

Reducing energy consumption by designing for chiller efficiency

Bernard Bekker¹ and Paul Carew¹

¹PJ Carew Consulting, Cape Town

Corresponding email: hello@pjc.co.za

SUMMARY

Chillers are responsible for a large percentage of the total electricity consumption of typical office buildings in temperate climates. A strong motivation therefore exists to improve their operational efficiency.

Factors that impact chiller efficiency are often dynamic, like the heat rejection temperature, supply water temperature and percentage loading, and different types of chillers respond very differently to variations in these factors. Industry metrics like the Integrated Part Load Value (IPLV) attempts to capture the impact of some of these efficiency-influencing factors, but with limited success due to the dynamic nature of these factors.

This paper demonstrates that significant energy savings can result if chiller selection, sizing and staging acknowledges these dynamic chiller efficiency dependencies. In order to do this, a visual process is proposed that matches chiller efficiency dependencies to the required building load and climatic context.

INTRODUCTION

In South Africa and other temperate climates, the cost of installing air conditioning systems are often disproportionately small compared to their contribution to the total electricity consumption of typical office buildings, as indicated in Figure 1 a) and b). As the cost of electricity increases, as is currently happening in South Africa, the incentive becomes stronger to maximize the operational efficiency of these air conditioning systems.

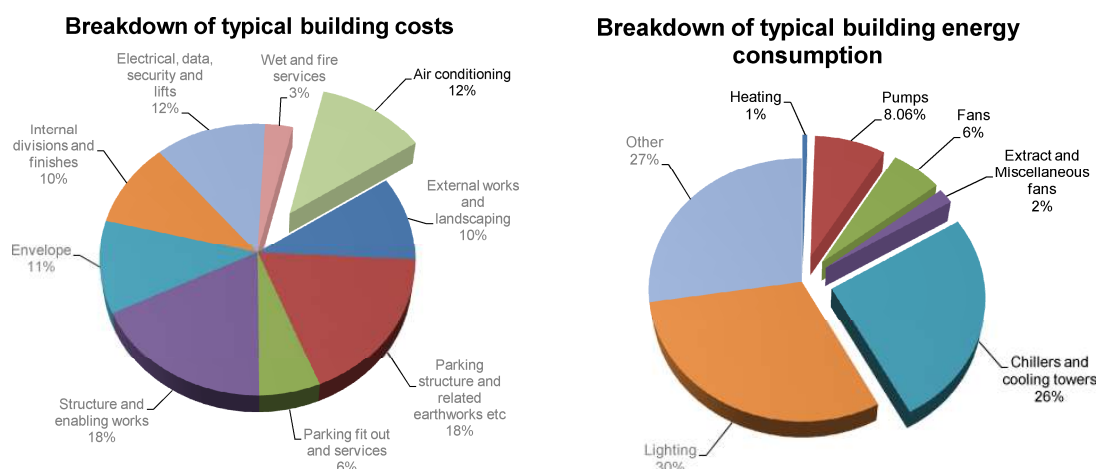


Figure 1. a) The contribution of air conditioning systems to a) the total building cost and b) electricity consumption of typical new medium-sized office buildings in South Africa [1].

The research presented in this paper focuses specifically on chillers: as can be seen in Figure 1 b) chillers are typically the air conditioning system components that consume most energy; lowering this consumption can dramatically impact total building consumption.

Another reason for focusing on chillers is based on our experience as passive and low energy design consultants for the building industry: chiller type, sizing and staging are often decided upon only based on parameters like price, peak COP¹, conventional wisdom and manufacturer preference. There is little understanding of the factors that influence chiller efficiency, sometimes significantly.

Attempts have been made to acknowledge some of these factors through industry metrics like the IPLV, which takes the impact of percentage loading into account to a limited degree by taking a weighted average of the chiller COPs at various part-loads [2]. These metrics are however incapable of representing the dynamic nature of these factors.

Within this context then, this paper's objective is to demonstrate that significant energy savings can result if chiller selection, sizing and staging acknowledge these dynamic chiller efficiency dependencies. In order to do this, a visual process is proposed that matches chiller efficiency dependencies to the required building load and climatic context.

Efficiency dependencies of individual chillers

Parameters that influence individual chiller efficiency include climatic dependencies like the *heat rejection temperature*, which for air-based chillers is the dry bulb temperature (Tdb), and for water-based chillers is the cooling water temperature (approximated as the wet-bulb temperature minus the design approach temperature of the cooling tower).

System and load dependencies also impact chiller efficiency, like the *percentage loading of the chiller* (part load or % loading), the *supply water temperature* and the *type of chiller*.

The curves in Figures 2 demonstrate the impact of the heat rejection temperature (Tdb for air-cooled chillers) and % loading on the efficiency (COP) of three distinct types of air-cooled chillers: micro-centrifugal, scroll and screw. The shape of COP curves like these vary widely for different chiller sizes and manufacturers: the ones shown here are well suited to this paper's objectives, but are not necessarily typical for the specific chiller types.

Efficiency dependencies of staging multiple chillers

Where multiple chillers are used, the choice of the *staging strategy* that defines when to use which chiller will impact the total efficiency of the combined chillers.

Two basic and simple to implement control strategies are shown in Figure 3 a) and b). In a) the first chiller of three equally sized chillers² will supply small building loads up to its maximum capacity (or a preset maximum % loading), at which point chiller 2 is added until it too reaches its peak, etc. In b), all three equally sized chillers are linked and increase their loadings equally as the system load increases.

¹ Coefficient of performance, defined as the cooling kW produced for each electrical kW consumed.

² Only the staging of equally sized chillers will be considered in this paper, in order to avoid the additional complexity from including "swing-chiller" type asymmetric designs [3]. This will avoid detracting from the paper's central objective: demonstrating the benefits of acknowledging efficiency dependencies.

These two basic staging strategies ignore the dependency of chiller COP on the heat rejection supply water temperature, and only acknowledge the impact of % loading to a very limited extent, through the selection of the preset maximum % loading.

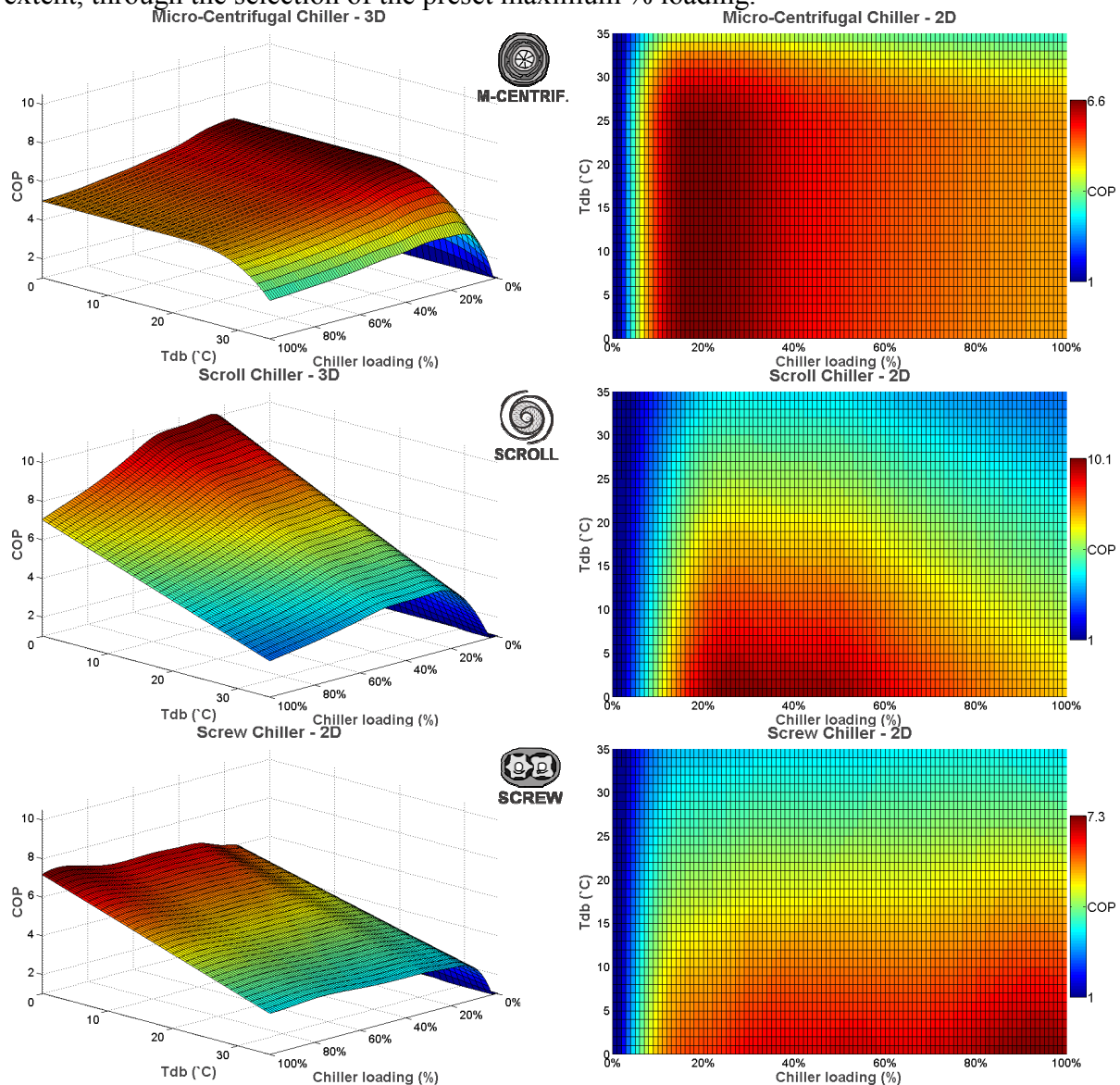


Figure 2. Impact of heat rejection temperature and % loading on the COP of different types of air-cooled chillers in the 450-650kW range: a) micro-centrifugal, b) scroll and c) screw

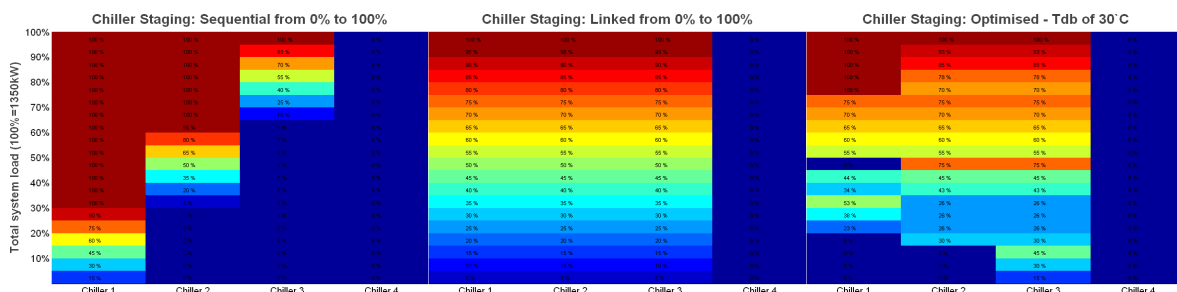


Figure 3. Three staging control strategies, using three equally sized chillers: basic a) sequential [5] and b) linked staging, insensitive to changes in rejection heat and water supply temperature, and c) COP-optimised staging, shown here for a Tdb value of 30 deg Celsius.

In the case of COP-optimised staging, as shown in Figure 3 c), the staging algorithm ensures that the most efficient combination of chiller loadings are used for every variation in total system loading, by acknowledging heat rejection and supply temperatures, and % loading.

METHODS

Climate and building loads

The simulations in this paper was done within the climate of Pretoria, South Africa, as shown in Figure 4: this temperate climate has the characteristic of a relatively wide Tdb range within which cooling is required, and is therefore well suited for this demonstration.

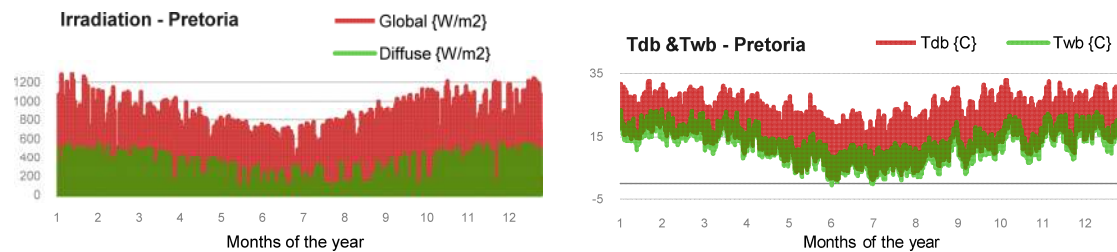


Figure 4. Yearly variations in solar irradiation and temperatures for Pretoria, South Africa [5]

In order to best demonstrate the impact of chiller efficiency dependencies, two extremes of building load datasets were generated: the first dataset with a high peak load but low average load, and the second dataset with a flatter and more constant load.

The same design building, with regards to structure, layout and envelope was used in both cases. This building is oriented 7° off North as shown in Figure 5, and has been modeled in Energy Plus to have a repetitive floor plan of six levels, three control zones each, with each floor having 3900mm floor to ceiling heights.

In order to generate the high peak loads dataset, it was assumed that *services* based office industries (e.g. consulting firms, lawyers and financial advisors) occupied the design building. With service industries the actual building occupancy is quite low, because employees are often outside the building during the day (client meetings etc), but high peaks occur when high internal loads and peak weather conditions coincide.

For the opposite extreme, the constant loads dataset, a 24-hour/7-days *call centre* occupied the design building. Constant high occupancy is a characteristic of this type of use, with relatively flat peaks as the cooling load is dominated by internal loads.

The two *load occurrence diagrams*, shown in Figure 5 right), offers a useful way of visualizing the building loads in terms of frequency of occurrence of a specific % chiller loading requirement at different Tdb values. The top diagram (representing the services load) shows that, assuming that the load peak is matched by the chiller peak, the chiller will mainly operate between 15% and 50% part load, between 8 and 32 deg Celsius, with the most frequent loadings occurring around 40% and 25 deg Celsius.

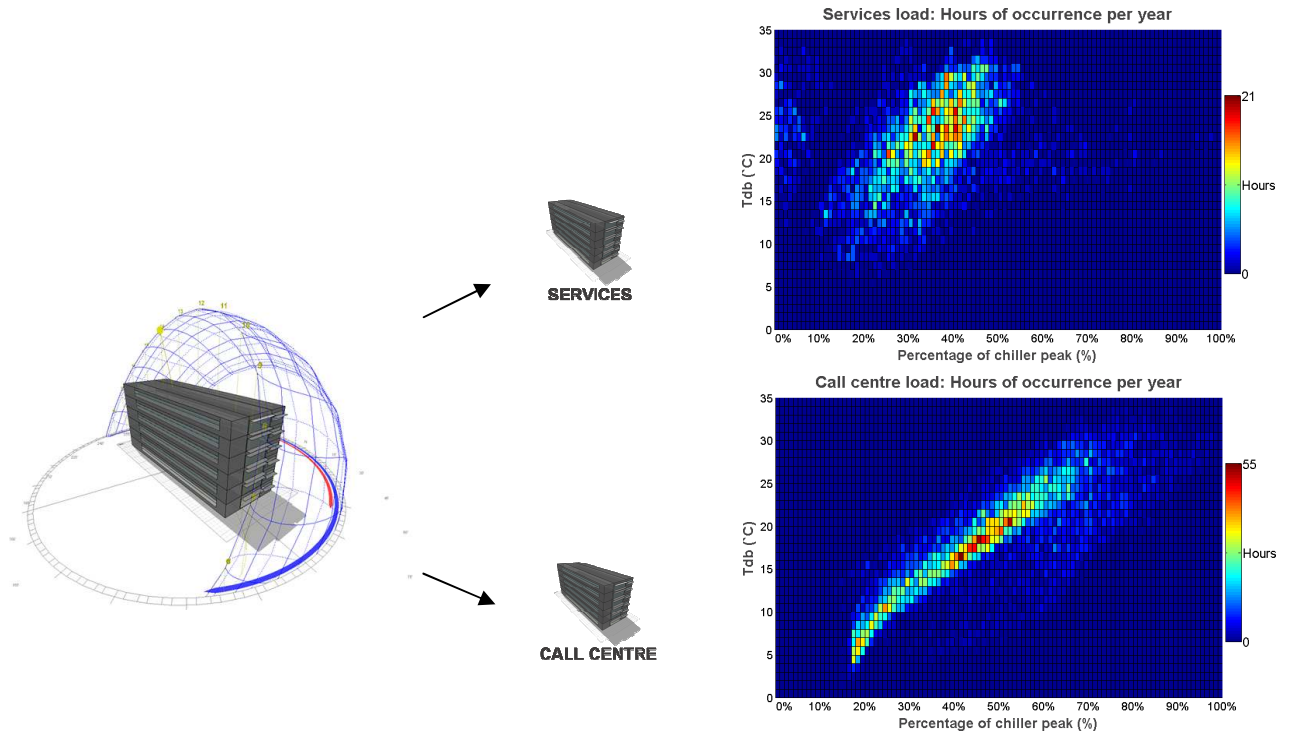


Figure 5. The same base building was used to generate both load datasets, shown here with sunpath diagram (left). The load occurrence diagrams (right) are shown for both the high peak load (services building) and constant load (call centre building) datasets.

Simulation process

The three chiller COP curves, the three different staging strategies, and the two building load datasets defined above will now be used in two simulations.

In the first simulation a variety of building load / individual chiller combinations will be used to illustrate the impact on energy efficiency of matching the building load and climatic context to the selection of chillers. In the second simulation the three staging strategies introduced earlier will be used to demonstrate the impact on energy consumption of matching chiller type, building load and staging strategy.

A Matlab-based software program developed in-house, called ChillerView, will be used to simulate the efficiencies of various chillers and staging strategies, given the climate and building load data sets defined earlier. This program is capable of hourly simulations, and can model a wide variety of air-conditioning related parameters accurately.

RESULTS

Simulation 1: demonstrating the impact of matching building load and chiller selection

In this simulation a base case of accurately matched load-chiller pairs will be compared against a scenario where the chiller peaks are all oversized by 40% relative to the peak loads they supply.

Individual chillers of the three types introduced earlier will be used (sized at 450kW and 630kW, i.e. 40% oversized, respectively) to supply both building load datasets (normalized to both have a peak load of 450kW).

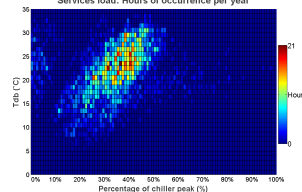
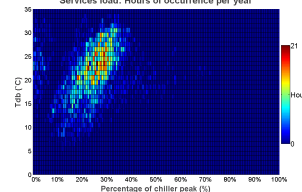
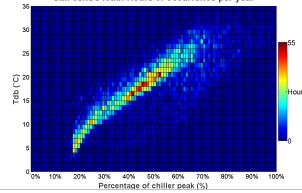
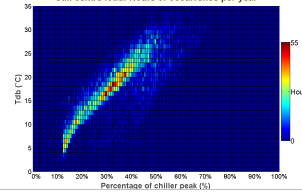
	CHILLER MATCHES LOAD	CHILLER 40%OVERSIZED
 SERVICES		
 M-CENTRIF.	20.5 kWh/m ² /a	-5% consumption
 SCROLL	19.9 kWh/m ² /a	+1% consumption
 SCREW	27.9 kWh/m ² /a	+3% consumption
 CALL CENTRE		
 M-CENTRIF.	35.3 kWh/m ² /a	-6% consumption
 SCROLL	33 kWh/m ² /a	-6% consumption
 SCREW	42.5 kWh/m ² /a	+2% consumption

Figure 6. Table showing the results of simulation 1

Simulation 2: demonstrating the impact of matching load, chiller type and staging

In this simulation, a base case of a basic sequential staging strategy will be compared to scenarios where a basic linked, and a COP-optimised staging strategy is used. Three air based chillers (with a combined peak of 3x450kW=1.35MW), of the three types selected earlier, will be used to serve the two load datasets (with a load peak of 1MW each).

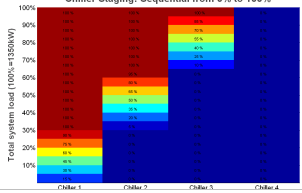
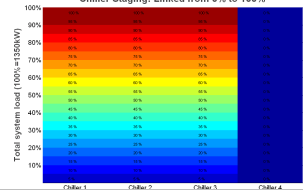
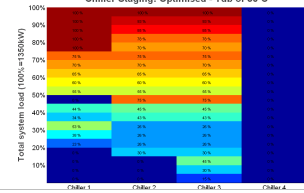
	SEQUENTIAL Chiller staging: Sequential from 0% to 100%	LINKED Chiller staging: Linked from 0% to 100%	OPTIMISED Chiller staging: Optimised - Tdb of 30 °C
 SERVICES			
 M-CENTRIFUGAL	23.8 kWh/m ² /a	-17.6% consumption	-18.9% consumption
 SCROLL	25.5 kWh/m ² /a	-22% consumption	-23.5% consumption
 SCREW	26.8 kWh/m ² /a	+6% consumption	-1.1% consumption
 CALL CENTRE			
 M-CENTRIFUGAL	38.5 kWh/m ² /a	-12.7% consumption	-14% consumption
 SCROLL	40 kWh/m ² /a	-22.3% consumption	-23.8% consumption
 SCREW	41.7 kWh/m ² /a	+3.8% consumption	-1.9% consumption

Figure 7. Table showing the results from simulation 2.

DISCUSSION

Interpretation of results from simulation 1

A visual process, where the load occurrence diagrams shown in Figure 6 is superimposed on the 2-dimensional COP curves shown in Figure 2, will assist with the interpretation of the results of simulation 1.

The result is shown in Figure 8 below: on the left, the accurately matched services building load is superimposed on the COP curve of the micro-centrifugal chiller. As can be seen, for a significant amount of hours per year the building load falls outside the area of highest COP of the chiller, i.e. the chiller will operate less efficiently during these hours. In Figure 8 on the right, the oversized load occurrence diagram is superimposed over the same micro-centrifugal chiller COP curve: most of the building load now occurs within the chiller's area of highest efficiency. The oversized load in this case therefore aligns better with the chiller efficiency dependencies than the accurately matched load, allowing us to predict that it should therefore result in reduced energy consumption. The results from Simulation 1 confirm this: electricity consumption decreases by 5% in the scenario of oversized chiller.

The same logic applies to the screw chiller in simulation 1: in this case the COP of the chiller improves as its part load increases (see Figure 2 c)), which means that a leftward shift of the load on the load occurrence diagram, caused by oversizing the chiller, will result in less efficient chiller operation. This is again confirmed by the simulation results in Figure 6, which indicates that the oversized screw chiller consumes more electricity in both load cases.

In the case of the scroll chiller, which has a much more pronounce area of high COP than the other chiller types, the impact of a leftward movement of the load occurrence is less easy to predict. In the case of the call centre load the leftward movement moves more load into the high COP area of the chiller (6% decrease in consumption), while for the services load the energy consumption actually increase as load is moved out of the high COP area.

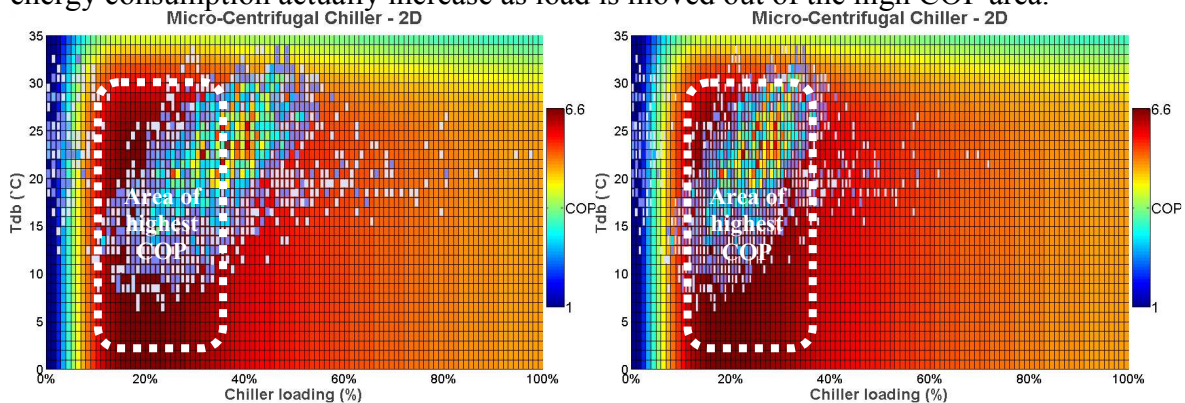


Figure 8. Services building load occurrences diagram superimposed on the micro-centrifugal chiller COP curve (Figure 2a), with left) a accurately match load-chiller, and right) a 40% oversized chiller.

Interpretation of results from simulation 2

To understand the results of simulation 2 it is helpful to revisit the two basic staging graphs, shown in Figure 9 below. The consistent (and significant) improvements found when using linked compared to sequential staging for the micro-centrifugal and scroll chillers can be explained by the fact that the chillers' peak COP areas occur in the region of 15% to 50% part

load, which is similar to the area of maximum load occurrence of both building loads. In comparison, with sequential staging one of the two active chillers will be operating at a inefficient 100% load for a large percentage of the load occurrence hours.

In this simulation the screw chillers are better matched with sequential staging, as these chillers are most efficient at full load.

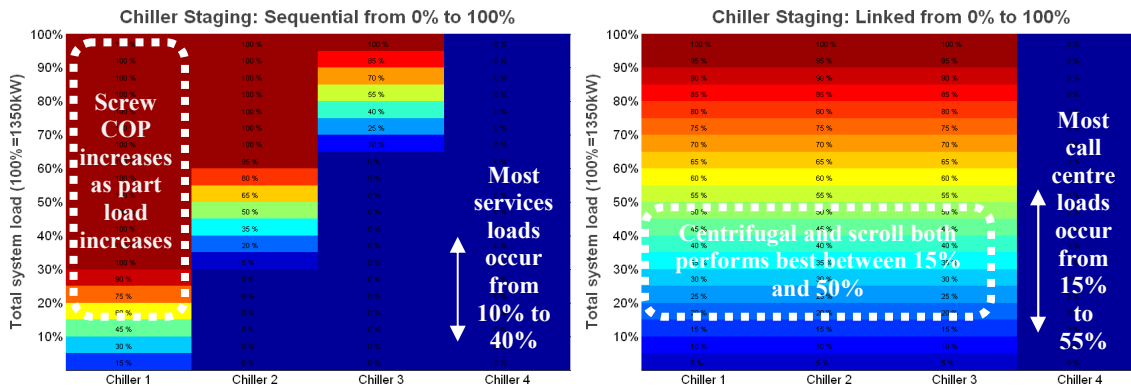


Figure 9: Basic staging graphs explaining the impacts of matching building load occurrence, chiller COP dependencies and staging methods.

Another interesting result from simulation 2 is that COP-optimised staging does not offer much improvement on the basic staging methods if these basic methods are appropriately chosen. COP-optimised staging can however potentially offer significant savings when replacing an unsuitable staging strategy.

Conclusions

The above simulations and discussions satisfied this paper's objective, to demonstrate that significant energy savings can result if chiller selection, sizing and staging acknowledge the dynamic nature of chiller efficiency dependencies, including the building load and heat rejection temperatures.

Designers should be aware that chiller to load matching will vary according to chiller type and the nature of the load and climatic context. This should be considered in the chiller selection and the control strategy design and commissioning. The visual method proposed in this paper will aid this process.

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