Sensitivity Analysis of Optimised Large Scale District Heating Heat Pump Concepts

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Abstract

This paper investigates the sensitivity on choice of heat pump concept to uncertainties and variations in boundary conditions for large scale heat pumps with a Danish district heating system as case example. A performance map-based heat pump model is used to evaluate performance of different heat pump concepts. The heat pump concepts are optimised in terms of concept design and prepared for evaluation of feedback control parameters and on/off strategies, which calls for a nonlinear optimiser such as genetic algorithms. The optimisation considers the operational price of the concept, regarding Coefficient Of Performance (COP), heating capacity and investment cost and is followed by investigations of the possibility for providing ancillary services. A sensitivity analysis is carried out to investigate whether, which and how variations in cost function weighting affects the optimisation and consequently the choice of heat pump concept. The results indicate a very robust optimised concept.

Keywords: heat pump modelling, large scale heat pumps, optimisation

1 Introduction

By 2050, Denmark should be completely independent of fossil fuels. One essential field in the solution of this is the synergy between the power- and heating grid. With the district heating sector having great potential to be included in solutions across energy sectors, large scale heat pumps have recently received increased interest since it in nature provides a power-to-heat conversion and since tax-reductions and potential for ancillary services likewise suggest large scale heat pumps as a favourable part of the solution (Kortegaard Støchkel et al., 2017). However, focusing on the Danish district heating system, the experience in implementing large scale heat pumps is very limited.

From (Rambøll et al., 2019) it was found that the heating capacity of most large scale units currently in operation in Denmark are in the order of 0.2-10 MW_q. As have been presented in the planned projects in (Fjernvarme Fyn and Odense Kommune, 2020) and (DIN Forsyning and Rambøll, 2020), heat pump units of significantly higher capacity (up to 100 MWq) is expected to be introduced in the Danish district heating system. A few examples of heat pump units with this high capacities can be found in Norway, (Hoffmann and Forbes Pearson, 2011) and Sweden (Friotherm AG, 2017), and common to these are that the desired capacity is achieved by a combination of a number of smaller heat pump units. There is however no unique formula on how to combine the units. As was stated in (Rambøll, 2019) and in (Meesenburg et al., 2018), especially when bearing the potential for ancillary services in mind, the design of the heat pump concept (i.e. the internal connections and the size of the individual units), should be considered carefully, which due to the lack of experience in ancillary services was found to be challenging.
(Rambøll, 2019) has additionally been conducting some tests of a 0.25 MW_e ammonia heat pump to investigate the potential for providing ancillary services. With the requirements for ancillary services valid for the eastern part of Denmark, it was found that when using the power consumption from the heat pump as set point for control, the response time improved significantly indicating that heat pumps can be applied for providing ancillary services. The experience is however still very limited, and a general approach for designing the large scale heat pump concepts has to the best of the author's knowledge, not yet been presented.

This paper presents a general approach for optimisation of heat pump concepts in future energy systems. The purpose is to develop and demonstrate a heat pump optimisation tool in order to locate the parameters, which dominates the choice of heat pump concept with regard to the number of heat pumps, the size of the heat pumps and the connections between them.

2 Method

To demonstrate the idea of the simulation and optimisation approach, an ongoing project in Esbjerg, Denmark, is used as case example. With boundary conditions and heat pump requirements set by the case, the modelling approach and the simulation- and optimisation setup was developed in three steps, which will be presented in the following sections as:

- A general representation of the heat pump performance.

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Table 1. The definition of the seven categories representing an example of the annual operation of the heat pump concept illustrated in Figure 1. Heat load corresponds to the relative amount of heat delivered in each category (in MWh_q) on a yearly basis i.a. category 1 is responsible for 2 % of the total amount of heat delivered during a year.

Category	T_{sea} [°C]	$T_{\text{dh,out}}$ [°C]	Heat load [%]	Ref. load [%]	α_i [DKK/year]	β_i [DKK/year]
C1	>10	50-55	2	59.8	638 385.0	82 839
C2		60-70	23	86.4	9 077 708.9	
C3	6-10	50-55	14	59.4	5 681 650.3	406 225
C4		60-70	11	69.2	4 600 325.3	
C5	2-6	60-70	39	89.9	17 502 111.2	9 658 168
C6		50-55	3	90.6	1 153 986.	
C7	<2	50-55	9	95.2	4 132 657.0	5 164 456

- A dynamic model.
- A suitable heat pump concept optimisation.

2.1 Case study: Esbjerg District Heating

In Esbjerg, Denmark, a 460 MW_q coal fired heat- and power plant is set to close in March 2023. A considerable amount of heat pumps are included in the road-map for installation of the new heating production. A 50 MW_q sea water based heat pump unit is among other things expected to operate along with wood chip boilers, electric boilers and gas boilers (DIN Forsyning and Rambøll, 2020).
As a part of the initial study of a possible solution, the 50 MW_q is delivered from a heat pump concept consisting of four 12.5 MW_q sea water heat pump units connected internally as seen in Figure 1.

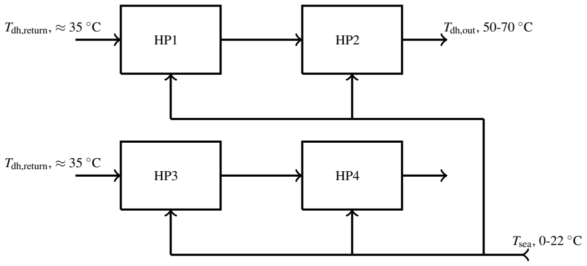

Figure 1. Reference heat pump concept with four 12.5 MW_q heat pumps with two parallel strings each with two heat pumps in series.

The heat pump concept in Figure 1 is referred to as the reference concept. Data on an example of the expected operation of this concept is applied for the heat pump concept optimisation. Divided into seven categories, the annual operation can be considered as seen in Table 1. The categories are chosen instead of the full annual operational profile to smooth out the build in bias towards the reference concept to which the operating profile is optimised. The heat demand presented in Table 1 forms the operating conditions for the simulations conducted. Notice, that these categories change, if the heat pumps are combined with e.g. wind power or combined heat and power plants. The heat pump system used for simulation is presented in the following sections.

2.2 Model

The heat pump model and the simulation model is formulated in the multi-domain, object oriented modelling language, Modelica (Modelica Association, 2019) and implemented in Dymola (Dassault Systémes, 2019). The heat pump system makes use of pipe, flow source/sink and sensor models found in the Buildings library (Wetter et al., 2014). Using the Modelica language implies a high degree of reusability and flexibility in the modeling and does further allow for easily exporting the model as a functional mockup unit (FMI) and further simulating the model in e.g. Python through the functional mockup interface (FMI) standard.

2.2.1 Heat pump model

As suggested in (Dott et al., 2013) and similarly applied in the energy simulation software EnergyPlus (Department of energy, 2019), a typical approach for performance evaluation of heat pumps is by a *performance map*. A common method for applying the performance map approach is to use data points either to interpolate between or by using an equation fit to create a polynomial plane. Inspired by this, the performance of the heat pump model is described by two equations developed from data obtained using the product selection software, GEA RTSelect, provided by GEA (GEA Group, 2019). The performance map describes the heat output, $\dot{Q}_\text{h}$ and the Coefficient of Performance, COP of a single heat pump unit. The performance degradation due to part load operation is included in the performance map by introducing both the desired outlet temperature of the district heating water, $T_{\text{dh,out}}$ [K], the evaporation temperature, T_{eva} [K] and load, L [%] as variables for the equation fit.

By stepwise including the three variables to the fit of the performance data, Equation 1 and Equation 2 was created using R (R Foundation, 2019).

$$\begin{aligned}\dot{Q}_\text{h} &= \theta_0 + \theta_1 L + \theta_2 L^2 + \theta_3 T_{\text{eva}} \\ &\quad + \theta_4 T_{\text{dh,out}} + \theta_5 L T_{\text{dh,out}} + \theta_6 L T_{\text{eva}}\end{aligned} \tag{1}$$

With θ_i and γ_i being the regression coefficients found in Table 2 and Table 3. Applying Equation 1 to test data showed a maximum deviation of ≈ 5 %. A similar test on the validity of Equation 2 shows a maximum deviation of ≈ 7 %. It should additionally be noticed, that the

Table 2. Values of the regression coefficients, θ for the equation fit of the heat output.

θ_0	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
- 241 000	- 1 063 000	70.96	-1 667	10 030	4001	306.7

map (Equation 1 and Equation 2) is only guaranteed valid within the range of the data. This corresponds to a district heating outlet temperature between 45 °C and 80 °C and a sea water temperature between 2 °C and 17 °C.

$$\begin{aligned}\mathrm{COP} = {} & (\gamma_0 - \gamma_1 \exp(-\gamma_2 L)) + \gamma_3 T_{\mathrm{eva}} + \gamma_4 T_{\mathrm{eva}}^2 \\ & + \gamma_5 (\gamma_0 - \gamma_1 \exp(-\gamma_2 L)) T_{\mathrm{eva}} + \gamma_6 T_{\mathrm{dh,out}} + \gamma_7 T_{\mathrm{dh,out}}^2 \\ & + \gamma_8 (\gamma_0 - \gamma_1 \exp(-\gamma_2 L)) T_{\mathrm{dh,out}} + \gamma_9 T_{\mathrm{eva}} T_{\mathrm{dh,out}}\end{aligned} \tag{2}$$

At a constant evaporation temperature of 5 °C, the surface of Equation 2 is seen in Figure 2. Equation 1 and Equation 2 form the basis of the heat pump model in Dymola.

The heat pump model consists mainly of three components: a *heat moving component*, a pipe representing the condenser and a pipe representing the evaporator, as seen in Figure 3.

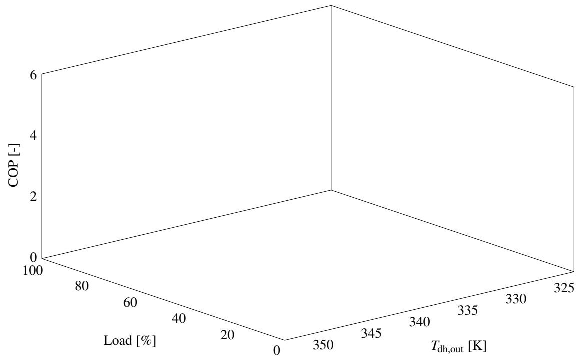

Figure 2. Surface plot of the regression equation for COP, with a evaporation temperature of 5 °C.

The *heat moving component* includes the performance map described by Equation 1 and Equation 2 and the correlations presented in Equation 3 and Equation 4.

$$\dot{Q}_{\mathrm{c}} = P(\mathrm{COP} - 1) \tag{3}$$

$$P = \dot{Q}_{\mathrm{h}} - \dot{Q}_{\mathrm{c}} \tag{4}$$

The combination of Equation 1 to Equation 4 represents the amount of heat added to the condenser pipe, the amount of heat removed from the evaporator pipe and the electricity consumed by the heat pump unit. The two pipes are found from the buildings library and allow for adding/extracting a prescribed heat flow to the fluid flow in the pipe. Using the buildings library, (Wetter et al., 2014), additionally provides a simplified medium model (assuming constant density) which improves the simulation time.

The performance map approach and the chosen Modelica formulation do however not include any information on the dynamic behaviour of the heat pump unit. For the compressor, the dynamic effects are accounted for by limiting the allowable load gradients corresponding to $t_{\text{min-max}} = 120s$ and $t_{\text{max-min}} = 60s$. Notice that this is not the actual compressor dynamics, but represents the effect of the dynamics related to the compressor.

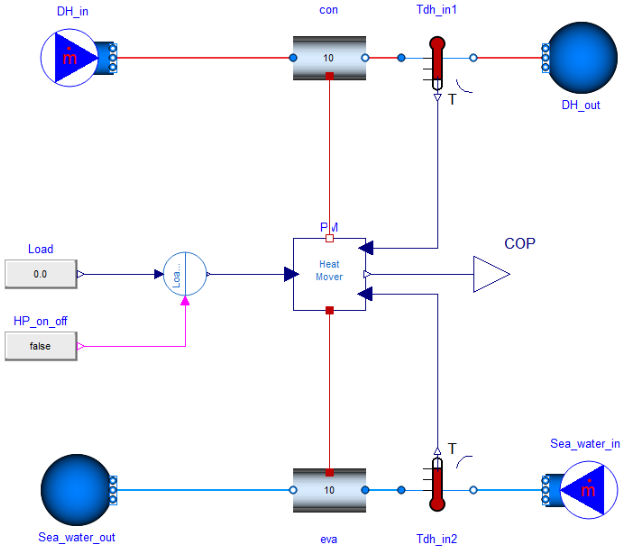

Figure 3. Simplified sketch of the heat pump unit i Dymola. The heat mover contains the performance map equations.

In (Farouk Fardoun et al., 2011) it was however found that the dominating dynamic is related to the heat exchangers and not the compressor. The dynamic in the heat exchangers is accounted for by the volume of the pipes representing the heat exchangers, which is set to ≈ 4 m^3.

2.2.2 Heat Pump System

The heat pump model described in the previous section forms the base of the model used for simulation and following optimisation. The general idea of the simulation model is sketched in Figure 4. Based on the total $50\mathrm{MW}_{\mathrm{q}}$ heat requirement for the case in Esbjerg, a maximum of nine units is assumed. The nine heat pump units can be arranged with maximum three parallel strings each with maximum three heat pumps in series. As appears from Figure 4, each heat pump unit has its own mass flow source. However, the flow in each parallel string is identical, and the individual mass flow sources are introduced to avoid including dynamic effects of heat pumps, which are not included in the concept when performing the optimisation.

Table 3. Values of the regression coefficients, γ for the equation fit of the COP.

γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9
- 12.52	3.076	-0.074	0.710	0.001	0.030	-0.474	0.001	-0.024	-0.002

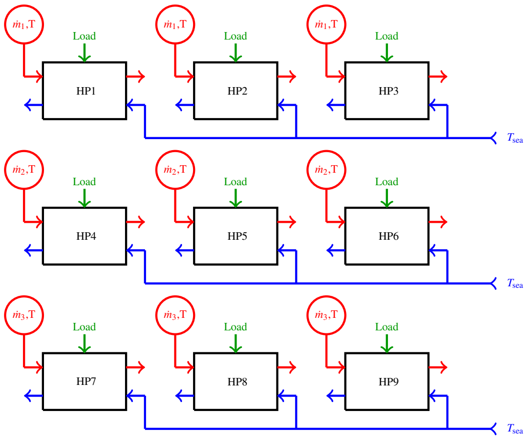

Figure 4. Simplified sketch of the heat pump concept simulation model with nine possible heat pumps with a maximum 3-by-3 configuration.

2.2.3 Control

Depending on whether the heat pump concepts are evaluated according to their COP, heating capacity or dynamic response, different requirements or approaches exists. For evaluation of COP and heating capacity, both load control and temperature control are applied. The temperature control adjusts the mass flow rate of the district heating water to achieve the desired outlet temperature. This control is only applied for the evaluation of COP and heating capacity.

For the load control, two approaches can be used: heat output control or power consumption control. The heat output control is applied for steady state evaluation of the COP and heating capacity, while the power consumption control can be applied for evaluation of dynamic performance. Last mentioned is especially an advantage when considering ancillary services, since this was found to allow for faster regulation (Rambøll, 2019).

3 Heat Pump Concept Optimisation

From the heat pump simulation model in Section 2, the optimisation presented in this paper seeks to find the optimum heat pump concept according to its steady state COP, heat output and the depreciation expense.

3.1 The Concept Optimisation Problem

The vector **u** contains the optimisation variables.

$$\mathbf{u} = \{\dot{Q}_{\text{h,n},1}, \dot{Q}_{\text{h,n},2}, \dots, \dot{Q}_{\text{h,n},9}\}$$

With $\dot{Q}_{\text{h,n},i}$ representing the nominal heating capacity of a heat pump unit, $0 < \dot{Q}_{\text{h,n},i} < 18.5\ \text{MW}_\text{q}$. All units with $\dot{Q}_{\text{h,n},i} \leq 2$ are truncated to 0, and is consequently not included in the concept. The annual expenses include the costs related to COP, the total heating capacity of the concept and the total depreciation expenses. Based on the case in Esbjerg, the expected operation and the expected performance of the reference concept give rise to some expected costs. Changing the reference concept in Figure 1 will in most cases also change its performance, and the investment cost. The concept optimisation problem can be formulated as seen in Equation 5.

$$\begin{aligned} \underset{\mathbf{u}}{\text{minimise}} \quad & \text{COST}_\text{HP} \\ \text{subject to} \quad & \dot{x}(t) = f(\mathbf{V}, \mathbf{u}, \mathbf{x}(t)), \\ & \mathbf{G}\,\mathbf{u} \geq \mathbf{g}, \\ & \mathbf{x}(0) \geq \mathbf{x_0} \end{aligned} \tag{5}$$

With COST_HP representing the annual costs for the heat pump, $\mathbf{x} \in \mathbb{R}^q$ being the system state vector and $\mathbf{V} \in \mathbb{R}^m$ the input vector with external boundary conditions. The nonlinear, dynamic model formulated in Dymola, is represented by f, and the constraints in the matrix **G** and vector **g**.

3.2 Micro-Genetic Algorithm

Due to the non-linearity of the optimisation problem, there could be multiple local suprema, and a global optimisation method must consequently be applied. For this purpose, the μGA proposed in (Krishnakumar, 1990), seen in Figure 5 is proposed and the specific parameters are based on suggestions from (Vinther et al., 2017).

Initialisation

Using a population size of $N_s = 5$, individuals are picked randomly from a normal distribution with center defined by the best solution so far and with a standard deviation set to 50 % of the distance between minimum and maximum bounds of the optimisation variables. Additionally, the picked parameter is truncated to be within the min/max bounds, which means that the odds for picking values close to the current best solution and at the bounds increase.

Automatic restart

To avoid getting stuck at a local optimum, an automatic restart is triggered whenever the individuals are converged. This happens when all pairs in all individuals are within 5 % of their full range. The automatic restart mean that new individuals are picked as presented in the previous section while keeping the best (elite) individual.

Fitness evaluation

The fitness of each individual is calculated using a cost function.

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Deterministic Tournament Selection

Two individuals are picked randomly from the population and the most fit of the picked individuals are chosen as a parent for crossover.

Crossover - Gaussian Fitness Based

New individuals (children) are produced from the parents. This is done by randomly picking values from a normal distribution with center closest to the fittest parent and the standard deviation set to 50 % of the distance between the parents.

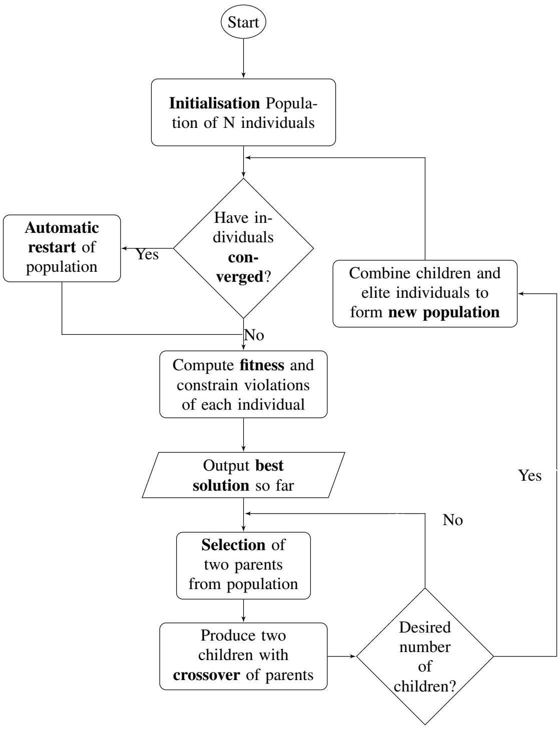


Figure 5. Flow chart of the μGA used for the optimisation of the heat pump concept.

3.3 Cost Function

To evaluate the fitness of different heat pump concepts according to their COP, heating capacity and investment cost, the cost function in Equation 6 is introduced.

$$\mathrm{COST_{HP}} = \mathrm{COST_{COP}} + \mathrm{COST_{Heat}} + \mathrm{COST_{CAPEX}} \quad (6)$$

The general idea of the cost function in Equation 6 is to represent the difference in annual cost between the reference concept in Figure 1 and the concept in question. Descriptions of each term in Equation 6 (COP, heating capacity and investment cost) are presented in the following sections.

3.3.1 Cost: Coefficient of Performance

Increasing the COP compared to the reference concept leads to an overall reduction in electricity consumption from the heat pumps and vice versa. The steady state COP is evaluated in each of the seven categories presented in Table 1 as seen in Equation 7.

$$\mathrm{COST_{COP}} = \sum_{i=1}^{7} \alpha_1 \left(1 - \frac{\mathrm{COP}_i}{\mathrm{COP}_{\mathrm{ref},i}}\right) \quad (7)$$

The unit of the coefficients, α_i, is in DKK/year, and represents the cost penalty or profit achieved from either reductions or improvements in COP, weighted according to the energy content in each category as seen in Table 1. This assures, that the highest profit or penalty is associated with the category with the highest heating demand.

3.3.2 Cost: Heating Capacity

Combining category 1 and 2, 3 and 4, 5 and 6 and keeping category 7 from Table 1 forms the boundary conditions applied for the evaluation of the heating capacity. In each of these categories, the reference concept is capable of delivering 66.7 $\mathrm{MW_q}$, 55.8 $\mathrm{MW_q}$, 49.3 $\mathrm{MW_q}$ and 44.3 $\mathrm{MW_q}$ respectively. These maximum capacities are used as a benchmark for the evaluation of the heating capacity. If the capacity of the heat pumps is reduced, other units (gas boiler, wood chip boiler etc.), must compensate leading to increased costs. On the other hand, increasing the capacity is undesirable, meaning that no profit can be achieved by increasing this. The cost function describing the heating capacity is seen in Equation 8.

$$\mathrm{COST_{heat}} = \sum_{i=1}^{4} \max\left(0, \beta_1 \left(1 - \frac{\dot{Q}_{\mathrm{h},i}}{\dot{Q}_{\mathrm{h,ref},i}}\right)\right) \quad (8)$$

Similar to Equation 7 for COP, the β_i coefficients are weighted according to the heating load in each category. The values of α_i and β_i are found in Table 1.

3.3.3 Cost: Investment and Depreciation Expense

The reference price and the assumed effects of economy of scale are based on numbers presented by (Danish Energy Agency and Energinet, 2016). This mean, that the reference price is based on a 4 $\mathrm{MW_q}$ heat pump with a cost of 4.95 MDKK/MWq. The effect of economy of scale is set to 0.8. Based on this, the total investment cost is described by Equation 9

$$\mathrm{COST_{inv}} = \sum_{i=1}^{9} 6e6\, \dot{Q}_{\mathrm{h,n},i}^{0.848} \quad (9)$$

Expressing the investment cost relative to the reference case and in terms of depreciation expense results in Equation 10. A 20 year annuity with an interest rate of 1.8 % is assumed.

$$\mathrm{COST_{CAPEX}} = (0.06\,\mathrm{COST_{inv}} - 0.06\,\mathrm{COST_{inv,ref}}) \quad (10)$$

4 Results and Discussion

4.1 Optimisation

The optimisation is initially conducted using the cost function as it is described in the previous section, with a maximum allowable heat pump unit size of 18.5 $\mathrm{MW_q}$.

4.1.1 Convergence

One challenge when optimising a non-linear system, is to ensure that the suggested optimum is a global optimum. The optimisation allows the modeller to provide some guesses on heat pump concepts for the initial generation. However, if a global optimum is found, the end result both with and without a guess on a heat pump concept should be consistent. For a 500 generation run this was tested and the result is presented in Figure 6.

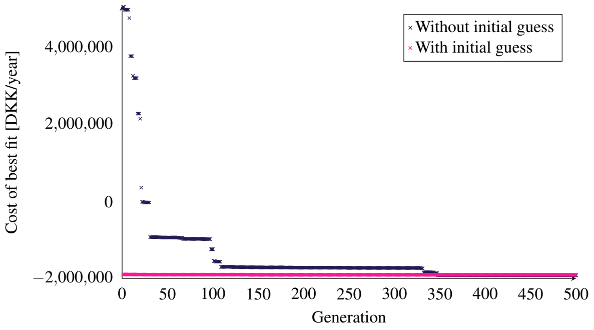


Figure 6. Convergenve plot showing the cost of the best fit during 500 generation test runs with and without initial guesses.

Figure 6 shows that the end results are consistent when running 500 generations with and without initial guesses. This indicates that a global optimum has been reached. Figure 6 also indicates, that the number of required generations reduces significantly, when the initial guess is close to the optimum. However, care must be taken for a low number of generations as this might lead to a local optimum.

4.1.2 Optimised Heat Pump Concept

A sketch of the optimised heat pump concept is seen in Figure 7.

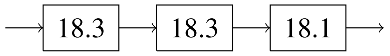


Figure 7. A sketch of the optimised heat pump concept. The numbers inside the each heat pump box represent the chosen nominal capacity of the heat pump.

As seen from Figure 7, the optimum heat pump concept at the given conditions consists of three heat pump units in series each with a capacity of ≈ 18.2 MW_q. Notice, that these heating capacities sum to ≈ 54.5 MW_q, which is due to the different nominal conditions assumed for the performance map. The costs for the optimised concept are allocated as seen in Table 4.

Table 4. Cost allocation for the optimised heat pump concept.

Cost [DKK/year]	Optimised concept
$Cost_{COP}$	- 1 385 935
$Cost_{heat}$	1417
$Cost_{Invest}$	- 501 896
Total Cost	-1 886 414

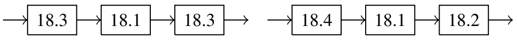
Compared to the reference the results show, that by increasing the number of heat pumps in series to three instead of two, the COP improves. This is consistent with expectations. At the same time, the cost pr. MW_q reduces due to the increased unit size and the reduced number of units.

4.2 Sensitivity Study

The results of the optimisation provides the best possible concept in terms of COP, heating capacity and investment cost. However, from the investors point of view the robustness of the optimised concept is not insignificant. To demonstrate the capability of the simulation model- and optimisation setup, a sensitivity on 3 parameters related to the cost function will be presented in the following sections.

4.2.1 Variations in Costs for Electricity

The penalty/profit related to reductions or improvements in COP is based on the expected costs for electricity. Consequently, changes in the expected cost for electricity naturally leads to changes in the total annual costs for the heat pump concept. A significant change of ± 40 % was considered initially. The results of the two optimisations are presented in Figure 8.



(a) Elspot + 40 % **(b)** Elspot - 40 %

Figure 8. A sketch of the optimised heat pump concept, when the estimations of the expected elspot price is reduced by - 40 % (fig. a) and increased by + 40 % (fig. b).

The optimum concepts for both an increase and a reduction in costs for electricity are, as seen in Figure 8, similar to the concept found from the original optimisation. The costs are allocated as seen in Table 5.

Table 5. Cost allocation for optimisation with the cost for electricity increased by 40 % and reduced by 40 %.

Cost [DKK/year]	+ 40 %	- 40 %
$Cost_{COP}$	- 1 728 332	- 1 078 343
$Cost_{heat}$	2 889	1 728
$Cost_{Invest}$	- 503 097	- 502 245
Total Cost	- 2 228 542	- 1 578 865

Since the concepts are similar to the concept found from the original optimisation, the costs regarding heating capacity and investment are similar as well. As expected, an increase in costs for electricity increases the profit achieved by improving the COP, whereas reduced costs for electricity reduces the profit achieved from improving the COP. With three large units, the investment costs are at a minimum due to the effects of economy of scale, and since the COP is maximised by connecting the three large heat pump units in series, the result is consistent with expectations.

4.2.2 Adjusting the Benchmark for Investment Cost

The investment costs in the initial optimisation is based on the numbers presented in (Danish Energy Agency and Energinet, 2016). However, a lower cost estimation and a higher cost estimation is presented as well. Similar to the electricity costs, adjusting the benchmark for the investment costs does not change the design of the optimised heat pump concept, meaning that the the result of the optimisation again suggest three serial coupled heat pumps of ≈ 18.2 MW_q. The costs are allocated as seen in Table 6.

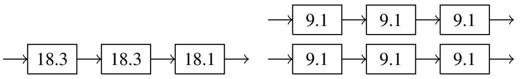
Table 6. Cost allocation for optimisation with the low cost estimation benchmark and with the high cost estimation benchmark (Danish Energy Agency and Energinet, 2016).

Cost [DKK/year]	Low benchmark	High benchmark
$Cost_{COP}$	- 1 403 569	- 1409 097
$Cost_{heat}$	1 306	74 784
$Cost_{Invest}$	- 336 398	- 922 706
Total Cost	- 1 738 661	- 2 257 019

Observing the investment costs, the low benchmark produces a reduction in the effect of investment cost whereas the high benchmark increases the profit from choosing the concept with the lowest possible investment costs. On the other hand, the increased investment reference price implies that the optimisation reduces the capacity to a minimum in order to achieve the highest investment cost profit.

4.2.3 Changes in Effects of Economy of Scale

The assumed economy of scale-effect of 0.8 is as the last parameter varied. Firstly by increasing the effect to 0.5, meaning that a doubling of the heat pump capacity only give rise to a 50 % cost increase. Secondly the effect of economy of scale was removed completely. The optimum concepts under these conditions are seen in Figure 9.



(a) EOS = 50 % **(b)** No effects of EOS

Figure 9. A sketch of the optimised heat pump concept, when the effects of economy of scale are incresed to 50 % (fig. a) or removed completely (fig. b).

The noticeable result from this optimisation, is that removing the effects of economy of scale, does, contrary to all other sensitivities conducted, produce a different optimised heat pump concept. The reason for this becomes more apparent when considering the cost allocations presented in Table 7.

Table 7. Cost allocation for optimisation with increased effects of economy of scale (0.5) and with no effects of economy of scale.

Cost [DKK/year]	EOS = 0.5	EOS = 1
$Cost_{COP}$	- 1 403 654	- 1 721 945
$Cost_{heat}$	1 703	52 540
$Cost_{Invest}$	- 777 417	38 286
Total Cost	- 2 179 368	- 1 631 119

By having two parallel strings instead of one as suggested in the original optimisation, the profit from COP increases from $\approx$ 1.4 million DKK/year to $\approx$ 1.7 million DKK/year. The reason for this can be found in the chosen control strategy, which ensures that whenever more than one string is present in the heat pump concept, the second string, third string etc. will remain inactivated until the first parallel string reaches 100 % load. The apparent consequence of this is that the COP during the first categories increases due to increased load-levels caused by the reduced activated capacity, when the second string has not yet been activated. On the other hand, removing the effect of EOS makes it impossible to achieve any profits in terms of investment costs and for that reason, the total annual savings are slightly less than for the original optimisation.

One noticeable potential achieved from the combination of the dynamic model in Dymola and the chosen optimisation algorithm is that it allows to include a wide number of parameters in the optimisation. In this paper, only the steady state COP, heating capacity and investment costs of the heat pump concept are included. However, the setup has the potential to include Dynamic effects as e.g. control parameters and ancillary services as well. Parameters as maintenance and ensuring redundancy would most likely also affect the final choice of heat pump concept. Last mentioned is especially interesting regarding the concept suggested by the optimisation, since it has only a single parallel string. A consequence of this is that in order to ensure redundancy, extra piping etc. for bypass would be necessary, which in the end increases the investment costs. Additionally, requirements and potential limitations defined by the heat pump suppliers could furthermore influence the result of the optimisation. These effects could, similar to dynamic effects and control strategies be included in the optimisation if it is quantified.

To demonstrate, that other parameters such as the potential for providing ancillary services might affect the optimisation results, a small capacity test on the reference concept and the optimised concept was conducted. Assuming that during ancillary services, the maximum capacity provided corresponds to one parallel heat pump string running at 10 % load. For the reference concept this corresponds to a maximum regulation capacity of 11.1 MW_e while the optimised concept has a maximum of 10.4 MW_e. The question is whether this difference in capacity for bids affects the annual costs for the concept. Assuming the following availability payments (Energinet, 2019), the difference in annual profit from availability payments are found in Figure 10:

- FCR_{up} = 276 DKK/MW_e/h
- FCR_{down} = 26 DKK/MW_e/h
- aFRR = 150 DKK/MW_e/h

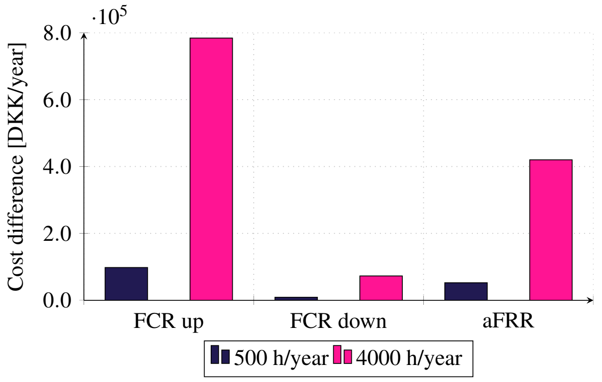


Figure 10. Lost availability payment from ancillary services relative to reference concept for 500 h/year and 4000 h/year respectively.

Figure 10 illustrates first of all that the difference in potential availability payment depends on the amount of hours won. Secondly, it can be seen that if assuming 4000 availability hours per year, the difference in maximum capacity implies a significant profit increase for the reference case.

5 Conclusion

A heat pump concept optimisation setup was developed and demonstrated based on an ongoing project in Esbjerg. The combination of a dynamic model formulated in Dymola and the micro-genetic algorithm formulated in Python was found to be a promising tool for heat pump concept optimisation, especially due to the potential to include everything from the relatively simple steady state COP evaluations presented in this paper, to more complex dynamic effects as control parameters and ancillary services.
The sensitivity analysis indicated that with the optimisation variables and cost functions presented in this study, the optimised heat pump concept is very robust to changes in both costs for electricity and the basis of the calculation of the investment costs. Removing the effects of economy of scale does however change the optimum concept from a single heat pump string with three large scale heat pump to a concept with two parallel strings each with three heat pumps in series.

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