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Predictive Simulation-based Optimisation of Cooling System Including a Sprinkler Tank

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Prerequisite for an efficient cooling energy system is the knowledge and the optimal combination of different operating conditions of individual compression and free cooling chillers. The performance of cooling systems depends on its part load performance and its condensing temperature, which are often unknown. Recorded energy data remains unused and manufacturers' data significantly differs from the real performance. For this purpose, manufacturer and real data are combined and continuously adapted to form partial load curve models. This study applied a predictive optimization algorithm to calculate the optimal operating conditions of multiple chillers. A sprinkler tank offers the opportunity to store cold-water for later utilisation. This potential is used to show the load shifting potential of the cooling system by using a variable electricity price as an input parameter of the optimisation. The set points from the optimisation have been continuously validated by a dynamic simulation. Finally, a case study of a plastic processing company evaluated different scenarios against the status quo. Applying an optimal chiller loading and charging strategy of a sprinkler tank increased the energy efficiency of up to 40 % during colder and around 17 % during warmer periods. The total energy savings highly depended on the weather conditions. For the consider fluctuations, the electricity price had only a minor effect.

1. Introduction

In Germany, more than 9 % of the net electricity consumption is used for providing cold water for industrial processes. The overall energy efficiency ratio (EER) in the industry is less than two. The ongoing digitization of many processes in the industry enables an automated and optimised operation of utilities. A high system efficiency can be achieved by an efficient and flexible utility system. The basis is the linkage of cross-sectional technologies, processes and process control systems to collect and analyse the energy data. Prerequisite for an efficient cooling energy system is the knowledge and the optimal combination of different operating and performance conditions of individual compression chillers. The performance of cooling systems depending on its part load performance and its condensing temperature are often unknown and overlooked. As a result, manufacturer performance data differs significantly from the real performance (Peesel et al., 2017).
A literature review reveals that the energy saving potential varies between 5 % (Huang et al., 2015) and 40 % (Thangavelu et al., 2017) depending on the use case. Kapoor et al. (2013) showed that implementing a 15,000 m³ cold water storage tank results in a cost saving of around 13 %. Many different methods for optimal chiller sequencing control are used. Some examples are the branch-and-bound method (Chang et al., 2005), dynamic programming (Chang, 2006), gradient method (Chang et al., 2010), genetic algorithms (Chang, 2005), simulated annealing (Chang and Yung-Chung, 2006) and the particle swarm optimisation (Lee and Lin, 2009).
The novelty of this study is the evaluation of the interdependency between part load ratio, variable electricity prices, and a sprinkler tank using data from an industrial energy monitoring system. The modelling of the utilities, the load profile of cold water and the framework conditions are based on the energy data of a plastics processing company. The optimisation algorithm is applied to case studies of plastic manufacturers in Germany and Spain.

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The aim of this study is to develop and apply a predictive optimisation algorithm for multiple compression chillers, a free cooling chiller and a sprinkler tank as a cold-water storage tank considering part-load and dynamic operation. The algorithm is based on the work of Peesel et al. (2017), who introduce a predictive simulation-based optimisation to a food processing factory and save up to 23 % per year of electrical energy.

2. Modelling method

Figure 1 shows the general methodology of the simulation-based optimisation with energy data from an industrial plant.

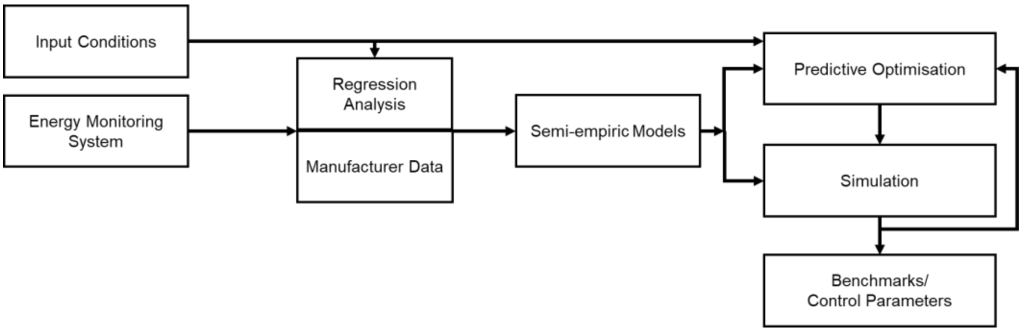

Figure 1*:* Methodology of simulation-based optimisation

The input conditions include the ambient temperature, the residual load and the electricity price for a production site. The energy monitoring system collects the operating data of the cold utility system for all occurring conditions. For the modelling of the utility manufacturer and performance data are combined and continuously adapted to form part-load performance curve models. For the compression chillers, the models are based on the EER, the condensing and evaporating temperature. The ambient temperature, the cold-water supply and return temperature and the EER are the main parameters for the free cooling chiller. Former studies show that even two structurally identical compression chillers perform differently in the same location (Brenner et al., 2014). This results in a need for empirical models for each utility system. In operating areas with a significant quantity of energy data, empirical models describe the system performance in the best way. Whereas, in areas of extrapolating semi-empirical models are more accurate. The linking of physical and empirical modelling ensures an acceptable accuracy in both fields of interpolating and extrapolating. Therefore, the compression and free cooling chiller models are based on the simpler multivariate polynomial regression model (SMP model).

2.1 Mathematical model

The optimisation is formulated as a mixed-integer linear programming (MILP). Since the control parameters of the chillers are discrete, the solutions must be integers. The goal of the optimisation is the optimal distribution of the cold-water demand to multiple chilling systems by having the lowest energy costs. In addition, the optimisation problem is solved for the sum of cold-water demands of N timesteps in the future. The sprinkler tank offers the opportunity to store cold water for later utilisation. This potential is used to show the load shifting potential of the cooling system by using a variable electricity price as an input parameter of the optimisation. The following equations describe the minimisation problem.

$$min \sum_{t=1}^{N_T} \sum_{n=1}^{N_{cc}} \sum_{st=1}^{N_{St}} (costs_{tnst}\, X_{tnst}) + SC_{tn}\, Z_{tn} \tag{1}$$

$$subject\ to\ \ X_{tnst} \in \{0,1\}\, , Z_{tn} \in \{0,1\} \tag{2}$$

$$\frac{T_{res}}{3600\frac{s}{h}} \cdot \sum_{t=2}^{N_T} \sum_{n=1}^{N_{cc}} \sum_{st=1}^{N_{St}} (CC_{tnst}\, X_{tnst}) \ \le\ Q_{pred} + Q_{plus} \tag{3}$$

$$\frac{T_{res}}{3600\frac{s}{h}} \cdot \sum_{t=2}^{N_T} \sum_{n=1}^{N_{cc}} \sum_{st=1}^{N_{St}} (CC_{tnst}\, X_{tnst}) \ \ge\ Q_{pred} - Q_{minus} \tag{4}$$

The different operating states (N_{St}) are between 0 and 100 % while the smallest step size is 1 %. The lower bound of the operating states and the step size are set by the used chilling machines. The number of chillers is defined by N_{cc}. The number of timesteps (N_T) describes the prediction horizon of the optimisation. For example, an N_T of 3 by a step size of 3,600 s means that the optimal load distribution is found for the sum of the loads of the current hour and the following two hours. Additionally, the starting costs (SC) consider the extra energy demand when starting a machine. Also, SC help to prevent an unnecessary starting and stopping of the machines if the gain in efficiency is very low. Equation 3 and 4 describe the constraints for the lower and upper bound of the optimisation. The total cooling supply by the chillers must be lower or equal to the total cooling demand of all timesteps and the cooling capacity of the sprinkler tank. Additionally, the total supply cannot be lower than the total cooling demand minus the current cooling power of the sprinkler tank.

2.2 Simulation

The results of the optimisation are the control parameters for each chilling machine in the current timestep. These parameters represent the operating schedule for the simulation. The set points from the optimisation are continuously validated by a dynamic simulation on the response and feedback effects from the system. These include thermal inertia of the cooling system, start-up characteristics as well as the physically modelled heat losses of the storage tank. There is also difference in the start-up characteristics for a compression chilling machine in the optimisation and the simulation. In the optimisation, the full cooling capacity of the chiller is immediately available due to the linear programming. Whereas, in the simulation, the chiller needs a few minutes to ramp to full capacity. Comprehensive measurements have shown that the ramp time can vary from one to five minutes or even longer for larger machines. The simulation compensates the limitation of the linear optimisation and verifies the operating schedule. Additionally, the complex heat loss mechanisms of a storage tank are modelled more accurate in a simulation than in a linear model. This method eliminates unrealistic starting points. The initial states of the optimisation are reset by the simulation results of the former timestep.

3. Plastic processing case study

The evaluation of the optimisation and the simulation is done by a case study on two plastic processing companies that produce injection moulded parts for the food sector. This requires high hygiene standards for the production hall. One is located in Germany and one in Spain. The injection moulding machines are cooled continuously by two different cooling circuits. On the one hand, the mould cooling circuit at a temperature level of about 14 °C and a machine cooling at about 30 °C. The relative high process cooling temperature of 14°C offers the opportunity to integrate free cooling chillers as well as multiple compression chillers. The refrigeration of the moulding circuit is carried out by two air-cooled compression chiller machines and a free cooling chiller which is also used for winter relief. The cooling of the machines is provided by cooling towers. Therefore, the predictive simulations-based optimisation is well suitable for the mould cooling circuit in the plastic processing industry. Moreover, the company has a 900 m³ sprinkler tank that can be used as a cold-water storage tank at a temperature level of 14 °C. The plastic processing companies often have large warehouses. Fire safety regulations require a quick access to a high volume of extinguishing water. In this study, the prediction horizon is 7 h and the step size is 1 h. The N_{CC} is 3 and the N_{ST} varies from 4 for the compression chillers to 9 for the free cooling chillers. The cooling demand is based on the measured data for the year 2017. The cooling demand varies between 0 and 145 kW. T_{Res} is equal to the step size. The maximum cooling energy stored in the cooling tank is fixed by the maximum temperature difference of 3 K and the 900 m³ of water. The limit is 3,140 kWh. The costs for the optimisation are calculated by the product of the current energy consumption of the chillers and the current spot market price for electricity. The prices vary between 75 and 150 €/MWh. The following table gives an overview of the installed cooling utilities.

Table 1: Utility systems of the plastic processing company

Utility	Quantity	Temperature level	Cooling capacity	Number of stages	Lower bound	Step size
Air-cooled scroll chiller	2	14 °C	200 kW	4	25 %	25 %
Free cooling chiller	1	14 °C	200 kW	9	1 %	10 %
Cooling towers	2	30 °C	250 kW	4	25 %	25 %
Sprinkler tank	1	14 °C	3,140 kWh	-	-	-

4. Results and Discussion

This study compares the results of three different scenarios. The reference scenario is based on the energy monitoring data of the plastic processing company. It represents the status quo of the control of the cooling system. In the second scenario, the company is located in Germany and purchases its electricity on the epex spot market to a variable price. In the third scenario, the same company is in Spain and orders its electricity for the same price as in Scenario 2. The cooling demand for moulding cooling circuit is in all three scenarios identical since hygiene standard forbids any window opening and therefore the production hall is air-conditioned to a design temperature of 21 °C. Choosing different locations enables showing the influence of the ambient temperature on the results of the optimisation. The following Figure 2 shows the sum of electrical power consumption of all three components for all scenarios in an exemplary month in a colder period.

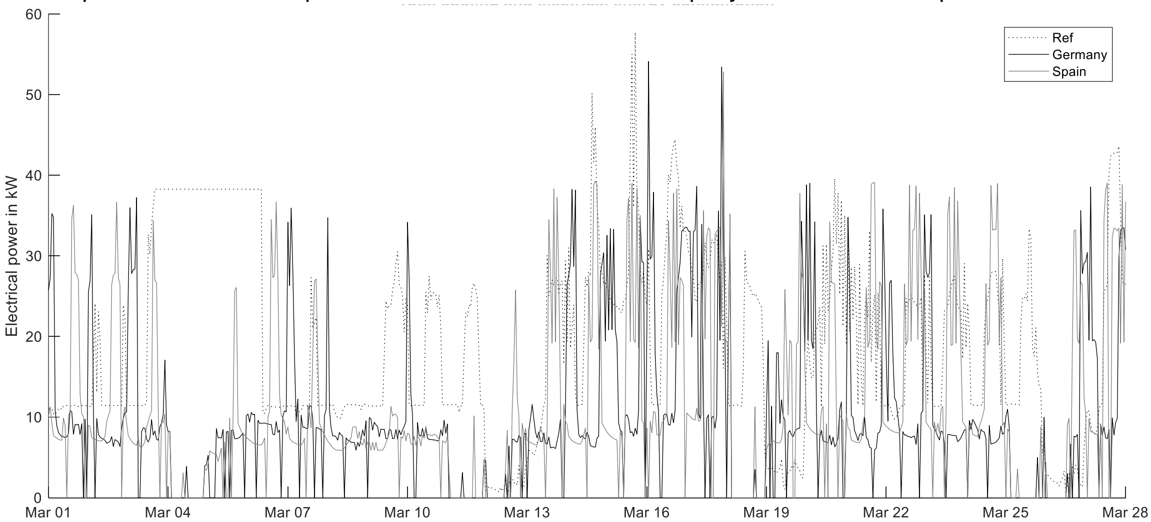

Figure 2: Electrical power consumption of all components in the colder period

The results show that in Scenario 2 the cooling utility system has the lowest electrical power consumption comparing to the other scenarios. The optimisation finds the operating points for all components with the lowest electrical energy costs to fulfil the cooling demand. In comparison to Scenario 3, the lower ambient temperatures lead to lower condensing temperatures for the compression chilling machines and more operating hours of the free cooling chiller. A reduced condenser load resulted in a more efficient operating compression chiller and the free cooling chiller has a significantly higher EER compared to the compression chiller.
Figure 3 visualises the same but for an exemplary month in a warmer period. In this period the electrical energy consumption in Scenario 3 is lower than in Scenario 2.

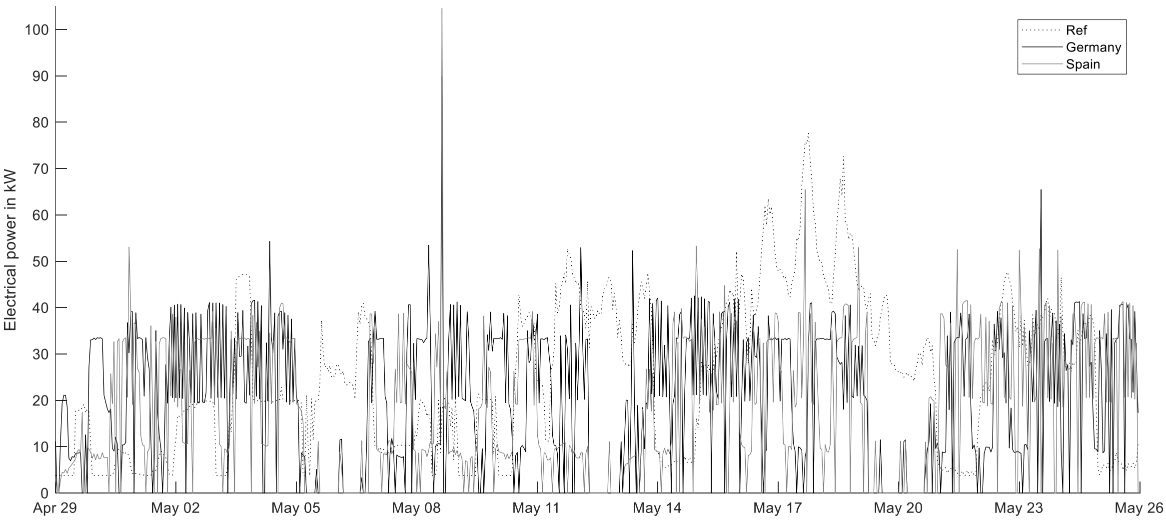

Figure 3: Electrical power consumption of all components in the warmer period

The mean ambient temperature in May in Spain is lower than in Germany. Additionally, the ambient temperatures are more often below 12 °C and this results in longer running hours of the free cooling chiller.
To benefit from purchasing electricity for a variable price it is reasonable to shift loads. The sprinkler tank enables the cold utility system to store cold-water in times of no or little demand. This allows the optimisation algorithm to start chillers in times of low electricity prices and stop the machines in times of high prices. This increases the optimisation options. The following figures show the quantity of cold water at 14 °C and 17° C in the tank for the same period as the previous figures. Additionally, the variable electricity price is shown.

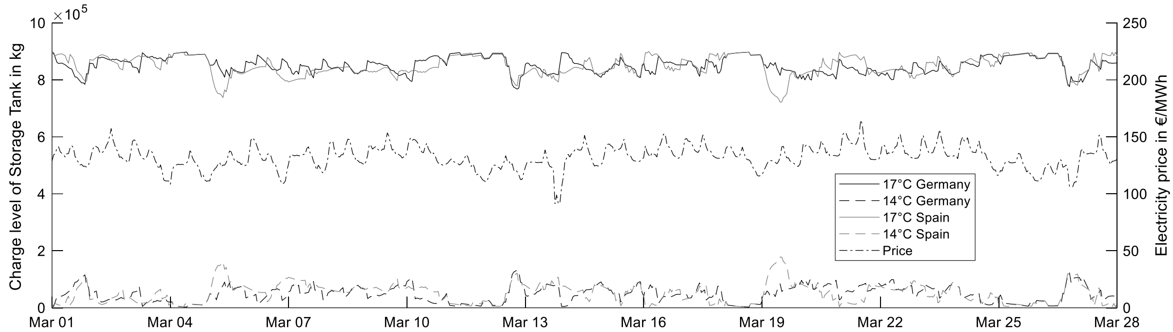

Figure 4: Charge level of sprinkler tank in the colder period

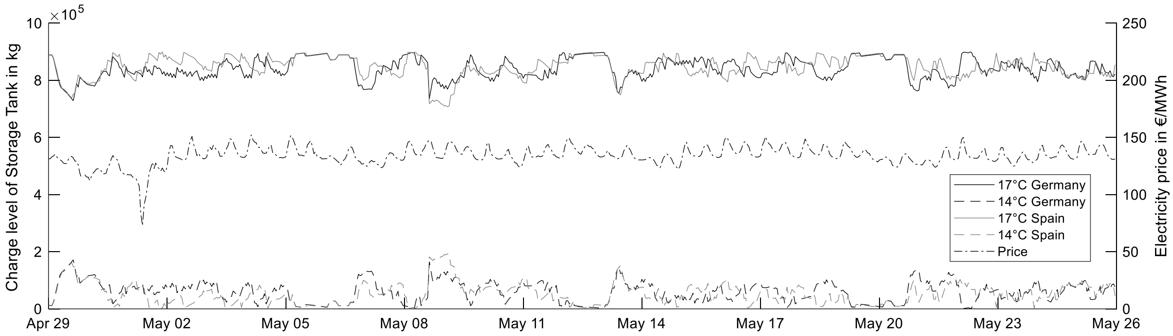

Figure 5: Charge level of sprinkler tank in the warmer period

The cold-water storage is more charged and discharged in the warmer period and in the location with higher ambient temperatures. The predictive optimisation algorithm cools down the storage tank in times of low ambient temperatures and low electricity costs. When the ambient temperature increases and the price rises, the moulding cooling circuit is supplied by the cold-water storage tank. This ensures that all components of the utility system operate when their efficiency is high. However, Figure 4 and 5 show that the variable electricity price has only a minor or no influence on the charging and discharging strategy of the system. A reduction of the electricity price between 1-30 % only reduces the total costs by this reduction. Increasing the running hours of the free cooling chiller or operating the compression chillers in better part-load ratios can reduce the total energy costs by 40 – 60 %. Buying electricity at a variable price has only minor benefits for the plastic processing company.

5. Conclusions

At times with a high share of renewable energy in the grid, the price is low and vice versa. This resulted in optimised operating conditions for the chillers in terms of load shifting and costs. The predictive simulation-based optimisation of a cooling system of a plastic processing company saves between 17 % in a warmer and 40 % in a colder period in Germany. For a location in Spain, the energy savings are between -11 % for a warmer and 11 % in a colder period in comparison to the optimisation in Germany. Including dynamic modelling in the optimisation ensured a more accurate result of the energy savings potential due to starting and switching times of the machines as well as heat transfer mechanisms of the storage tank. The optimisation strategy can be easily adapted to industrial cold utility systems by adapting the control system. The rules of control are defined by the different states of the cooling demand and the ambient temperature. The optimisation method can run offline and the results can be fed into a control loop. In addition, the integration of a variable electricity price and a large cold-water storage tank reduced the energy costs for the utility system, supporting the electrical grid by load shifting. For the analysed plastic processing company, the differences in the price for electricity are too low to have a significant influence on the cooling utility system. If the company should support the electrical grid and have an own benefit, the price differences need to be higher or extra incentives are necessary. A dynamization of the tax on electricity are a chance to increase the differences in the variable prices and make demand side management more attractive for medium sized companies.

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Nomenclature

N_{CC}	Number of chilling machines
N_T	timesteps
N_{ST}	Number of states of chilling machine
Q_{pred}	Total cooling demand for all timesteps
Q_{plus}	Cooling capacity of sprinkler tank
Q_{minus}	Current cooling power of sprinkler tank
SC	Starting Costs
T_{Res}	Simulation time
X_{tnst}	State of chilling machine
Z_{tn}	On/Off Variable

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