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Influence of cooling load profile on the prediction of energy use in commercial refrigeration plants

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ABSTRACT

The cooling load of a commercial refrigeration system is affected by the operating conditions of the refrigerated display cabinets and cold rooms, mainly through their mutual interactions with the indoor environment in terms of temperature and humidity. In this paper, the effects of cooling load profiles in the prediction of the annual energy use are investigated, comparing constant and simplified load functions to a more realistic simulation-based approach. The latter is made using a calibrated hourly model of the whole commercial refrigeration system, which includes a transcritical CO_2 booster system with its control rules and the simulation of the display cabinets and cold rooms. These user-defined components are implemented in the TRNSYS environment and linked to the dynamic building simulation. The analysis is performed for different system configurations and weather conditions. The results show that the load profile affects the comparison in terms of energy effectiveness among different system configurations, and should be considered for a fair assessment.

Keywords: Modelling, Load profile, commercial refrigeration, display cabinets, cold rooms.

1. INTRODUCTION

The need of new refrigerants with low environmental impact in commercial refrigeration has opened a great discussion, where synthetic and natural refrigerants are compared, and where numerous system configurations are considered. This is particularly true when CO_2 is employed, whose energy efficiency suffers the high outdoor temperature typically faced in Mediterranean countries. In this case, various approaches are followed, using components among which different kinds of subcooling systems, parallel (auxiliary) compressors, overfed evaporators, ejectors and so on. Such configurations allow better performance each at specific conditions, e.g. high outdoor temperature, partial or full load and, ratio among LT and MT cooling capacity. Therefore, the advantages of a refrigeration system against another in terms of energy efficiency must be assessed making reference to the peculiar climate conditions and cooling load profile. (Minetto et al., 2018)

The comparisons among different systems available in the literature refer to various operating conditions (Tsamos et al, 2017, Karampour, 2018, Thanasoulas et al, 2020). Some are performed at the design conditions for both the outdoor temperature and cooling load, thus giving a punctual view. When the annual energy use is computed, constant cooling load for the whole year is often considered, so as to implement the so called "temperature bin" method based on the frequency of outdoor temperature values met during the year. In other cases, the cooling load is estimated based on the compressor flow rate or is estimated from the design value of cabinets, both adjusted depending on the annual outdoor temperature profile.

The authors have developed a comprehensive model which estimates the cooling load of a commercial refrigeration system based on the calculation, for each cabinet, of the cooling capacity based on its design heat extraction rate as per the ISO Standard 23953, adjusted with the effects of defrosting, lights, openings, and depending on the indoor temperature and humidity. Indoor temperature, in turn, can be estimated by another model of the transient thermal behaviour of the whole building. The annual cooling capacity profile is then used as input for the comparison of various refrigerating system configurations in an annual time horizon at different climate conditions.

This procedure showed to be reliable and allowed to perform an effective assessment of diverse solutions tested in the framework of the past EU project CommONEnergy. However, the complexity of such approach is clearly a drawback when the model must be generalized. For this reason, the authors wish to check whether simplified approaches can be successfully applied to the estimation of the cooling load profile, in view of predicting the annual energy use of a commercial refrigeration unit in various system configurations, and identify the most effective.

2. COOLING LOAD PROFILE

The refrigeration system of a small supermarket with a selling area of 1200 m^2, located in Modena, Northern Italy is taken as demo case. It is a CO_2 transcritical booster with parallel compression and two temperature levels, -35 °C for the frozen food equipment (LT) and -10 °C for the chilled food (MT). The commercial refrigeration unit (CRU) was fully instrumented in the framework of the FP7 European Project CommONEnergy (Cortella et al. 2014) and the field data available from one year monitoring were used for the validation of the model of the entire refrigeration system (i.e. CRU, refrigerated display cabinets and cold rooms) as discussed in D'Agaro et al. (2019).

The cooling load of the CRU is produced by approximately 14 m of refrigerated display cabinets and 8 cold rooms for the low temperature level and 63 m and 2 cold rooms for the medium temperature level. The list of refrigerated display cabinets is reported in Table1. They have been grouped by the typology, type of protection of the refrigerated volume, operating and evaporator temperatures. The rated total cooling capacity, stated by the manufacturer according to the ISO Standard 23953, has been referred per unit length.

Table 1. List of display refrigerated cabinets

Temperature Class	Typology	Open - Closed	Length [m]	Operating Temperature [°C]	Evaporator Temperature [°C]	Rated Total Capacity per Unit Length [W/m]	Lighting Power per Unit Length [W/m]	Fan Power [W/m]
H1	Vertical	Open	3.1	2	-6	1062	54.8	14.8
M1	Vertical	Open	5	0	-6	454	54.8	14.8
		Closed	2.5	0	-6	1005	54.8	11.6
			11.5	0	-6	1005	54.8	11.6
	Serve-Over	Open	9.4	0	-8	270	92	14.2
M2	Vertical	Closed	23.8	2	-3	460	54.8	11.6
	Serve-Over	Open	7.5	2	-4	880	92	14.2
L1	Vertical	Closed	14.4	-20	-29	491	21.2	12.8

2.1. Internal Temperature Dependent (ITD) detailed profile

The cooling load profile we take as reference is that obtained from the comprehensive model above mentioned, which predicts the indoor conditions with a time-dependent simulation of the building and takes into account the detailed operation of the cabinets. The building is simulated using the multizone building transient model of TRNSYS 17 Type 56, including the cabinet loads as internal loads and considering the dynamic thermal behaviour of the building.

The cooling load of the refrigerated display cabinets is given by the sum of the sensible load, the latent load and the auxiliary devices load. The sensible and latent loads are due to the heat and mass transfer occurring through the contours of the refrigerated volume, mainly because of the air and humidity infiltration which takes place in open-fronted display cabinets or during door openings; thus, the two contributions are strongly dependent on the temperature and humidity in the supermarket. The auxiliary devices load is the fraction of the sensible load from auxiliary devices which is removed by the evaporator, and it is partly dependent on indoor conditions (defrost and anti-mist heaters) and partly independent (lighting, fans).

A model, based on the one proposed by Faramarzi (Faramarzi, 1999), was implemented as "user-defined Types" in the TRNSYS environment (Klein et al., 2010) as described in detail in Polzot et al., 2017. Basically, the cooling capacity of each display cabinet at rated conditions (according to the ISO Standard 23953) is adjusted taking into account the actual and time-dependent working conditions in a supermarket (off-rated conditions). The cooling loads are dynamically calculated with a 15-minute time step as a function of the indoor air temperature and humidity as well as the time schedule for auxiliary devices (Polzot et al., 2016).

In the considered supermarket, the humidity is not controlled by HVAC, the indoor temperature is set to 20°C during the heating season and to 24°C during the cooling season, but it is influenced by outdoor conditions when the HVAC is switched off, i.e. in middle seasons and during the supermarket's closing hours.

Thus, the simulation of the cooling load is coupled with the dynamic simulation of the building, and it is strongly time dependent. As an example, in Figure 1 the total cooling load from the refrigerated food storage equipment is reported for a winter week and a summer week in the climate considered. It can be detected that the higher the indoor temperature the higher the cooling load, whereas the strongly uneven profile during constant temperature periods is due to on-off operation, defrost and drip-down periods in groups of cabinets.

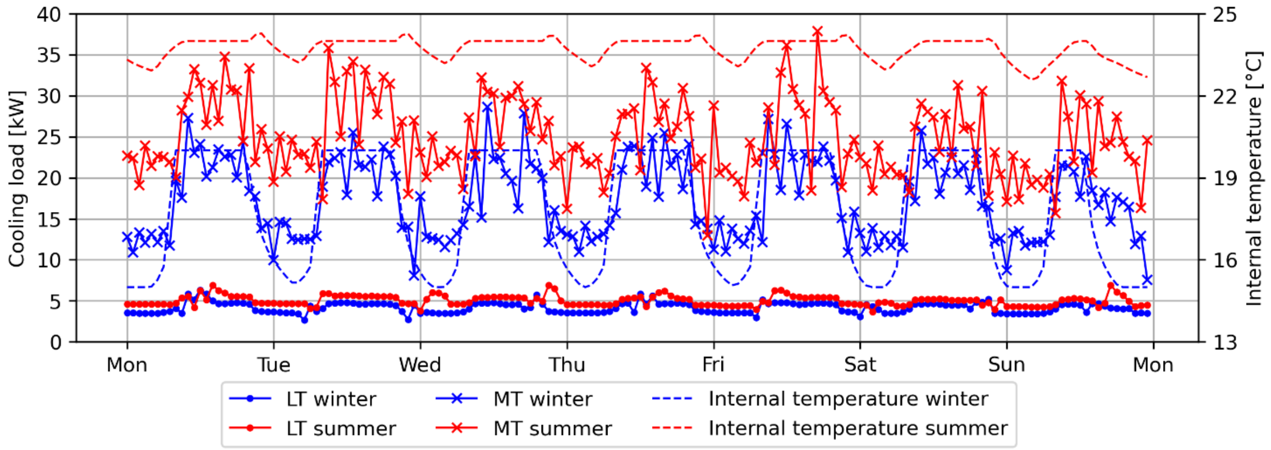

Figure 1: Internal Temperature Dependent simulated profile of the cooling load at LT level and at MT level for a sample winter week and a sample summer week.

2.2. Simplified profiles

In order to investigate the influence of the cooling load profile on the prediction of the refrigeration system performance and on the comparison among different CRU configurations, a set of simplified profiles has been defined. Each profile is calculated to give the same annual cooling energy as that resulting from ITD profile, i.e. from the simulation of the refrigerated equipment at indoor conditions. The profiles considered are:

- Constant profile: 21.6 kW for the MT evaporator level; 4.7 kW for the LT one, 24/24 hours;
- Closing Time Reduction (CTR) profile: a modulation of the cooling load based on the lower request when the supermarket is closed. It is step function with 25.1 kW for the MT evaporator level and 5.4 kW for the LT one during opening time; the load is reduced of the 30% during closing time. Closing time is set from 21:00 to 7:00 during week, from 14:00 to 7:00 during Sundays and all day during national holidays;

- External Temperature Dependent (ETD) profile: a modulation of the cooling load based on the external temperature. It is usually implemented when estimating the CRU performance at different climate conditions. As in Nebot-Andrés et al. 2017, where the BIN temperature methodology was used, we assume the following cooling profile: the full loads when the external temperature is over 31°C; 50% reduction when the external temperature is below 23°C and the linear dependence is assumed between 23°C and 31°C. The full load values, 38.7 kW for MT and 8.4 kW for LT level, are calculated to keep the same annual cooling load of the ITD profile. The ETD profile for the climate of the demo case is plotted in Figure 2.

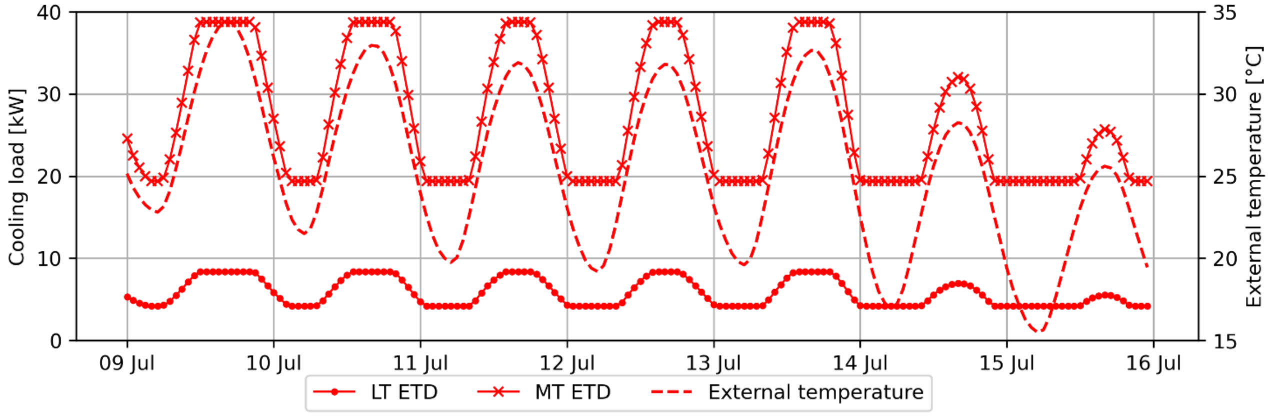

Figure 2: Cooling load profile dependent on the external temperature (ETD profile) at the at LT level and at MT level for a sample summer week.

3. CONFIGURATIONS FOR THE COMMERCIAL REFRIGERATION UNIT

The influence of the cooling load profile on the comparison among different configurations of the refrigeration system has been investigated. Three typical solutions in commercial refrigeration have been considered:

- Base: the basic transcritical booster system with two compression levels, a liquid receiver placed after a first expansion valve at the exit of the gas-cooler and the flash gas by-pass. The schematic is shown in black line in Figure 3.

- AUX: booster with auxiliary compression. In addition to the base configuration, there is a parallel compressor to process the flash gas coming from the liquid receiver in transcritical operation, i.e. for outdoor temperature over 26 °C. The additional component is shown in green in Figure 3.

- DMS: booster with Dedicated Mechanical Subcooling. In addition to the base configuration, there is a single stage refrigeration system to subcool the CO_2 at the exit of the gas cooler. The subcooler, shown in blue in Figure 3, is activated when the external temperature is over 19 °C.

The model is implemented in the TRNSYS environment and linked to the CoolProp libraries to calculate the refrigerant properties at the main states of thermodynamic cycle. The detailed description of the refrigeration system in the Base and AUX configurations is given in D'Agaro et al. 2019, including information on the compressors. In particular, the instantaneous mass flow rate is calculated to satisfy the cooling capacity. In the case of the ITD profile, a simulation as realistic as possible has been carried out implementing the sequence of activation in each compressor rank. The instantaneous cooling capacity defines the status of compressors: at lower mass flow rates, the variable speed compressor (master) is modulated from its minimum to its maximum displacement; then, for higher request, the on-off compressor (slave) is activated, and the master is modulated back to eventually cover the residual mass flow.

In the simulations of simplified profiles, we decided to keep as close as possible to models found in the literature. Thus, a variable speed compressor is used, not limited in size. Furthermore, this assumption avoids getting fictitious activation of the slave compressor due to fictitious values of the constant cooling capacity.

The parameters of R1234yf subcooler and the coupling with the booster system are described in detail in D'Agaro et al., 2021.

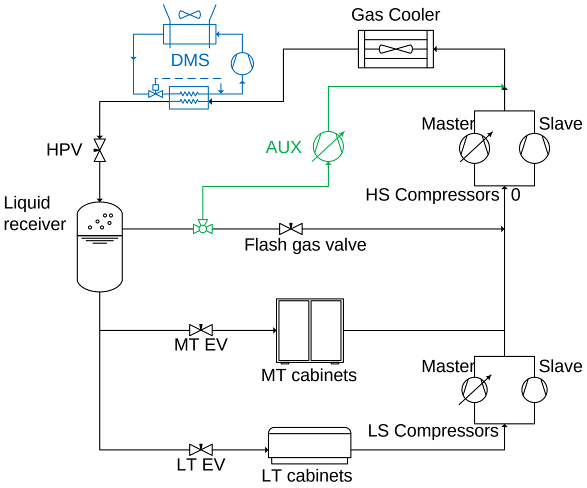

Figure 3: Schematic of the three configurations of the CO2 refrigeration system: Base in black line; AUX in black line plus the green components; DMS in black line plus the blue components.

4. SIMULATIONS RESULTS

Simulations have been carried out for the four cooling load profiles and the three CRU configurations described above.

4.1. Comparison at constant annual energy cooling demand

In Figure 4 the yearly distribution of the electrical energy demand of the base booster CRU is reported for different cooling load profiles. The effect of the external temperature on the performance of the refrigeration unit is clear from the case of "constant" cooling load profile and it is more marked during the summer period when the diurnal temperature range is higher. This effect is amplified in the ITD case by the combination with the daily cooling load profile depending on the indoor temperature, leading an even higher daily variation in the power demand.

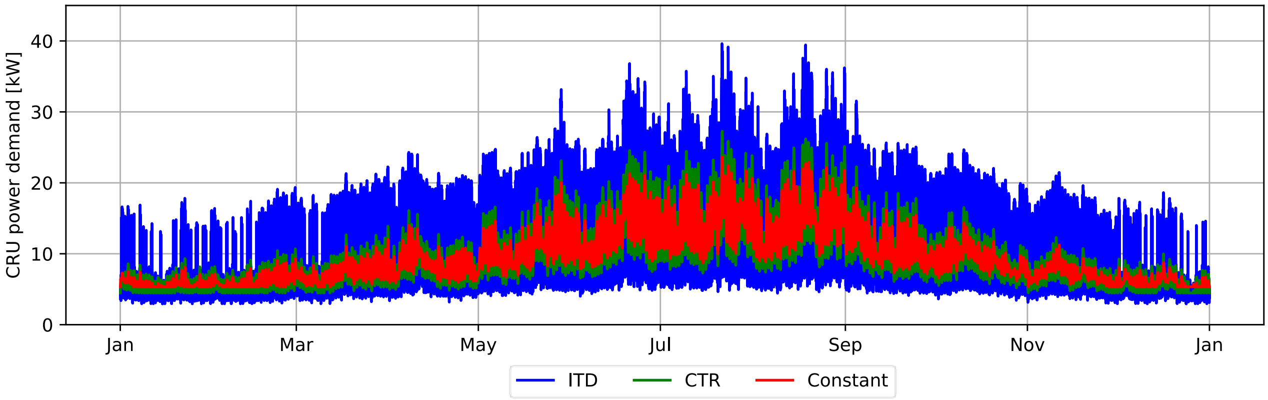

Figure 4: CRU yearly electrical power demand for the booster base configuration and different cooling load profiles.

The results in terms of electrical energy demand are presented on monthly basis in Figure 5 for the different configurations: booster (Base), booster with parallel compression (AUX) and booster with dedicated mechanical subcooling (DMS).

Since the different cooling demand functions have the same annual energy value (i.e. same integral of the 15 minutes time step distribution), the "constant" case overestimates the power demand with respect to the ITD profile in the winter months and underestimates it during the summer months. The same behaviour can be detected in the CTR case, where the cooling request is repeated with identical trend for each week of the year, except for the National holidays. On the other way round, the ETC case, where the external temperature influences directly both the cooling load and the CRU performance, presents a higher electrical request during the summer and lower in the winter months with respect to the ITD case.

Furthermore, the parallel compressor is activated in transcritical CRU operation whereas the DMS is activated for external temperature above 19°C. Thus, when the CRU operates in subcritical conditions, the electrical energy demand for a given cooling profile is the same between Base and AUX and slightly different between Base and DMS, as it appears by comparing Figure 5a, 5b and 5c for months from November to March.

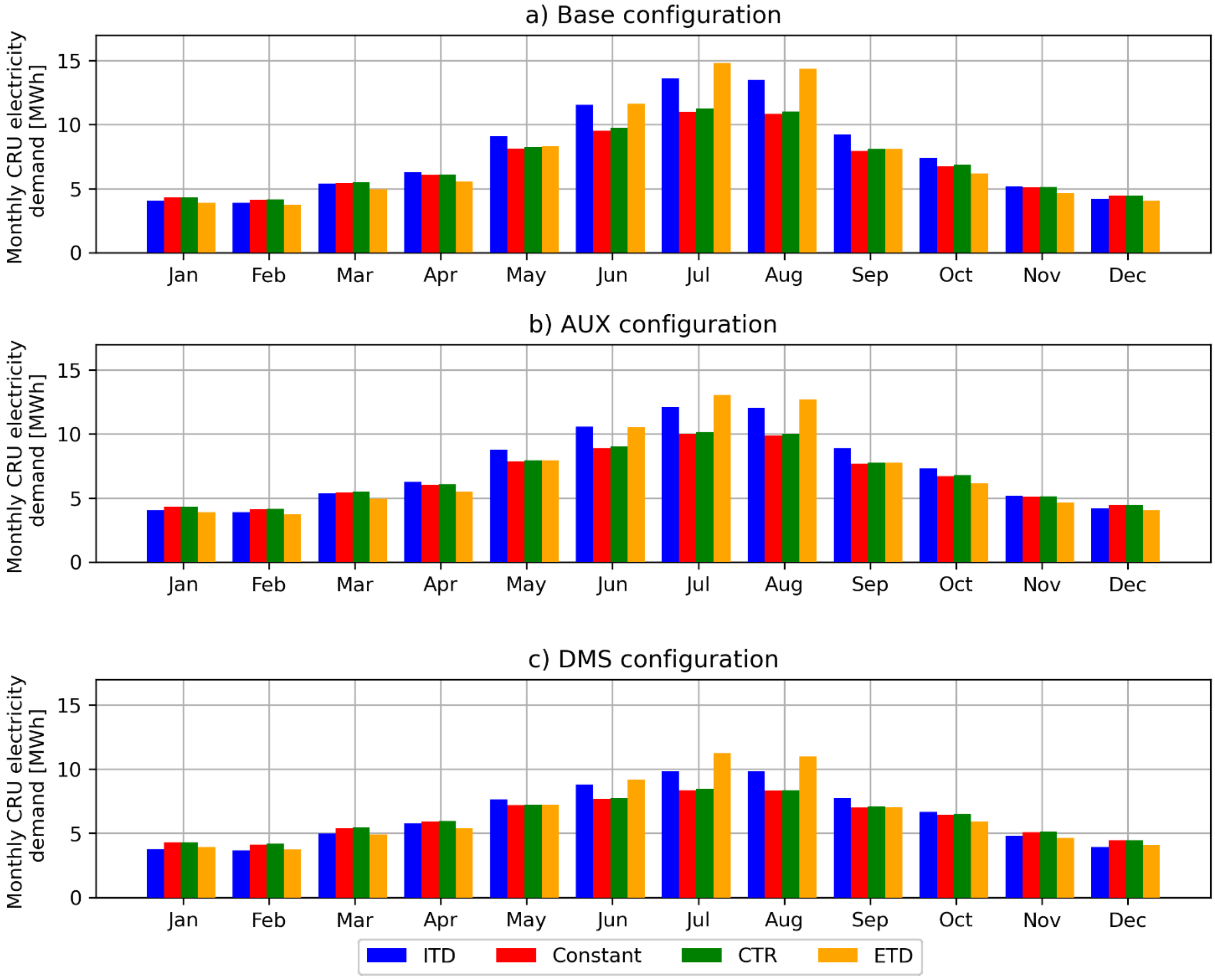

Figure 5: CRU monthly electrical energy demand for the cooling load profiles considered: a) Base; b) AUX configuration; b) DMS configuration.

4.2. Configuration comparison on different cooling load profile basis

The electrical annual energy demands are reported in Table 2 for all the simulated cases in the climate of Modena. The variations in the CRU annual electrical energy demand for the AUX and DMS configurations with respect to the Base configuration are reported for the different cooling load profiles. Obviously, as already widely stated in the open literature, the parallel compression of the flash gas (AUX) brings always benefits to the basic booster system. The performance of the system with DMS are even more marked, recording a reduction up to 17% for the climate considered.

The interesting aspect this paper is dealing with, is to assess how much the assumption of a particular profile in the cooling capacity may influence the comparison between performance of different CRU configurations, in particular the prediction of the annual electrical energy demand. For a given annual demand, the constant and the two-step profile (CTR) slightly underestimate the benefits of AUX solution versus the basic booster showing a reduction of -3.8% and -4.3% respectively with respect to the 5% reduction of the profile depending on indoor thermal temperature (ITD). The cooling load profile dependent on the external temperature overestimates the electrical energy reduction (5.9%) when compared to ITD one. In the comparison of DMS solution versus the basic booster system, the ITD profile leads to estimate the best benefit, with a 17,1% reduction in annual electrical energy demand.

Furthermore, the differences in the estimation of the annual total electrical energy for different profiles with respect to the ITD profile for each solution are reported in Figure 6. In all cases, with the exception of the ETD profile in the DMS configuration, the electrical energy request calculated with the ITD profile is higher than other profiles. The differences are more marked in the basic solution and lower in the DMS one. The reason can be found in a lower impact of different profiles in the summer months when the DMS is more effective. Thus, simulations have been carried out for two additional climates hotter than Modena.

Table 2. Annual electrical energy demands calculated for the climate of Modena, Northern Italy.

Load Profiles		Annual CRU Electricity Demand [MWh]				
		Base	AUX	DMS	AUX vs Base	DMS vs Base
Indoor Temperature Dependent	ITD	93.4	88.7	77.4	-5.0 %	-17.1 %
Constant	Constant	83.7	80.6	74.3	-3.8 %	-11.4 %
Closing Time Reduction	CTR	85.0	81.4	74.9	-4.3 %	-11.8 %
External Temperature Dependent	ETD	90.2	84.9	78.2	-5.9 %	-13.3 %

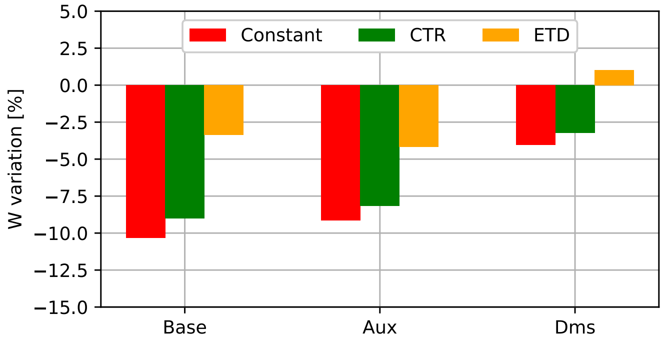

Figure 6: Variation in annual CRU electrical energy demand of different profiles with respect to the relative ITD profile.

4.3. Influence of climate conditions on configuration comparison

In order to investigate if the influence of the cooling demand profile on the comparison among CRU solutions depends upon the climate conditions, simulations have been carried out for the three CRU configurations and the five cooling load profiles in the climates of Cairo and Bangalore. It should be pointed out that the building simulation has been performed for each new climate to establish the correct time dependent indoor temperature and thus the associated cooling load profile ITD. The constant, CRT and ETD profiles have been calculated to get the same value of the cooling loads, at the LT and MT levels, on annual basis. The distribution of the outdoor air temperature at these locations is represented in D'Agaro et al. 2021.

The reduction in the annual electrical energy demand of the CRU with parallel compression (AUX) versus the basic solution (Base) is reported in Figure 7. The trend is similar for different climate conditions, the benefits calculated with the ITD profile are slightly underestimated by the constant and the CTR profiles, slightly overestimated by the ETD profile. The differences in the Bangalore climate are limited, AUX configuration allows a reduction around 8% in the annual electrical energy demand for all the cooling load profiles.

Figure 8 shows the same comparison between the DMS solution and the basic booster. In this case, the simplified profiles always underestimate the benefits of DMS solution with respect the ITD profile, from 3 p.p. for Bangalore to a maximum of 5.8 p.p. for Modena constant profile.

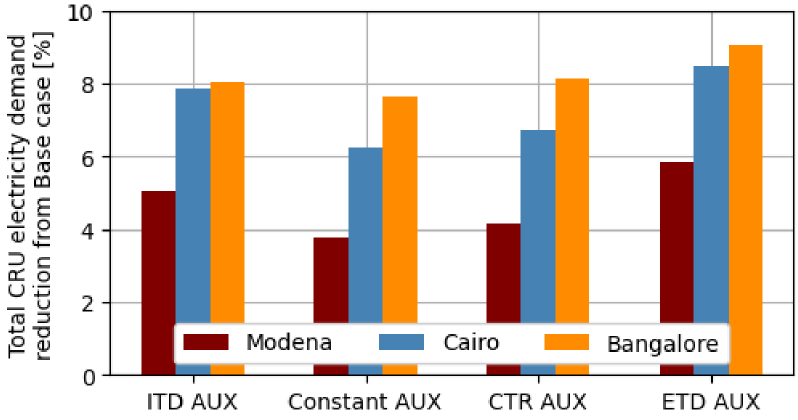

Figure 7: Variation in annual CRU energy demand of the AUX configuration with respect to the Base configuration simulated with the five loads at three climates.

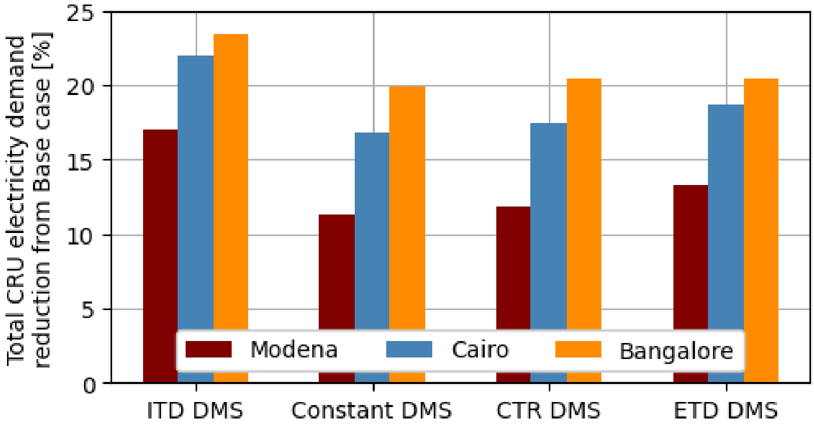

Figure 8: Variation in annual CRU energy demand the DMS configuration with respect to the Base configuration simulated with the five loads at three climates.

5. CONCLUSIONS

Different methods to assign a cooling load profile when modelling diverse system configurations have been considered, and their effect on the annual electrical energy use prediction have been evaluated. A detailed estimation of the cooling load amplifies the variation in the electrical power demand and is the only way for a reliable detection of peaks. Whatever simplified model is used, peaks are considerably shaved, and daily variations smoothed. Using simplified profiles doesn't change the performance ranking of different configurations, even if the absolute values of annual energy demand and consequently the energy saving change considerably. This is much clearer when the energy savings are higher, thus suggesting that configurations leading to poor energy saving would not be fairly compared with simplified load profiles. A thorough cost analysis would be anyway compromised. The ETD profile, where the cooling load is modulated based on the external temperature, gives the most similar results when compared to a detailed modelling, and should be preferred to those profiles where constant values or two-levels values are adopted. Finally, also the climate conditions do affect the comparison, and their influence is clearly linked to the configuration of the system compared, and how they operate to improve the energy efficiency.

In conclusion, a comparison of different system configurations to identify the most promising one for energy efficiency can be performed with simplified cooling load profiles; a thorough prediction of the energy use for the purpose of cost analysis cannot do without a detailed estimation of the time dependent cooling load profile.

ACKNOWLEDGEMENTS

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NOMENCLATURE

CTR	Cooling Time Reduction, two step profile	*ITD*	Internal Temperature Dependent, profile from refrigerated equipment simulation
ETD	External Temperature Dependent, profile modulated on external temperature	*RTD*	Refrigerated Display Cabinets

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