Optimization of cooling appliance control parameters

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Abstract
This paper presents the optimization process and its simulation tool, for the optimization of the control parameters in the cooling appliance. The simulation tool simulates temperatures inside the cooling appliance at different modes of regulation. In our appliance some of the cabinets have a common cooling system, which means that the regulation of the cabinets is interdependent. The result of simulation consists of data, which is used during the optimization process to evaluate each found parameter setting. The optimizer uses an evolutionary heuristic search approach to find the optimal set of control parameters iteratively over evolving generations. The approach is based on probabilistic methods to decide on changes and the direction of search. The aim was to use a parameter-less algorithm that is able to find optimal, or at least very good solutions, relatively quick, and without the need for an algorithm parameter setting specialist. The implemented evolutionary algorithm, with the origins in genetic algorithm, does not need any predefined control parameters values. We were able to find a set of control parameters of a cooling appliance, that give an optimal performance with the lowest possible energy consumption. Additionally, we found out that the results of the optimization, resulting in one prototype, do not apply to another. Namely, change of the characteristics of the appliance and its thermal responses, also change the optimal settings. Nevertheless, if we find out that some components bring improvement to the appliance, they are further optimized; but those without influence to the appliance performance are omitted, which leads to cost reduction. This is some kind of the evolutionary selection of the reliable and robust components.

Keywords: Optimization, Simulation, Cooling appliance, Production.

1. Introduction
Market demands household appliances with high added value, with a wide range of embedded functionalities, and with minimal power consumption. Regarding household appliances, refrigerators/freezers are among the largest energy consumers. The leading Slovenian manufacturer of household appliances develops energy-efficient appliances with optimal performance. For optimal performance of a cooling appliance the lowest possible energy consumption is needed to cool the cabinets to the desired temperature. To optimize the performance, it usually requires a lot of long-term measurements or detailed theoretical analysis of the cooling system and the construction of complex mathematical model for simulation \cite{3, 6, 7, 8, 9, 11}. The latter approach requires a lot of time and specific knowledge on expensive simulation tools, like Gambit, Fluent, or Matlab. Besides, any change of the geometrical characteristics causes the restart of model description and analysis.

In the cooling appliances production, each new type of appliance has to be measured to determine its optimal performance. Thermal processes in the cooling systems are, by their nature, very slow. Thus, to determine the energy consumption it may take several days of measurements. In this paper we present a simulator that operates on a minimum set of specific short measurements. These measurements are entered into a generally applicable and widely spread program, Microsoft Excel, which implements the simulator. Simulation, with the use of Excel, requires only minimum computer skills of the user. In the case of changes in the cooling appliance (geometric dimensions, embedded components, method of regulation) the limited set of measurements is repeated, and measures are entered into the spreadsheet again. This means that we can improve the simulator without significant effort and investments. In the case of manufacturing a completely new appliance, we can use the proposed automated measurements, to be able to adapt the simulator, for use with the new appliance, in a very short time. Because of these advantages, the Excel program became a tool capable of simulating various complex systems \cite{2, 10}. Simulation results were compared with the measured values and showed that it can accurately and reliably simulate the cooling system, without special knowledge of programming languages or the use of expensive software tools. Further, the simulator was upgraded with advanced optimization algorithm to automatically find the optimal control parameters of an appliance.
2. Cooling Appliance Description
In general, the appliance consists of three cabinets; the upper one has a refrigerator function (Fresh Food - FF). Central one is designed to produce ice (Ice Maker - IM). The bottom one can operate in several different modes (Convertible Drawer - CD). Temperature regulation is performed with a cooling system consisting of variable-speed compressor, which drives the gas that expands in the evaporator and withdraws the heat from the evaporator. The evaporator cools the air that is blown into the cabinets by the fans through the ventilation system. IM and CD cabinets have a common cooling system (compressor, evaporator and fan), which means that the regulation of the cabinets is interdependent. Therefore, both CD and IM cabinets have hatches at the input of the ventilation system, to regulate the flow of cold air in each cabinet. Both compressors can change the frequency input signal to change the number of revolutions per minute (hereinafter: the compressor frequency), thus changing also cooling capacity. The speed of rotation of the fan can be switched among maximum, medium and minimum speed. Varying speed of rotation of fan influences the quantity of injected cooled air into each cabinet, thus influencing on cooling process.

3. Measurements and Analysis
The detailed analysis [13] of all available measurements showed that a satisfactory prediction of the temperature at the sensor and the cabinet temperature can be done by taking into account only measurements of temperature sensors as a function of the compressor. Therefore we measured only the temperatures at the sensors, cabinet temperatures, and compressor power. Measurements of all other temperatures do not give any significant prediction accuracy for the temperature sensor, since there are too many interdependencies between the different temperatures. At the same time, there is also some difference between the measurements carried out under the same conditions, due to the further influences (insulation material, sensor position...), which cause some additional undetermined noise.
For measurement processing we used MS Excel, and created several custom worksheets and macro programs. The macro program automatically calculates the average value of the curves in the specified range, and calculates the coefficients of the curve that approximates the observed curve. The calculation is performed by the polynomial regression method [4]. As a result we get the fourth order polynomial coefficients $a, b, c, d, e$, Eq. (1).

$$ T = at^4 + bt^3 + ct^2 + dt + e $$

There are also coefficients $a, b$ of the exponential function, Eq. (2), which represent the approximation of the compressor power.

$$ P = at^b $$

The coefficients calculated by a macro program are recorded in a table, to be easily exported and used by other programs.

4. The Simulator
The Simulator is designed in Microsoft Excel. It consists of several worksheets and macro programs to simulate the cooling device operation.
In the simulator (Figure 1) we set the desired temperature of IM and CD, and the value of the hysteresis for the IM and CD. Additionally, we can set a level of temperature in each cabinet when the hatch opens, although the on-temperature is not achieved yet, but due to opened other hatch (and the running compressor) it is reasonable to cool that cabinet too. The level value is given as a percentage of the difference between on- and off- temperature in each cabinet. To find an optimal control algorithm, the compressor cycle is divided into five intervals. The first interval starts on each compressor start-up, the second interval begins after the completion of the first, etc. If the compressor is on for more than the sum of the duration of five intervals, the settings of the last (fifth) interval are used. In each interval the compressor frequency and the fan speed is set. The frequency range (it is a discrete range of frequencies) is determined by the development team, while the fan speed can be maximum, medium or minimum. Additionally, we can set the simulated period and the period of the total simulated time to be considered in the calculations of energy consumption. With the later, we ensure that transitional state ceases and the appliance operates in steady state.
Simulation takes about 10 seconds to simulate 48 hours of operating time on a computer with 2GHz processor. The results of a simulation show: energy consumption in kWh per day, mean temperature in the IM and in the CD cabinets, the compressor duty cycle.

To calculate the energy consumption, the maximal interval within the period for the calculations which contains the whole cycles (interval starts with the beginning of one cycle and ends just before the start of the last non-complete cycle). In such a way, the calculation of energy consumption and other values is more accurate, since it takes into account only whole cycles; this is equivalent to calculation procedure of the measuring system in the laboratory, as defined by the standard [1]. The daily energy consumption in our case is therefore calculated as presented in Eq. (3).

\[
\text{consumption} = \frac{\text{consumption}_{\text{interval}} \times 2880}{\text{length}_{\text{interval}} \times 12000} \quad \text{kWh/day}
\] (3)

The mean temperatures IM and CD are the average temperatures in each cabinet throughout the calculation period. Duty cycle is the fraction of time within a period when the compressor is on.

Besides the numerical results, the solutions should also be feasible in the real appliance; therefore the simulator also shows the movement of the simulated temperatures over the simulated time. It is shown either for the entire simulated period, to observe the operation of the appliance before the steady state, and after it reaches it, or it can be shown for the steady state only (period for the calculations only). Figure 2 shows the movement of temperature on the sensor, the mean temperature in the cabinet, and the compressor power.
4.1. Validation of the Simulator
The validation of the simulator was carried out in the R & D laboratory. It was based on comparison of the results of measuring and the results of simulation, obtained at the same parameter settings. Differences between measured and simulated curves were negligible, and acceptable. The differences were even smaller than expected according to the number of factors that affect the operation of the appliance.

![Figure 3: Comparison of measured and simulated curves](image)

In Figure 3 the accuracy of the simulation is presented. The thicker and lighter curves represent the measured values, while the thinner and darker curves represent the simulated values. Here, minor differences are seen due to the impact of random noise. Similar difference is noticed, when comparing two measurements at the same settings. It is clear that the operating stability of the appliance is impacted by many factors and not all can be identified. This also means that the obtained solution for the appliance regulation must be sufficiently robust to ensure reliable operation.

5. The Optimizer
One of the reasons for development of the simulator was its need in the optimization process. The simulator was used as a tool for evaluation of different settings that were obtained by the optimizer. Optimizer is a program implemented in the C language, which is based on advanced mathematical tools for searching the optimal set of control parameters. The optimizer uses a heuristic search approach to find the solution iteratively over evolving generations. The evolutionary approach is based on probabilistic methods to decide on changes and the direction of search; while the used parameter-less algorithm is able to find optimal, or at least very good solutions, relatively quick, and without the need for a parameter-setting specialist. The implemented parameter-less evolutionary search (PLES) [12] algorithm (see Figure 4), with the origins in genetic algorithm (GA) [5], does not need any predefined control parameters values, as population size, number of generations, probabilities of crossover and mutation are, which are used for successful work of genetic algorithms and similar optimization techniques. The values of algorithm control parameters depend on the complexity of the problem and are adapted according to the behavior and convergence of the found solutions.

5.1. Initialization
The chromosome that represents the appliance control parameters is constructed upon their number and their dependencies. For \( n \) independent variables the chromosome looks like the string of \( n \) values in the order as described in the input specification.

The population size \( \text{PopSize} \) is proportional to the complexity of the problem, i.e., the number of
Parameter-Less Evolutionary Search

Set the initial population.
Evaluate each individual of initial population.
Perform statistical calculations.
While stopping criterion (based on statistics) not met
    Force better individuals to replace worse.
Move each individual in the population.
Evaluate each individual in the population.
Perform statistical calculations.

Figure 4: Outline of the PLES algorithm.

parameters and their resolution. This is needed to ensure higher versatility among the chromosomes in the population. Therefore more solutions can be searched in parallel in each iteration. The initial population size ($PopSize_0$) is set by Eq. (4),

$$PopSize_0 = n + 10\log_{10}(\sum_{i=1}^{n}(\max_i - \min_i)10^{\text{decplc}_i})$$

(4)

where $n$ is the number of variables to be optimized, $\max_i$ and $\min_i$ are the upper and the lower limit of the $i$-th parameter, respectively, and $\text{decplc}_i$ is the number of decimal places (the resolution) of the $i$-th parameter.

5.2. Stopping Criterion

Optimization is running while better solution is found every few generations. But when there is no improvement for a couple of generations, the optimization process stops. The $\text{Limit}$ (i.e., number of generations since the last improvement) for stopping the optimization process is defined with Eq. (5),

$$\text{Limit} = 10\log_{10}(\text{PopSize}_0) + \log_{10}(\text{Resting} + 1)$$

(5)

where $\text{Resting}$ is the number of generations since the last improvement of the global best solution.

5.3. Variable Population Size

During the search process the population size is changed, Eq. (6), since the quality of the solution might depend on the size of population. The population size is changed every few generations ($\text{Limit}_5$) based on the average change of the standard deviation ($\text{StDev}$) of solutions over a last few generations. When the standard deviation increases over a few generations than the population size is decreased, and vice-versa.

$$PopSize_i = \frac{PopSize_{i-1}}{\text{StDev}_{i-1} + \text{StDev}_{i-2}}$$

(6)

The change of population is limited to 25% per change and is further limited to $[\frac{PopSize_0}{5}, 1.1 \ PopSize_0]$.  

5.4. Force Better Solution

In every generation worse solutions are replaced with better solutions. Here, every $s_{ij}$ (parameter $j$ of the solution $i$) is randomly changed up to 25% of the difference between the parameter’s current value and its limit (upper or lower, regarding the move direction).

$$s_{ij} = \begin{cases} 
    s_{(i-1)j} + \text{rnd}(\max_j - s_{(i-1)j}) & ; \text{rnd} \geq 0 \\
    s_{(i-1)j} + \text{rnd}(s_{(i-1)j} - \min_j) & ; \text{rnd} < 0 
\end{cases}$$

(7)

where $\text{rnd}$ is a random number in the interval [-0.25,0.25].

This operator has (i) the function of elitism, while forcing to replace worse solutions with better, and (ii) the function of crossover, while taking the good solutions and slightly change them on some positions.

5.5. Solution Moving

In PLES, mutation is realized through the moving of some positions in the chromosome according to different statistical properties. First, only the solutions that were not moved within the "Force better" operator are handled here. In other words, solutions of the previous generation that were better than average are moved. The $\text{Ratio}$ of the parameters in the chromosome to be moved is calculated on the basis
of standard deviation of the solutions in the previous generation and the maximal standard deviation as stated in Eq. (8).

\[
Ratio = \tanh \left( 1 - \frac{StDev_{i-1}}{StDev_{max}} \right) \times n
\]  

(8)

where \(StDev_{i-1}\) and \(StDev_{max}\) are the standard deviation of the solution fitness of the previous generation, and the maximal standard deviation of all generations, respectively.

The size of the move is calculated according to the difference between the value of the parameter of the global best solution and current solution, as presented in the following equations,

\[
Move = \tanh \left( \frac{s_{best_j} - s_{ij}}{average_j - s_{ij}} \right)
\]  

(9)

where \(s_{ij}\) is the value of the parameter \(j\) of the current solution \(i\), and \(s_{best_j}\) is the value of parameter \(j\) of the globally best solution, \(average_j\) is the average value of the parameter \(j\) in the previous generation.

\[
Range = s_{best_j} - s_{ij}
\]  

(10)

\[
s_{ij} = s_{ij} + Direction \times Move \times Range
\]  

(11)

where \(Direction\) is randomly selected number (-1 or 1) to determine the direction of the move.

5.6. Solution Evaluation and Statistics
Each population is statistically evaluated, where the best, the worst, and average fitness value in the generation are found. Furthermore, the standard deviation of fitness values of all solutions in the generation, maximal standard deviation of fitness value over all generations, and average value of each parameter in the solution is calculated.

5.7. Input Data
The input data of the optimizer consist of: a list of all coefficients of the curves; the length of the simulated period; the desired average temperature in the cabinets; and constraints (lower, upper limits and step) of the parameters that we want to optimize. The optimizer searches for the optimal setting of control parameters. The search is performed with respect to the specified constraints (parameter limits). The result is a set of control parameters that lead to lowest consumption, while providing the desired mean temperature in the cabinets.

5.8. Validation of the Optimizer
The validation of the optimizer consists of the verification of the feasibility of obtained solutions. With the simulator we have identified some unfeasible settings of control parameters. Consequently, we further limited the parameters and ensure more feasible solutions in a consecutive runs of the optimizer. That led to the feasible solutions, which were applicable to the real appliance.

Based on an analysis of each solution we further improved the simulator, to provide even more feasible solutions. Most of the changes have been towards finding similar cycles; towards uniform compressor-on times; towards minimal number of on/off switches; etc.

6. Results
The optimizer must investigate rather large space of possible settings, e.g., for FZ area it is approximately \(10^{20}\) solutions. The implemented evolutionary search is able to relatively quickly find good solutions. To evaluate about 4000 different settings a computer with 2 GHz processor needs about 10 seconds. Due to the stochastic search method the results of the optimization are slightly different from one run to another in general, as well as search time can vary. The constraints and ranges of the optimized parameters also influence the search time significantly.

Optimization based on stochastic search method, gives several possible solutions. Criteria for choosing the appropriate one is not only the smallest energy consumption and the desired temperature, but it is also necessary to verify the behavior of the components. Namely, frequent on/off switching of them shortens their life cycle. It is also important that the difference between the minimum and maximum operating temperature is within the constraints, set by the standard [1].
Figure 5 shows the comparison of the results in different simulation settings. The duty cycle of the compressor is correlated with energy consumption. It should be noted that the measured consumption varies by about 1% due to disturbances. Disorders that affect the energy consumption are the noise of the ambient temperature, the accuracy of the measurement system, power supply voltage oscillation, etc. The results of the FF part of the appliance are not so much significant as for FZ part. The reason is in less complex FF part, comparing to FZ part. So, setting the desired temperature is already sufficient to minimize the energy consumption while reaching the set temperature. Although the results of the optimization of FF part have not contributed to a significant reduction in energy consumption, we obtained the optimal results for the FF part already in the first setting of control parameters. Besides, it is possible to determine, how many different options (variable frequency compressor, variable speed fan) are needed for the control of a FF part. Consequently, this leads to a simpler regulation algorithm, and a simpler and less expensive control electronics of an appliance.

7. Conclusion

A satisfactory prediction of the temperature sensor and the cabinet temperature can be done by taking into account only the limited number of measurements of temperature sensors as a function of the compressor. Within the project we found out that the results of the optimization, resulting in one prototype, do not apply to another. Change of the characteristics of the appliance and its thermal responses, also change the optimal settings. Nevertheless, if we find out that some components bring improvement to the appliance, they are further optimized; but those without influence to the appliance performance are omitted, which leads to cost reduction. This is some kind of the evolutionary selection of the reliable and robust components. There is already a new development phase of a new appliance prototype, with even better thermal insulation properties compared to the previous one. By estimations, this better insulation will reduce the energy consumption for up to 10%. Furthermore, the simulator shall optimize the operation and give further reduction of 10% in the FZ part, and up to 5% reduction in FF part. Thus, achieving the desired objectives: the energy-saving appliance, and reliable operation of the appliance. With the developed simulator we are able to simulate the appliance in a few seconds, as the ten-second simulation replaces a two-day measurement. This replace a large part of the development measurements and thus reduce development costs. Computer simulations showed the potential of unlimited improvement and optimization of prototypes of cooling appliances. Such an approach can reduce development times and gives several optimal solutions. Moreover, a similar practice could be used also in the development process of control electronics for other appliances (e.g., cooking), where long-lasting thermal processes are slowing down the development process.
Acknowledgements
This project was funded by Gorenje, d. d., from Velenje, Slovenia.

References


