Enthalpy difference across the two phase region of the evaporator
$\dot{m}$ [$kg\cdot s^{-1}$]	Mass flow rate, subscript describes the context
V_{suc} [m^3]	Volume of the suction manifold
ρ_{suc} [$kg\ m^{-3}$]	Density of the refrigerant in the suction manifold
$\nabla\rho_{suc}$ [$kg\cdot J^{-1}$]	Pressure derivative of the refrigerant density
Cap	Delivered compressor capacity
η_{vol}	Volumetric efficiency
$\dot{V}_{sl}$ [$m^3\cdot s^{-1}$]	Swept volume flow rate
COP	Coefficient of performance
f_{sw} [Hz]	Switch frequency of the compressors

supermarket is the refrigeration plant. In a supermarket, the refrigeration system accounts for 40–60% of annual electrical energy consumption Energie-Konsens (2005). 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 common practice within the industry is that the design of a compressor rack for a supermarket refrigeration system is usually based on two basic requirements. The first requirement concerns the ability to provide sufficient cooling at maximum load on the hottest day of the year and the second requirement is to have the option for future expansion of the cooling demand, e.g. adding another display case to the system. This design strategy leads to an over dimension rack with an average operating point significantly lower than what has been used for the design. Non-optimal operation not only affects the cooling efficiency and food quality but also have direct impact on the operational life-time of the components. Proper optimisation tools/methods can not only be used to optimise the performance of an operating system but also assist the design engineering group to choose appropriate components of right dimensions/capacities at more suitable costs in future plants. An appropriate performance function for plant-wise operation should include contributing terms that describe the quality of products, system efficiency, as well as the operating life-time of the subsystems. Optimisation of refrigeration systems have been attempted in other references such as He et al. (1998) where multi variable control is used to get a better performance of a vapour compression system. Jakobsen et al. (2000) introduces an energy optimal control approach for refrigeration system and in Larsen et al. (2004) an online steady state energy minimisation is presented, where the minimisation is relying on a model of the refrigeration system.

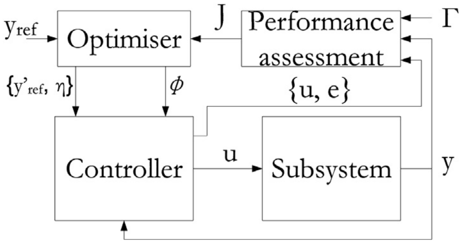

Fig. 1 – Block diagram illustrating the system-wide performance assessment and optimisation approach.

The strategy toward system-wide performance assessment and optimisation, proposed in this paper, can be described by using Fig. 1. In Fig. 1 the optimiser adjusts the behaviour of the controller for the subsystem. This is achieved by passing an alternated reference signal y'_{ref} and excitation signal η, or by changing the parameters, φ. The output from the optimiser is based on the performance function, J which is the output from the performance assessment block. The performance assessment was based on the control error, e, the output from the controller, u, the output from the subsystem, y, and contribution from the other subsystems, Γ. The contributions from the other subsystems ensure that the system-wide perspective is preserved.

Supermarket refrigeration systems, like many other plants in the process industry, operate in steady state conditions in the majority of their operating time it is reasonable to separate the optimisation task in two parts; the first one will be addressing the plant-wide optimisation in steady state conditions and the second one will be focussing on optimising the local subsystems' dynamic behaviour. To perform the optimisation task an appropriate performance function is proposed in Section 2.3. Optimisation in steady state is typically formulated in terms of set-point optimisation. For considered supermarket systems the suction pressure is chosen as the dominating variable. In Section 4.1 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. The knowledge based on investigating the resulting performance under different load conditions is used in Section 4.3 to suggest a simple procedure for determining the pressure set-point that leads to optimal operation for any given load condition. In Section 4.4 the approach is generalised to the case where a compressor rack with three compressors is employed.

Carrying out the dynamic optimisation task will be a challenge as refrigeration systems usually operate in steady state conditions and, therefore, will not be affected by a change in controller parameters unless the dynamics of the local subsystem is actively excited. This leads to the problem of designing/choosing auxiliary signals for a given subsystem that can be used for optimisation without affecting the performance of the subsystem. The problem is accumulated by the fact that there is little or no prior knowledge of the underlying system dynamics. In Section 5.1 the design of appropriate excitation signals will be discussed and a design method will be suggested.

In complex plants, such as large supermarket systems, when the subsystems are coupled and interact dynamically, local tuning of individual controllers for each of the subsystems does not guarantee that an optimal plant-wide performance can be achieved. Furthermore, due to the lack of knowledge of the underlying dynamics, it is very difficult to use the same techniques/methods that are typically used for local control tuning/subsystem optimisation. As the predominant used controllers in the process industry are of PI(D) types there exist a number of optimisation/tuning methods that can be utilised to modify the controller parameters in order to achieve improved performance (see for instance, Åström and Hägglund (2006, 1995); Smith and Corripio (1997)). However, these methods are developed in order to achieve local performance optimisation. The optimisation techniques in these methods are often gradient based and utilise the derivative of a performance function. An alternative is utilisation of derivative-free search algorithms, which use the performance function and constrain values to steer towards the optimal solution. Recently, genetic algorithm Goldberg (1989), particle swarm optimisation Kennedy and Eberhart (1995), ant colony optimisation Dorigo et al. (1996), simulated annealing Otten and van Ginnekent (1989) and tabu search Pham and Karaboga (2000) have been extensively used for optimisation and have shown high capability of searching for global minimum in different engineering applications Razavi-Far et al. (2009); Boeringer and Werner (2004). Invasive Weed Optimisation (IWO), which is introduced in Mehrabian and Lucas (2006) for the first time, is a bio-inspired numerical optimisation algorithm that simply simulates natural behaviour of weeds in colonizing and finding suitable place for growth and reproduction. In this work, invasive weed optimisation algorithm, IWO, is employed for plant-wide performance optimisation by finding the most suitable parameters for the local controllers. A short description of the IWO scheme is presented in Section 5.2. Simulation setup and results are presented (and discussed) in Sections 5.3 and 5.4. Finally, concluding remarks will be provided in Section 6.

2. System description

The refrigeration system considered in this paper is a simplified supermarket refrigeration system for which a sketch can be seen in Fig. 2. The refrigeration system is comprised of two display cases, a compressor rack which is comprised of two compressors and a condenser unit.

Each of the display cases are fitted with a cascade control comprised of an air temperature controller, (outer loop), and a superheat control, (inner loop). The air temperature controller provides reference to the superheat controller, which then manipulates the opening degree of the expansion valve. The superheat controller is assumed to be able to maintain a positive superheat at all times and the focus in this paper is therefore on the air temperature loop. The control task of the compressor rack is to ensure a certain suction pressure, by switching the compressors on or off, to fit the demand. In this work the condenser unit has been considered to be ideal and is therefore not explained further.

2.1. *Model of the simplified refrigeration system*

A slightly modified version of the model, for a supermarket refrigeration system, presented in Larsen et al. (2007) has been adopted. The model of the inlet valves has been changed from only modelling thermostat control to enable continuous control of the air temperature in the display cases. The mathematical model features two display cases, a suction manifold, a compressor rack and a condenser. The air temperature within each of the display cases is described by (1). The heat flow from the surroundings and into the display case is described by (2), see Larsen et al. (2007) for details, and is considered to act as a disturbance. The overall heat transfer coefficient, UA_{amb}, describes the heat transfer per temperature difference for the entire area of the display case. Hence, the notation UA_{amb} is used to describe the parameter.

The other terms in (1) are described in detail in Larsen et al. (2007).

$$\frac{dT_{air,i}}{dt} = \frac{\dot{Q}_{goods-air,i}(\cdot) + \dot{Q}_{airload,i}(\cdot) - \dot{Q}_{air-wall,i}(\cdot)}{M_{air}C_{p,air,i}} \tag{1}$$

$$\dot{Q}_{airload,i} = UA_{amb}\cdot(T_{amb} - T_{air,i}) \tag{2}$$

$$\frac{dM_{r,i}}{dt} = OD_i\cdot\alpha\cdot\sqrt{2\rho_{suc}(P_c - P_{suc})} - \frac{\dot{Q}_{e,i}}{\Delta h_{lg}} \tag{3}$$

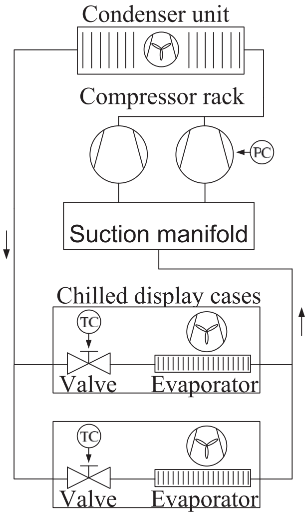

Fig. 2 – Schematic diagram of the supermarket system.

$$\frac{dP_{suc}}{dt} = \frac{\dot{m}_{in-suc}(\cdot) - \dot{m}_{comp}}{V_{suc}\nabla\rho_{suc}(P_{suc})} \tag{4}$$

In (3) OD denotes the opening degree of the expansion valve and P_c represents the condensing pressure. The heat removed by evaporation is denoted by $\dot{Q}_{e,i}$, and the enthalpy difference across the two-phase region is denoted by Δh_{lg}. For details about the modelling of $\dot{Q}_{e,i}$ and Δh_{lg} see Larsen et al. (2007).

The suction pressure is assumed to be the same across the low pressure section of the refrigeration system and is therefore modelled as a common state for all of the display cases in the suction manifold. The dynamics of the suction pressure is modelled by (4), where ρ_{suc} and $\nabla\rho_{suc}$ denote the refrigerant density and the pressure derivative of the refrigerant density. The mass flow rate into the suction manifold, $\dot{m}_{in-suc}$ is described by:

$$\dot{m}_{in-suc}(M_{r,i}, T_{wall,i}, P_{suc}) = \sum_{i=1}^{I} \frac{\dot{Q}_{e,i}(\cdot)}{\Delta h_{lg}(P_{suc})}, \tag{5}$$

which is a sum over the mass flow contributions from the I display cases. The terms Δh_{lg}, ρ_{suc} and $\nabla\rho_{suc}$ are all refrigerant specific functions which are explained in detail in Larsen et al. (2007) The mass flow rate created by the compressor rack is described by:

$$\dot{m}_{comp} = \mathrm{Cap}\cdot\frac{1}{100}\cdot\eta_{vol,i}\cdot\dot{V}_{sl,i}\cdot\rho_{suc}, \tag{6}$$

where the running compressor capacity of the rack is denoted by Cap and η_{vol} and $\dot{V}_{sl}$ denotes the volumetric efficiency and the swept volume flow rate, respectively. No dynamics of the condenser is modelled. Hence, the condenser simply defines a static condensing pressure and a static sub-cooling which indicates that the condenser is considered ideal.

2.2. Controller structure

The control structure is comprised of PI controller for each of the display cases, which controls the air temperature by manipulating the opening degree of the expansion valve, OD_i. In addition the suction pressure is controlled by a PI controller and switch logic that manipulates the running compressor capacity in the compressor rack. The discrete behaviour of the compressor rack is achieved by describing the delivered compressor capacity, `Cap` in (6) by:

$$\mathrm{Cap} = \sum_{i=1}^{i=N} \delta_i \mathrm{Cap}_i \tag{7}$$

In (7) $\delta_i \in \{0,1\}$ and $\sum_{i=1}^{N}\mathrm{Cap}_i = 100\%$. In this particular application two compressors are used i.e. $N = 2$, $\mathrm{Cap}_1 = 45\%$ and $\mathrm{Cap}_2 = 45\%$. A hysteresis band is applied around each compressor step to avoid excessive switching of the compressors. The layout of the compressor rack is based on a real supermarket system which has the same layout of the compressor rack.

2.3. Performance function

Improving the performance of any given plant requires a predefined notion for the performance. Evaluating the performance based on total cost of ownership, TOC, can be seen as the optimal solution. Direct measurement of the TOC is a difficult task and it can therefore be beneficial to identify certain performance criteria for the process and then use them as a performance measure. This idea has been presented in Green et al. (2010) where the following has been identified as relevant performance criteria for a supermarket refrigeration system:

- Food quality
- Energy efficiency
- Reliability

The food quality is monitored by measuring the control errors for the temperature controller and the suction pressure controller. The energy efficiency is measured by using the coefficient of performance, COP, in the setup. The COP is defined as the cooling load divided by the total electrical power consumed. The reliability of the system is measured by the switching frequency of the compressors because it gives an indication of the wear of the compressors. Excessive switching of the compressors will lead to unnecessary wear of the compressors and thereby increase the need for maintenance and thus decreases the general reliability of the refrigeration system.

Combining all of the three performance criteria in one performance function to provide a better overview of the performance was introduced in Green et al. (2010), and has been used in this work:

$$J(t) = \sum_{k=1}^{K} \|\mathbf{e}(k)\|_Q^2 + \sum_{l=1}^{L} \left\|\frac{1}{\mathrm{COP}(l)}\right\|_R^2 + \sum_{m=1}^{M} \|f_{sw}(m)\|_S^2 \tag{8}$$

The first term in (8) 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. The inverted COP is used to ensure that the term has the same properties as the two other terms in connection with performance optimisation. The performance function (8) is a sum of quadratic terms where the notation is given by:

$$\|\mathbf{x}\|_A^2 = \mathbf{x}^T A \mathbf{x}, \tag{9}$$

where x is a vector and A is a weight matrix for the particular term.

2.4. Normalisation

The performance function should be made of scalable terms that can be easily adapted for a given supermarket, because the main objective is of course to be able to employ the performance function and the related algorithms in various supermarkets (with different subsystems of different sizes and dimensions). To achieve scalability property the performance function has to be comprised of scalable terms. Normalisation of the terms in the performance function provides precisely this scalability. The choice of the weights Q, R and S for the performance function (8) will have to reflect the regional regulations on safety requirements as well as local operational expenses, for a particular supermarket.

The normalisation of the terms will be described hereafter. Each display case has a lower and an upper limit and the reference is chosen as the mean value of the temperature limits and this knowledge is then used to achieve the normalisation. By using the same argumentation on the suction pressure controller the normalisation of the error term can be described as:

$$\mathbf{e} = \begin{vmatrix} \frac{2}{(T_{\max,i} - T_{\min,i})} \cdot (T_{\mathrm{ref},i} - T_{\mathrm{air},i}) \\ \frac{2}{(P_{\mathrm{suc,max}} - P_{\mathrm{suc,min}})} \cdot (P_{\mathrm{sucref}} - P_{\mathrm{suc}}) \end{vmatrix} \tag{10}$$

Normalisation of the switch frequency term is achieved by dividing the measured switch frequency with the maximum allowable switch frequency of the compressors in the rack. Hence, the switch frequency term is normalised in the following way:

$$f_{\mathrm{sw}} = \frac{f_{\mathrm{meas}}}{f_{\max}}, \tag{11}$$

where f_{meas} denotes the measured switch frequency and $f_{\max}$ denotes the maximum allowable switch frequency of the compressors.

Due to the definition of the COP the term 1/COP is unit less and does therefore not need any normalisation. The range of all of the three terms **e**, 1/COP and f_{sw} will after normalisation be in the interval between 0 and 1 and the weight will therefore represent the cost associated with each of the terms. The weights Q, R and S represent the costs, in terms of economic penalties or lost profits, which are associated with the performance of each subsystem. The choice of the weights has to be done based on the impact on the total operation cost from each of the terms in the performance function.

The price associated with temperature requirements for the display cases in the supermarket should be used as a base for the weight in the error term, Q. Too high or low temperature will destroy the stored food and thereby provide a financial loss for the supermarket. The cost of electrical energy is the base for the weight on the inverted COP term, R, since it is basically an efficiency. The weight on the switch term, S, has to be based on all the cost associated with replacing and maintaining a compressor in the refrigeration system. Because some of the contributions to the cost are hard to define a significant freedom for manipulating the weights based on intuition is maintained. The simulation data presented in this paper is scaled. Thus, the absolute values of the performance function do not have any physical interpretation.

3. Optimisation formulation

The formulations of the optimisation problem will be presented in this section. For the majority of the operation time the supermarket refrigeration system is in steady state. However, the quality of the operation is still important under dynamic behaviour. Thus, the problem of optimising the general operation of the plant has been split into two separate tasks, where the first task is the optimisation of the steady state performance and the second tasks is optimising the dynamic performance. From here on they will be referred to as static optimisation and dynamic optimisation, respectively. The static and dynamic optimisation will be described in detail in 4 and 5, respectively. Depending on whether the optimisation focus is on static or dynamic performance, different parameters will be subject to optimisation. For the static optimisation case the proposed strategy is to identify the predominant subsystem, with respect to the performance measure for the entire refrigeration plant. The optimisation parameters should then be chosen to be the parameters with highest influence on the performance. Parameters with these characteristics are usually the set-points for the controllers. In the case of the supermarket refrigeration system the predominant subsystem is the suction pressure control loop and the optimisation parameter is the suction pressure reference. In the dynamic optimisation case the controller parameters will be the optimisation variables. The common optimisation problem can be formulated by rewriting the performance function in (8) as:

$$J(\phi(t)) = \sum_{i=1}^{I=K+M+L} J_i(\phi(t)), \tag{12}$$

where $J_i(\varphi(t))$ is the local performance function for the ith subsystem which is depending on the parameter set $\varphi(t)$.

4. Static performance optimisation

As supermarket refrigeration systems operate in steady state conditions most of the time it makes sense to first focus on optimising the system performance for steady state operations, henceforth denoted static performance optimisation. When the main objective is to optimise the static performance one should look for the subsystems that have the highest impact on the total performance of the plant. For supermarket refrigeration systems, like the one in Fig. 2, the conditions and objectives of the operation, are predominantly realised through the choice of appropriate set-points.

$\varphi(t)$ in (12) is the set of optimisation variables which, in the static case, is defined as:

$$\phi(t) = \left\{ Po_{\mathrm{ref}}(t), \dot{Q}_{\mathrm{airload}}(t) \right\}, \tag{13}$$

where Po_{ref}, denotes the suction pressure reference for the compressor rack controller, which is the controllable variable and $\dot{Q}_{\mathrm{airload}}$ denotes the heat loss to the surroundings in the supermarket sales are, which is considered to be the main disturbance in the system.

Set-point optimisation of the supermarket is defined as:

$$\min_{Po_{ref}} J(\phi(t)) \quad \forall\ \dot{Q}_{\mathrm{airload}} \tag{14}$$

The optimisation problem is to find the optimal value for $Po_{\mathrm{ref}}(t)$ that minimises $J(\varphi(t))$ for any given disturbance $\dot{Q}_{\mathrm{airload}}$. To solve the optimisation problem it is required to obtain deeper knowledge about the profile of the performance function $J\varphi$ over the relevant search space φ. This can be done by either carrying out comprehensive field tests or simulating the case by using appropriate models of the plant.

4.1. *Simulation setup and results*

The simulation model presented in Section 2.1 has been used for the purpose. Hence, the simulated refrigeration system is

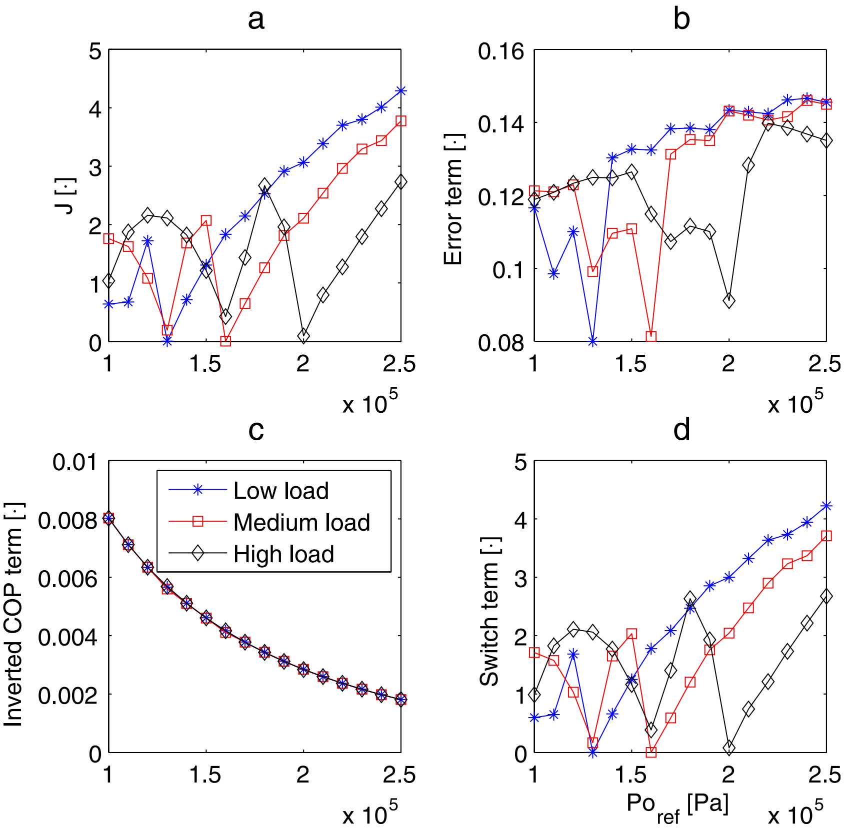

Fig. 3 – Performance function and each of the terms plotted separately versus Po_{ref} at different load levels. The top plot is the performance function and the following plots are the error term, the inverted COP term and the switch term of the performance function.

comprised of two display cases and a compressor rack comprised of two compressors. Simulations under varying loads and suction pressures have been performed to get a deeper knowledge about the performance function over a realistic search space. Investigation of simulation results leads to a proposed procedure for choosing the optimal set-point under any given load conditions. 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 per step. The pressure range is chosen to cover a relevant set for the suction pressure. The equivalent evaporation temperature range is −26.4 °C to −4.3 °C. The relation between the suction pressure and the evaporation temperature is given by a refrigerant specific function, see Skovrup (2000). 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.

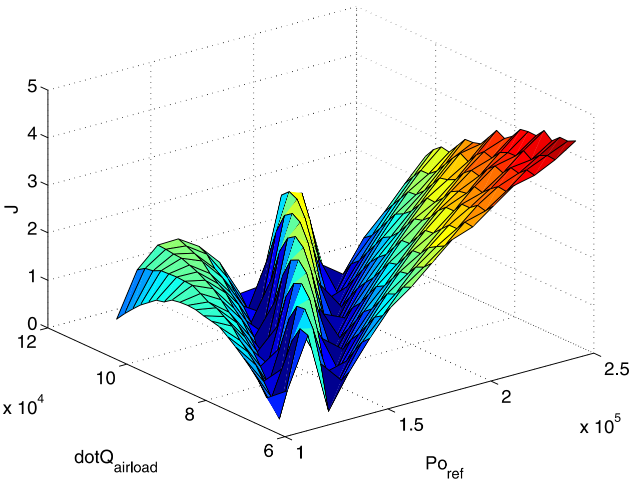

Fig. 4 – Performance function versus Po_{ref} and $\dot{Q}_{airload}$

Fig. 3a shows the performance function and Fig. 3b,c and d, shows 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. 3, 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. 4 shows the performance function plotted versus Po_{ref} and the load, $\dot{Q}_{airload}$ and it can be seen that the reference for

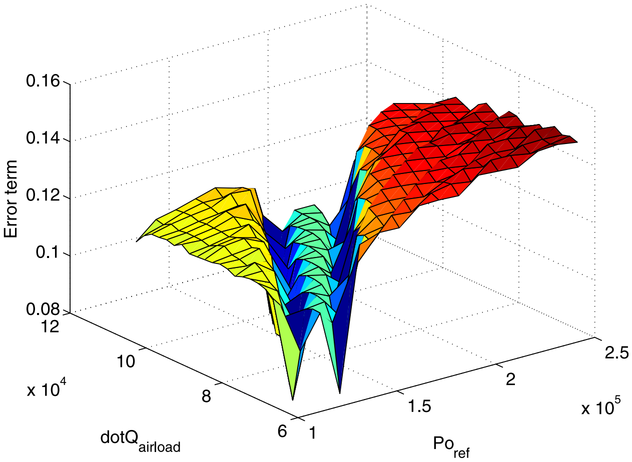

Fig. 5 – Error term from the performance function versus $\mathrm{Po_{ref}}$ and $\dot{Q}_{\mathrm{airload}}$

the suction pressure is dependent on the load, $\dot{Q}_{\mathrm{airload}}$. Since the valleys in the plot on Fig. 4 are not perpendicular to the $\mathrm{Po_{ref}}$ axis, an increase in the load, $\dot{Q}_{\mathrm{airload}}$, will move the optimal point in the positive direction on the $\mathrm{Po_{ref}}$ axis. Hence, an increase in the load will require an increase in the suction pressure reference if optimal operation should be maintained. The same conclusion can be made by looking at Figs. 5 and 6. The contribution from the inverted COP term is shown in Fig. 7, which represents the curve form that will be used for optimising a refrigeration plant. Hence, using the performance function (8) as shown on Fig. 4 for choosing the optimal suction pressure will present a better set-point than solely basing the choice on the inverted COP.

4.2. *Set-point optimisation*

Under realistic conditions generating complete set of data is not a viable solution. Nor it is normally possible to use a sufficiently detailed model of a given (arbitrary) refrigeration plant. However, it is feasible to online generate a limited data set. Taking these constraints into considerations and studying the simulation results lead to an interesting observation; the optimal set-points for suction pressure lie along two lines on the search space, see Fig. 8. Analysis of Figs. 4–6, shows that the optimal point is changing linearly with respect to the change in the disturbance, $\dot{Q}_{\mathrm{airload}}$. Therefore, by means of three or at least two optimal set-points, an optimal set-point line at different values of $\dot{Q}_{\mathrm{airload}}$ can be interpolated. These lines can be sufficiently characterised by a linear interpolation of the following form:

$$\mathrm{Po_{ref}} = \mathrm{Po}_{\mathrm{ref},a} + \left(\mathrm{Po}_{\mathrm{ref},b} - \mathrm{Po}_{\mathrm{ref},a}\right)\cdot\frac{\dot{Q}_{\mathrm{airload}} - \dot{Q}_{\mathrm{airload},a}}{\dot{Q}_{\mathrm{airload},b} - \dot{Q}_{\mathrm{airload},a}} \tag{15}$$

Hence, when at least two sweeps of the suction pressure and the interpolation have been executed, the optimal suction pressure reference will be uniquely given as a function of the load. Therefore, the optimisation problem could be solved by determining the value of $\dot{Q}_{\mathrm{airload}}$ at each instance and then set $\mathrm{Po_{ref}}$ to the corresponding value of $\dot{Q}_{\mathrm{airload}}$ based on the knowledge gained 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 $\dot{Q}_{\mathrm{airload}}$, the method relies on the changes of the disturbance over time and thereby renders sweeping at different load situations possible. 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.

4.3. *Choosing strategy of the optimal set-point*

For a given/estimated load the optimal set-point for the suction pressure needs to be identified. This can be done based on calculation of the minimum distance from the current operating conditions, i.e. $(\mathrm{Po}_{\mathrm{ref,current}}, \dot{Q}_{\mathrm{airload,current}})$ to the interpolated lines. The procedure is described in the following:

The distance d_i between the point $(\mathrm{Po}_{\mathrm{ref,current}}, \dot{Q}_{\mathrm{airload,current}})$ and the ith line $\lambda_i : \mathrm{Po_{ref}} = m_i\dot{Q}_{\mathrm{airload}} + b_i$, $i \in \{1, 2\}$ is given by the following formula:

$$d_i = \frac{\left|\mathrm{Po}_{\mathrm{ref,current}} - m_i\dot{Q}_{\mathrm{airload,current}}\right) - b_i|}{\sqrt{m_i^2 + 1}} \tag{16}$$

The candidate line, λ^*, will be the one that lies within the shortest distance from the working point, i.e.

$$\lambda^* = \lambda_i, \quad \text{such that :} \quad \forall j \neq i, \quad d_i < d_j \tag{17}$$

if $d_i = d_j$ then the candidate line should be chosen as the one that goes through the higher suction pressure.

The proposed method will provide a close to optimal set-point based on the interpolation.

4.4. *Generalisation of the method*

The considered system corresponds to a small supermarket refrigeration system where the compressor rack consists of two compressors. The compressor rack for larger supermarkets contains three or more compressors. Use of more compressors implies that it is possible to combine the compressors so that the risk of possible gaps in the delivered capacity is minimised. Furthermore, in compressor racks with more than three compressors it is customary to use at least one frequency controlled compressor. This will virtually remove any risk of gap in the delivered compressor capacity. However, as there is a large segment in the (small-medium) supermarket refrigeration systems where the compressor rack consists of three on-off compressors it is appropriate to generalise the method in order to cover this case as well.

The compressors in the compressor rack is denoted by C_A,C_B and C_C. The corresponding control strategy always pursues the following switching pattern:

$$\underbrace{\{C_A\}}_{Low} \leftrightarrow \underbrace{\{C_A, C_B\}}_{Medium} \leftrightarrow \underbrace{\{C_A, C_B, C_C\}}_{High},$$

i.e. start a compressor to deal with demands in low capacity area, then switch the second one when the demand increases to medium level. All compressors are then started in order to

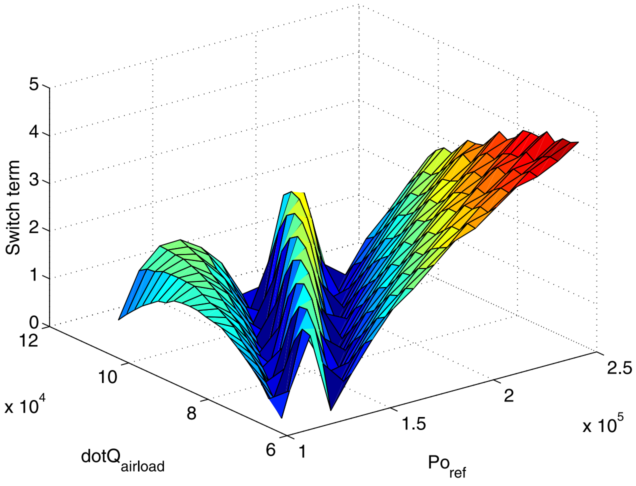

Fig. 6 – Switch term from the performance function versus Po_{ref} and $\dot{Q}_{airload}$

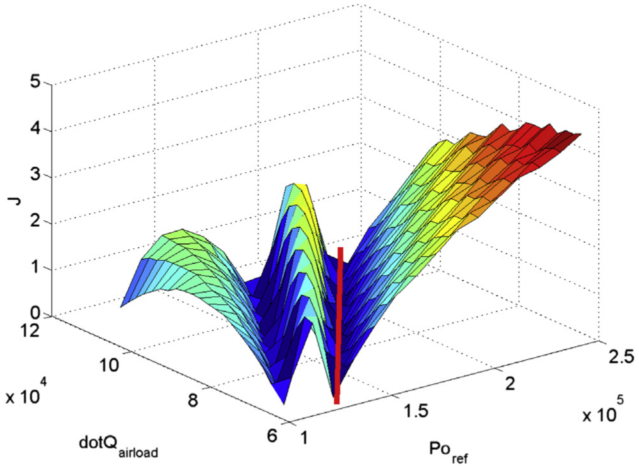

Fig. 8 – Performance function versus Po_{ref} and $\dot{Q}_{airload}$ with the optimal interpolated line.

meet high capacity demand. There are two possible gaps in the compressor capacities, i.e. one in the capacity area between $\{C_A\}$ and $\{C_A,C_B\}$ and the other one between $\{C_A,C_B\}$ and $\{C_A,C_B,C_C\}$. Similar to the two-compressor case, the performance of the system within each gap degrades, i.e. the value of the performance function (the cost) increases. Correspondingly, the profile of the performance function will look similar to the two-compressor case. The difference is that in stead of having two interpolated lines that represent the optimal set-points for the suction pressure for given external load, now we have three non-overlapping interpolated lines. The area between two neighboring lines corresponds to a gap in compressor capacities due to switches between two compressor configurations, for instance $\{C_A\}$ and $\{C_A,C_B\}$.To establish the three interpolated lines it is sufficient to perform a sweep over the suction pressure range for two different load conditions as it is prescribed in Section 4.2. Similarly, for a given load $\dot{Q}_{airload,current}$ the strategy of calculating the corresponding optimal set-point for the suction pressure follows exactly the procedure presented in Section 4.3. The only difference is that there are three interpolated lines, i.e. $i \in \{1,2,3\}$, that need be considered.

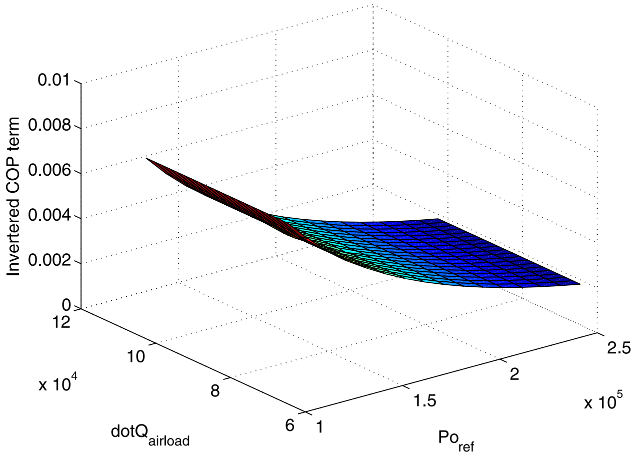

Fig. 7 – Inverted COP term from the performance function versus Po_{ref} and $\dot{Q}_{airload}$

5. Dynamic performance optimisation

As stated before optimising the dynamic behaviour of a supermarket refrigeration system with the controller parameters as optimisation variables, creates the need for active performance monitoring. The systems are usually in steady state for a significant amount of time, and a change in controller parameters will not affect the error and therefore not influence the plant-wide performance. Hence, excitation of the dynamics is required to optimise the dynamic behaviour of the system. The setup for active system monitoring is shown on Fig. 9, as a block diagram of the closed loop under investigation.

The controller is denoted by K and the system is denoted by G. The input to the system and the measured output is denoted by u and y, respectively and the reference to the controller is denoted by y_{ref}. The applied parameter change is denoted by $\Delta\xi$ and the contributions to the plant-wide performance function, J, is denoted by Γ. The excitation signal is denoted by η_Σ. The novel idea is in essence to excited relevant dynamics and then evaluate the current parameter setting with respect to J.

5.1. *Design of excitation signal*

A prerequisite for the active system monitoring scheme is the design of an excitation signal. Excitation of relevant dynamics of the system is the purpose and the problem is therefore to design a set of signals, $\{\eta_1, \cdots, \eta_m\}$, that lie in the appropriate frequency range of their corresponding closed loop systems. Since the dynamics of the subsystem in the closed loop under investigation is unknown the design problem is non-trivial. The knowledge regarding the closed loop is limited to a structural level. The use of design strategies from Niemann (2006) and Poulsen and Niemann (2008) is therefore restricted.

The intention is that the active performance monitoring setup should run on a supermarket refrigeration system in operation, and it is therefore important that an excitation signal does not compromise the operational performance significantly. In other words, the impact of on the system should be taken into account when the excitation signal is designed.

The air temperature control loop in the display case of a supermarket refrigeration system has been used show case for the proposed method in this work. The following facts are used as base for the design process hereafter:

1. The closed loop consists of a PI controller and a physical system, here a display case, for which the dynamics are unknown.
2. The parameters of the PI controller are known.
3. The existing controller is stabilizing the closed loop.

Furthermore, the following assumptions are used in the design process:

1. The system can be described sufficiently using a first-order model plus dead time (FOPDT).
2. The response time delay to an abrupt change in control action is known.

Verification of the first assumption can be obtained by consulting He et al. (1998); Rasmussen et al. (2006); Rasmussen and Larsen (2011) and the time delay can be measured with sufficient accuracy on the system. The following notation is introduced for the kth subsystem which is described as a first-order-plus-dead time (FOPDT) process model:

$$G_k(s) = \frac{k_{pk} e^{-T_{d_k} s}}{\tau_k s + 1},$$

where T_{dk} denote the time delay and k_{pk} and τ_k denotes the gain and time constant, respectively. The corresponding controller $C_k(s)$ is a PI type, i.e.

$$C_k(s) = k_c + \frac{k_c}{T_i s}.$$

The closed loop transfer function for the subsystem is then given by:

$$H_k(s) = \frac{C_k(s) G_k(s)}{1 + C_k(s) G_k(s)}.$$

For the chosen subsystem k, the task is then to find an appropriate set of excitation signals $\{\eta_1(t), \cdots, \eta_m(t)\}$ which excites relevant dynamics of the system and therefore assists in the task of finding the optimal controller parameters $\{k_{ck}, T_{ik}\}$ with respect to the plant-wide performance as describe in (8). The optimisation problem can be formulated as:

$$\begin{aligned} &\underset{k_{c_k}, T_{i_k}}{\text{minimize}}\ J(t) \\ &\text{subject to :} \\ &y_k(t) = (h_k * \zeta)(t), \quad \zeta(t) = \sum_{i=1}^{m} \eta_i(t). \end{aligned} \tag{18}$$

where y_k denotes the output of the kth system. '*' denotes the convolution function and represents the time domain description of $y_k(s) = H_k(s)\zeta(s)$. The excitation signal is represented by $\zeta(t)$. Hence, there exist two main problems that need to be solved. Firstly, the excitation signal has to be designed and secondly a suitable optimisation strategy has to be applied. The two problems will be dealt with in the following.

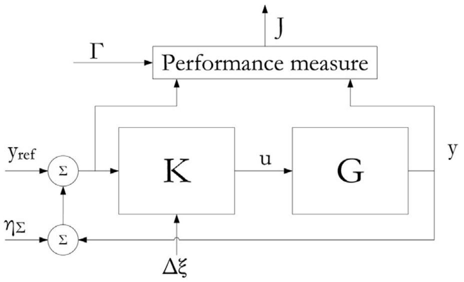

Fig. 9 – The general active system monitoring setup.

The design of the excitation signal has been split into two different tasks. The first task is to determine the frequency content of the signal and the second task is to determine a reasonable amplitude for the signal. To assist the design process the following simplification has been made:

$$\zeta(t) = \sum_{i=1}^{m} \eta_i(t) = \sum_{i=1}^{m} \eta(\omega_i t) \tag{19}$$

Thus, ζ is essentially a sum of identical functions with different frequency ω_i. The candidate function is chosen to be a sinusoidal function described by:

$$\eta_i(t) = A_i \sin(\omega_i t). \tag{20}$$

The excitation signal is then injected to the system as shown in Fig. 9.

The following will describe how the frequencies and the magnitude for the excitation signal will be described. Based on the knowledge of the controller parameters, k_c and T_i the corresponding system parameters, i.e. τ and k_p, can be estimated based on the desired gain and phase margins, see Green et al. (2011). The cutoff frequency ω_c of the closed loop can then be estimated based on the transfer function of the closed loop. The estimated parameters of a real system might deviate from the estimation by up to 100%. Hence, to ensure that the resulting excitation signal provides the proper impact on the dynamics a set of frequencies should be used.

Choosing the frequencies can be done based on the strategy presented in (22) and (21)

$$\omega_{\frac{m+1}{2}} = \omega_c \tag{21}$$

where m is chosen to be an odd number and hence the frequencies will be spread using (22).

$$\omega_i = \frac{1}{10} \omega_{i+1} \quad \forall i = 1, \cdots, m-1 \tag{22}$$

After the frequency content has been chosen the amplitude of the signal should be determined. The method for choosing the amplitude for the excitation signal will be described hereafter. Since the choice of the frequency content relies on the closed loop transfer function the assumption is that the current controller is able to stabilise the closed loop and the choice of amplitude can therefore be done by using the following method. The boundaries for a controllable signal is usually provided as constraints on the set-point which can be denoted by $\mathrm{SP_{upper}}$ and $\mathrm{SP_{lower}}$ and can therefore be used in the following way:

$$\mathrm{SetPoint} + \|\zeta\|_\infty < \mathrm{SP_{upper}} \tag{23}$$

$$\mathrm{SetPoint} - \|\zeta\|_\infty > \mathrm{SP_{lower}} \tag{24}$$

Extreme values for ζ does exists due to the definition in (19) and (20), which defines ζ as a bounded function. Furthermore by assuming that the closed loop has reached steady state the contribution from the P-term of the PI controller can be neglected and the I-term is the only contributer that enables the controller to keep set point tracking. Based on the discussion above, it is proposed to choose $\|\zeta\|_\infty$ using the following equation:

$$\|\zeta\|_\infty = \alpha\left|\frac{I-\mathrm{term}}{\widehat{k}_{p_k}}\right|, \tag{25}$$

In (25) $\alpha \in \{0.01 \cdots 0.25\}$ and $\widehat{k}_{p_k}$ is the estimated system gain. The value of α should be chosen as high as possible without violating (23), and (24). A reasonable choice is $\alpha = 0.15$. The correct amplitude for ζ is the sum of amplitudes of the sinusoidal function in (20) which are given by:

$$A_i = \alpha\left|\frac{I-\mathrm{term}}{m\,\widehat{k}_{pk}}\right| \quad \forall i \in \{1, \cdots, m\}. \tag{26}$$

After the design of the excitation signal a proper method for optimisation with respect to the plant-wide performance has to be employed.

5.2. *Invasive Weed Optimisation (IWO)*

The use of traditional optimisation techniques as those presented in Boyd and Vandenberghe (2004) is hard in complex industrial settings like the supermarket refrigeration system. The methods usually rely on the existence of a process model and secondly the methods are derivative-based, which means that they rely on calculating the derivative of the performance function. To avoid the problem of dealing with online calculation of the derivative of the performance measurement the aim has been to employ a derivative-free optimisation scheme. The invasive weed optimisation, which was introduces in Mehrabian and Lucas (2006), is a derivative-free optimisation scheme that in this paper has been used as a method for searching the parameter space.

The bio-inspired IWO algorithm basically tries to mimic the way an invasive weed colonises an area to find the best position for the weed. The idea proposed in this paper is to utilise the IWO algorithm to find the best parameters for the controllers with respect to the plant-wide performance measurement. The IWO algorithm searches the parameter space by randomly choosing an initial setup parameters in the predefined search space and then evaluating the performance of each parameter set. Then by applying the survival of the fittest principle only the best parameter sets are selected. For each of the following generations of the algorithm a new and randomly chosen parameter set is selected in a radius surrounding the surviving parameter sets from the previous generation. The radius is reduced after each generation of the algorithm and after a predefined number of generations a solution is provided. This process corresponds to an invasive weed that colonises a field with crops by randomly spreading seeds and then allowing them to grow into plants where the best plants will be able to spread their seeds until there is no more space between the crops.

5.3. *Simulation setup and results*

This section presents the simulation setup results for the use of the IWO algorithm for plant-wide optimisation of the dynamic performance of the supermarket refrigeration system. The basic idea is to employ the approach online on a real system and the method is therefore tested on the simulation model. The simulation model used in the setup is described in Section 2. The IWO algorithm has been used to find the optimal parameter set for the PI controller in a display case which is the controller gain, k_c, and the integration time, T_i. The size of the search space has been chosen based on the knowledge about what reasonable ranges can be accepted for the different optimisation variables. Furthermore, to assist the IWO algorithm an initial guess has been used in the first generation of the algorithm to ensure that at least one parameter set is reasonable.

In this setup the simulation runs for 5000 s to ensure that the performance function is in steady state with the given set of controller parameters, k_c and T_i.

5.4. *Results*

The result produced by the IWO algorithm over 150 generation can be seen in Fig. 10, where the minimum, the mean and the maximum values of the performance function is plotted for each generation each corresponding to a different parameter set. In Fig. 11 the evolution of the worst and the best

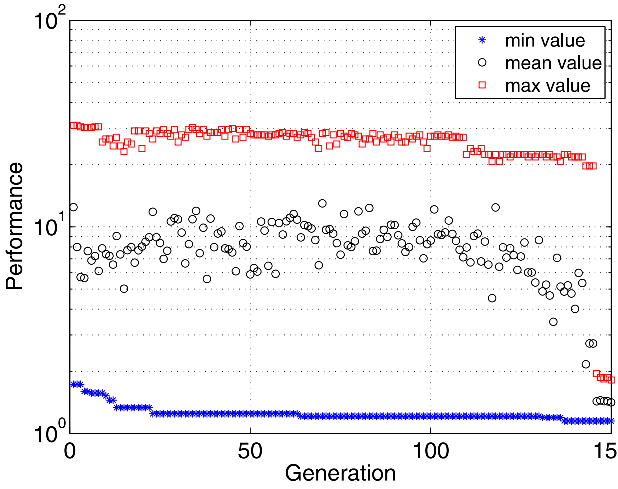

Fig. 10 – Generations versus the performance function *J*. The best achieved performance over 150 generations is 1.1512.

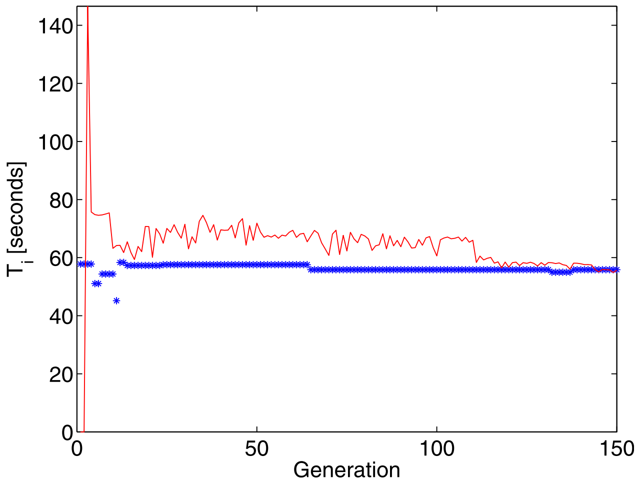

Fig. 11 – Evolution of T_i. The red line plots the evolution of the worst choice of T_i and the blue line plots the evolution of the best choice of T_i. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

integration time T_i is plotted and it can be seen that even the worst performing converges toward the solution. The worst and the best controller gain k_c is plotted in Fig. 12. In addition, it also shows that the worst performing choice of k_c is on the edge of the search space for many generations i.e. $k_c = -0.001$. However, despite that even the worst performing choice of k_c converges toward the best solution.

In Fig. 13 the integration time T_i is plotted versus the controller gain k_c and it shows that all the best performing parameter sets from all the generation are within a narrow area of the solution.

Another important point is that the initial guess of the controller parameter, $k_c = -0.1$ and $T_i = 100$, has never been the best performing parameter set. The initial parameter set is chosen based on empirical knowledge about the system. However, the solution provided by using the IWO algorithm is a controller gain of $k_c = -0.1716$ and an integration time of $T_i = 55.84$.

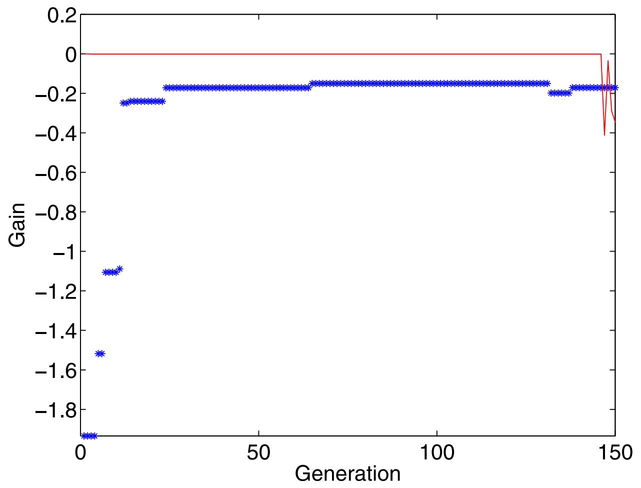

Fig. 12 – Evolution of k_c. The red line plots the evolution of the worst choice of k_c and the blue line plots the evolution of the best choice of k_c. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

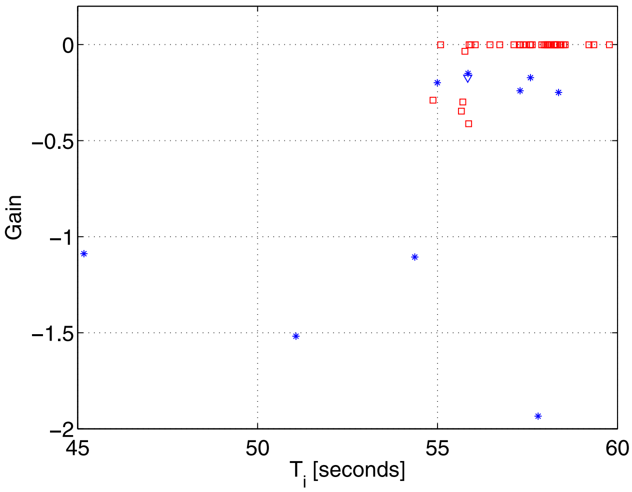

Fig. 13 – T_i versus k_c, The blue triangle indicates the end result for the parameters, $k_c = -0.1716$ and $T_i = 55.84$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusion

The focus of this paper was on achieving optimised system performance from a plant-wide point of view. To enable performance assessment and optimisation an appropriate performance function, which encompasses food quality, energy efficiency, and system reliability, was introduced. Due to the fact that the supermarket refrigeration systems operate the majority of time under steady-state (i.e. static) conditions, it was appropriate to consider the performance optimisation case under two different conditions; static (steady state) conditions and dynamic (transient) conditions. The static performance optimisation was realised through set-point optimisation. The simulation results on a supermarket refrigeration system with a compressor rack, consisting of two on-off compressors with different capacities, lead to a strategy for choosing set-point that is contrary to the existing practice. A generalisation of the method to a compressor rack with three compressors was also provided. As the system operates in steady state conditions most of the time, it is necessary to generate auxiliary signals in order to sufficiently excite the local subsystems to enable parameter optimisation of their corresponding controllers. The paper suggested a design strategy for these signals that also takes the realistic operational conditions into considerations. A derivative-free optimisation strategy, based on invasive weed optimisation method, was employed to search for optimal parameters of the local controllers. Simulation results were used to discuss and propose a strategy for appropriate employment of the optimisation method.

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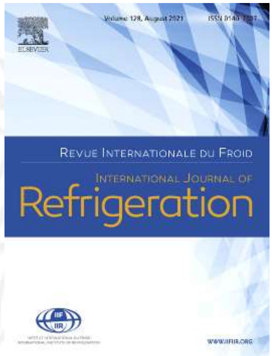

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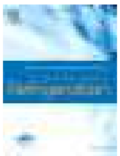	International Journal of Refrigeration	3

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Manuscript title	Revision	Date completed
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XXXXX3913	0	7 June 2013
Plant-wide Dynamic and Static Optimisation of Supermarket Refrigeration Systems	0	17 December 2012