Optimal Design of an Office Building for Low-Primary Energy Requirement and High-Indoor Thermal Comfort Level

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Summary

Reducing the heating, cooling, ventilation and lighting energy is an environmental target for buildings in sustainable communities. However this should to be achieved without compromising the required level of indoor wellbeing. In 2008, the Indoor Climate Classification of Finland has introduced strict definitions for higher thermal comfort categories (*S*1 and *S*2). *S*2-category is most often required in office buildings. The aim of this study is to achieve optimal *S*2-solutions.

Building performance simulation program (IDA-ICE 4.0) is combined with a modified multi-objective optimization approach to minimize three objectives: percentage of operative air temperature set-point deviations, primary energy consumption, and cooling equipment size. The study considers 24 design variables in the building envelope and HVAC system addressing the use of night cooling and daylight as sustainable solutions. The results show that it is difficult to achieve minimum energy requirements and cooling equipment size in *S*2-solution. The high thermal comfort levels limit the use of night ventilation. About 50% of cooling energy could be reduced if a free cooling option was implemented. Compared with a reference design, the simulation-based optimization approach allows 20% energy saving and 34% reduction in cooling equipment size.

Keywords: Optimization, Simulation, Thermal comfort, Primary energy, Cooling equipment size.

1. Introduction

The significance of indoor climate for health, comfort and productivity has been well recognized in Finland in recent decades. Study [1] summarized briefly the development of the indoor climate classifications in Finland and mentioned a set of drawbacks related to the lack of drivers in energy performance regulation. The most recent Indoor Climate Classification of Finland, (*Sisäilmastoluokitus* 2008 *Sisäympäristön tavoitearvot, suunnitteluohjeet ja tuotevaatimukset*), was released in 2008 [2]. The Classification categories the thermal comfort level into three classes: *S*1, *S*2, and *S*3. Class-*S*1 corresponds to the best quality, meaning higher satisfaction with indoor climate and lower health risk. Class-*S*3 is in line with the official quality set by building codes. According to 2008-Classification, the indoor operative air temperature is adopted as a thermal comfort criterion. The operative air temperature set-point and maximum/minimum limitations are given as functions of the 24 hr's mean-average outdoor air temperature ($ODT_{24hr\ average}$). Class-*S*2 requires keeping the indoor operative air temperature (T_{op}) within ± 1 ^{o}C of the set-point for 90% of the occupied hours. The set-point profile, the allowable deviation bands, the maximum/minimum limitations are shown in Fig. 1.

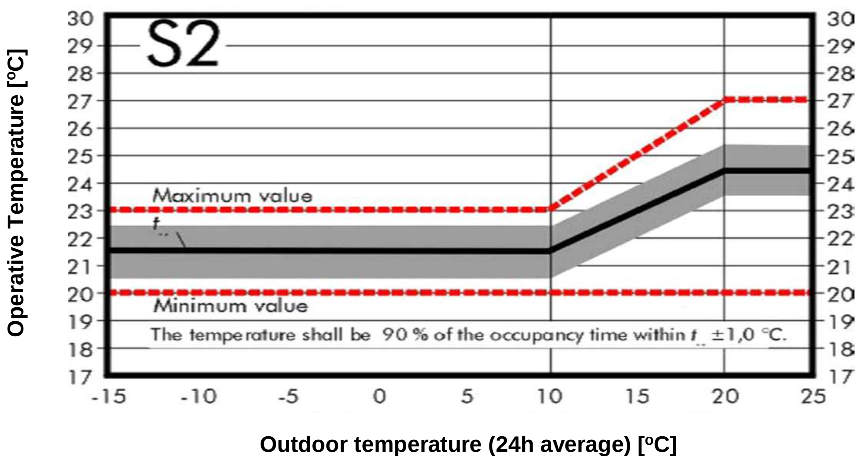

Fig. 1 S2 Operative temperature set-point as a function of the 24h average outdoor air temperature [Ref. 2]

The building energy consumption depends significantly on the desired thermal comfort level. The current study focuses on the medium level thermal comfort class (*S*2). In practice, *S*2 is the most often thermal comfort class required in office buildings.

Two typical office rooms with different orientation (north and south) are taken as a case study. IDA ICE4.0 (building performance simulation program) is used for simulation. A modified multi-objective optimization approach (PR_GA) is implemented for optimization. Two design solutions (reference and optimal) are compared assuming same level of thermal comfort (*S*2). The reference solution presents a simple approach to achieve *S*2-category. However the optimal one provides *S*2 solution with minimum primary energy consumption.

2. The building and HVAC system

2.1 Building and representative zones

An Office building (Kiinteistö Oy Lintulahdenvuori) is taken as a case study. One of the storeys (7th floor) is simplified and modeled by eight zones: LN-zone, North zone, machine room, RN-zone, interior zone, LS-zone, South zone, and RS-zone as shown in Fig.2. The two typical office rooms (north and south) are selected as representative zones in order to examine the primary energy consumption and operative air temperature at the two different orientations. The external walls are insulated based on the Finnish National Building Code C3-2007 (U-value = 0.24 W/m^{2}K). The window areas represent 35% of external walls. Pilkington 4-15Ar-SN6 (2-glass) with outer glass Optifloat Clear, cavity width 15 mm argon, inner glass is used as a reference design for windows. This type has the following specifications: solar heat gain coefficient (SHGC) = 0.6 and solar transmittance (T) = 0.48. The glazing U-value is taken as a design variable.

The simulation tool used was IDA ICE 4.0, a dynamic energy simulation tool, for advanced energy and indoor climate analysis [3, 4]. Validation tests have shown the program to give reasonable results and to be applicable to detailed buildings physics and HVAC simulations [5, 6]. IDA ICE, in standard level, simulates the thermal comfort at building level and zone level, while energy use is calculated only at building level. In the current study, advanced level of IDA ICE is used via macros to estimate the primary powers for ventilation, heating, cooling, and lighting at the zone level.

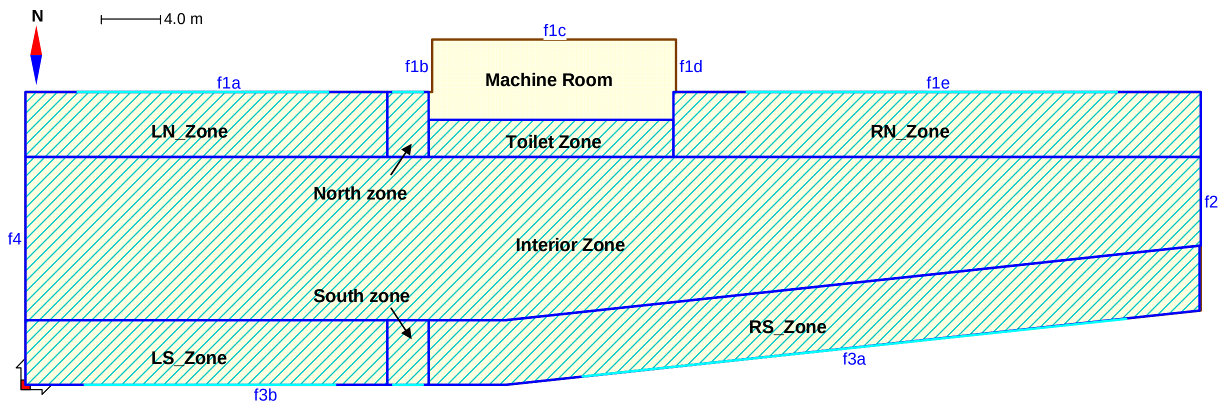

Fig. 2 Plan view for the simplified typical storey model

The building model used in IDA ICE is very detailed and has been validated against measurements and other calculation software in several projects. Unlike many similar programs a radiation balance is established based on view factors for the entire room. This makes it possible to calculate the operative temperature's variation in different positions. The operative air temperature is calculated at the two representative office rooms assuming the occupant is in the middle of the room with center of gravity (sitting) at 0.6 m above the floor. The occupant is assumed to be existed in the room during the working hours (from 8:00 to 17:00). One hour (from 12:00 to 13:00) is assumed as a lunch break (Fig. 3). One PC (150 W) and controlled artificial lighting (maximum 150 W) are assumed to be ON during the working hours. Saturday and Sunday are the weekend days.

The operative temperature is the average of the air temperature and radiation temperature at a certain point. In order to estimate accurately the mean radiant temperature of representative's wall surfaces, the whole storey (7th floor) is modeled. Average internal heat gains are assumed for unrepresentative zones. One person is assumed per each 12 m^2 floor area. Lighting system (12 W/m^2) and equipment (10 W/m^2) are assumed to be ON during the occupied hours. Fig. 3 shows the time schedule of the average internal heat gains. The influence of the unrepresentative zones on the exhaust air temperature is taken into account.

In order to reduce the time of simulation, the simulation is performed for only six months starting from 1st of February (2nd of Feb. is the coldest day) to 31st of July where July includes the warmest day. The simulation is performed using 2001-Helsinki weather. It worthwhile to mention that the suggested simulation period (6 moths) covers the extremes weather conditions.

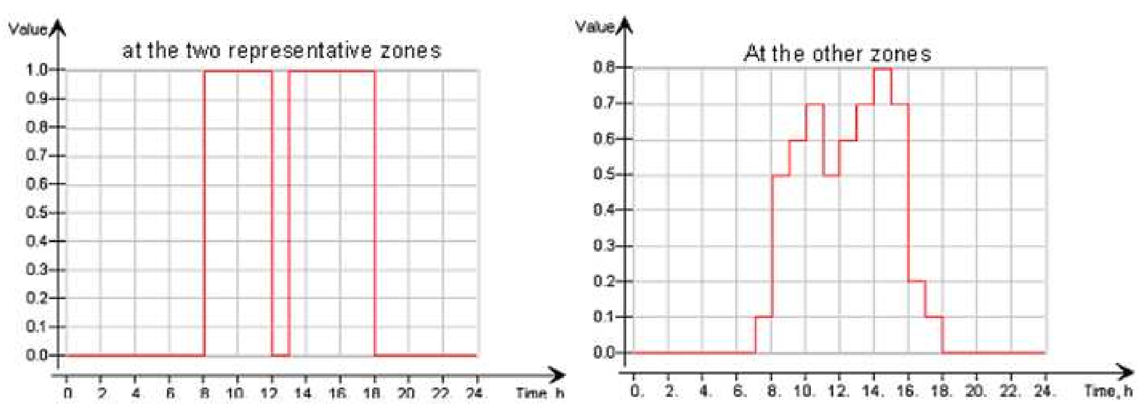

Fig. 3 Percentage of occupation at the different zones during 24 hours

2.2 HVAC systems

The office building is served by typical air conditioning and ventilation system in Finland. The HVAC system is a constant-pressure and mainly CAV system with active cooling beams. Rooms are heated by hot-water radiators (25 W per each square meter floor area). The water radiator set-point, night set-back, and controller dead band as well as the supply air temperature are taken as design variables in the optimization scheme. District heating is used to supply hot water to air handling unit heating coil and water radiators.

The supply air flow is selected on the basis of ventilation requirements of the room. Ventilation rate provides 22 l/s per each representative room. Room cooling is performed by chilled beams installed on the ceiling and controlled by operative room temperature sensors. The set-point resetting is according to the 24 hr's mean average outdoor air temperature (Fig.1). In the two representative rooms, the chilled beams sizes are assumed as design variables defined as maximum power at certain design operating temperatures. A chilled water system serves both the air handling unit and chilled beams.

The major part of the cooling and heating is supplied by the room units. The water is supplied at 14 ^{o}C to cooling beams. The supply hot water temperature is assumed as a function of the outdoor air temperature. The supply temperature at maximum water radiator power is 55 ^{o}C. The night ventilation is provided as an option where the control strategy parameters (minimum outdoor air temperature, minimum exhaust air temperature, and time schedule in which the night ventilation is enabled) are also taken as design variables through the optimization scheme.

3. Optimization scheme and results

The objectives of this scheme are to maximize the thermal comfort level and to minimize the primary energy consumption as well as the cooling equipment size. The thermal comfort level is maximized by minimizing the percentage of set-point deviations during the occupied hours. The primary energy is calculated assuming 0.5 and 2 primary energy factors for heating and electrical energy, respectively. The chiller is assumed with 2.5 annual coefficient of performance. Building envelope and HVAC parameters are addressed by proposing 24 design variables (Table 1). The design variables can be categorized as the following. Eight common design variables for the centralized AHU: two (X1 and X2) to define the optimal supply air temperature profile as a function of the outdoor air temperature (ODT); five (X3 to X8) to describe the optimal control strategy for night ventilation. In addition, eight design variables are taken per each two representative rooms: three (X9 to X11 for the north zone and X17 to X19 for the south zone) as selection parameters for a cooling beam; three (X12 to X14 for the north zone and from X20 to X22 for the south zone) to determine the optimal settings for the water radiator; two (X15 and X16 for the north zone and X23 and X24 for the south zone) to specify the window and shading properties.

To minimize the three objectives, the current study implements a two-phase multi-objective optimization approach (PR_GA), which was developed in a previous work [7]. MATLAB 2008a is used for the current study. The PR_GA is a combination between FMINCON (single objective deterministic optimization algorithm) and GAMULTIOBJ (Multi-objective genetic algorithm). In the first phase PR (preparation phase) the approach uses FMINCON (from MATLAB Optimization Toolbox) to minimize one objective considering constraints on the others. The second phase GA (from MATLAB Genetic and Direct Search Toolbox) addresses all the objectives using a good initial population from the first phase (i.e., the good initial population can be obtained by sorting all the candidate solutions of the first phase). The major advantage of PR_GA is that it tries to reduce the random behavior of GA in an attempt to obtain good solutions with lower number of evaluations (simulation-runs).

Table 1 24 design variables

Design Variables				Bounds	
Location		**X**	**Description**	**Lower**	**Upper**
AHU	**Supply air Temp. Profile**	X1	Ts at ODT ≤ 16 [C]	16	24
		X2	Ts at ODT ≥ 24 [C]	16	24
	Night Ventilation Control Strategy	X3	Min. ODT [C]	5	20
		X4	Min. dT (Tex - ODT) [C]	1	3
		X5	Min. Tex [C]	18	24
		X6	Ts Setpoint drop during night ventilation [C]	5	10
		X7	Start hour (before the occupied period) [h]	0	7
		X8	Stop hour (after the occupied period) [h]	0	6
North Zone	**Cooling Beam**	X9	Maximum power of the cooling beam [W]	200	600
		X10	dT(coolant) at max power [C]	2	5
		X11	dT(zone air-coolant) at max power [C]	6	9
	Water Radiator	X12	Night set-back temperature [C]	18	21
		X13	Set-point temperature [C]	20	21.5
		X14	Dead band of the controller [C]	0.3	3
	Window	X15	Glazing U-value [W/m2K]	1	2.5
		X16	Internal shading relative darkness [ratio]	0	1
South Zone	**Cooling Beam**	X17	Maximum power of the cooling beam [W]	300	600
		X18	dT(coolant) at max power [C]	2	5
		X19	dT(zone air-coolant) at max power [C]	6	9
	Water Radiator	X20	Night set-back temperature [C]	18	21
		X21	Set-point temperature [C]	20	21.5
		X22	Dead band of the controller [C]	0.3	3
	Window	X23	Glazing U-value [W/m2K]	1	2.5
		X24	Internal shading relative darkness [ratio]	0	1

ODT: Outdoor Air Temperature,
T_s: Supply air temperature set-point,
T_{ex}: exhaust air temperature.

In the current study the first optimization phase (PR) made in two steps. The first step addressed the north zone. The primary energy is taken as an objective to be minimized while constraint is imposed on the thermal comfort level (S2 set-point temperature deviations ≤ 10 %). The south zone is addressed with the same optimization scheme in the second step. The two steps required 162 and 256 simulation-runs, respectively. The results of the 418 simulation-runs are sorted two times. The first sorting considered the first two objectives (thermal comfort level and the primary energy). The thermal comfort level and cooling equipment size are considered in the second sorting step. From the two sorting steps, 40 design-variable combinations are selected and introduced as individuals in the initial population of the second optimization phase (GA). The multi-objective GA is implemented using 30 generations. The population size is assumed three times of design variables (72 individuals). The total number of simulation-runs for GA is 2160. The optimization scheme achieved 1015 feasible solutions satisfying *S*2 requirements at the two representative zones and 16 optimal solutions (Pareto front). Fig. 4 shows all the candidate solutions presenting the feasible ones by blue circles and the optimums by red squares.

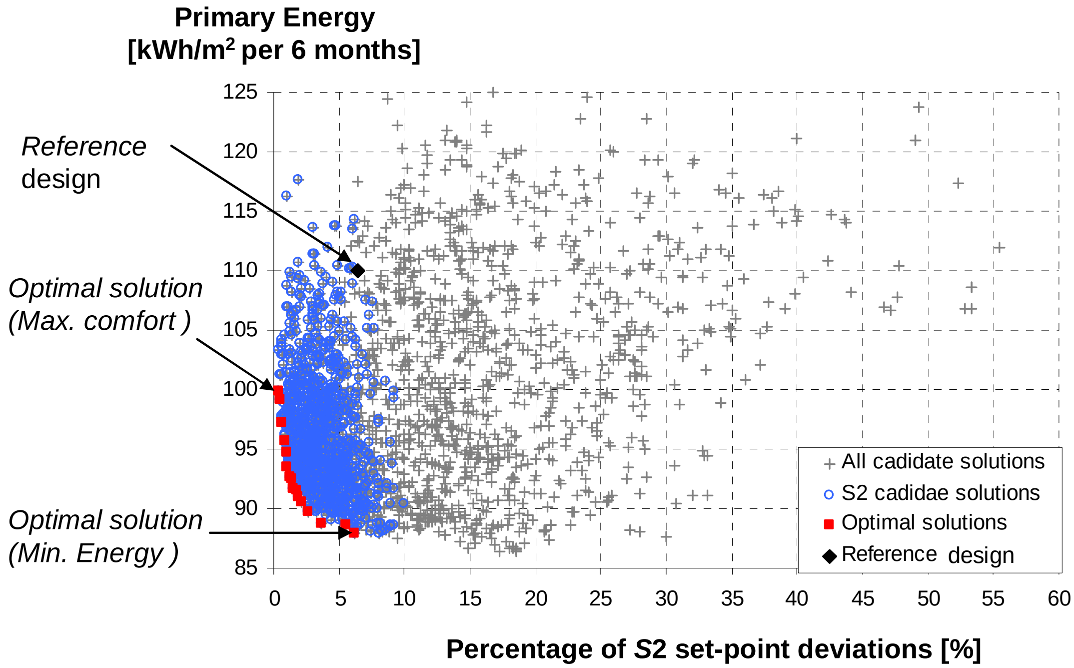

Fig. 4 The results of the optimization process

4. Discussion

The optimal solutions, presented in Fig.4, show a trade-off relation between the thermal comfort level and primary energy consumption. Table 2 presents reference design and two extremes optimal solutions: maximum thermal comfort and minimum energy solution. The minimum-energy optimal solution has a thermal comfort level of 6.2% *S*2 set-point deviations. A suitable cooling equipment size is selected for the reference design to achieve same level of thermal comfort. Compared with the minimum-energy optimal solution, the reference design requires 14% and 34% larger cooling beams at the north and the south zone, respectively. On the other hand, the reference design requires about 44 kWh/m^2 annual primary energy consumption more than the optimal one.

The reference design presents a simple approach to achieve a certain level of thermal comfort. In the reference design, the ventilation air is supplied at a constant temperature (18 ^{o}C). Neither night ventilation nor night setback options are used to avoid much of early morning overcooling. Water radiators with 2^{o}C dead-band are used in the both representative zones. Medium shading is selected to compromise the lighting and cooling minimum energy requirements (i.e., light shading could maximize the day light; however, it could increase the cooling energy demand). Window type is selected with U-value = 1 W/m^2 K.

The comparison between optimal solutions and the reference design shows that the simulation-optimisation approach can reduce 20% energy consumption achieving the same level of thermal comfort (6.2% *S*2 set-point deviations) or can reduce 9% energy consumption achieving better thermal comfort level (the maximum comfort optimal solution has 5.7% *S*2 set-point deviations less than the reference design). The optimal solution (max. comfort) has thermal comfort level of 0.43% *S*2 set-point deviations. The optimal solutions show that reducing 1% *S*2 set-point deviations requires additional 19.5 kWh/m^{2}a primary energy if the *S*2 set-point deviations from 0.43 to 1%. However, 4.8 kWh/m^{2}a is required if the *S*2 set-point deviations from 1 to 2.6%. Less energy requirements (0.7 kWh/m^{2}a) is needed if the *S*2 set-point deviations from 3.6 to 6.2%.

Table 2 Optimal ranges, optimal solutions, and reference design

		Optimal rang		Optimal solution		Reference
X	**Design Variables**	**Min.**	**Max.**	**Min. Energy**	**Max. Comfort**	**Design**
X1	Ts at ODT ≤ 16 [C]	16.01	18.51	16.1	18.36	18
X2	Ts at ODT ≥ 24 [C]	18.78	21.78	18.82	20.04	18
X3	Min. ODT [C]	7.13	10.63	9.84	7.93	20
X4	Min. dT (Tex - ODT) [C]	1.04	2.76	1.64	1.4	3
X5	Min. Tex [C]	22.8	23.9	22.8	23.9	24
X6	Ts Setpoint drop during night ventilation [C]	5.89	8.77	6.9	8.77	10
X7	Start hour (before the occupied period) [h]	0.04	0.74	0.12	0.4	7
X8	Stop hour (after the occupied period) [h]	0.29	0.97	0.67	0.29	6
X9	Maximum power of the cooling beam [W]	208.6	498.9	259.14	457.77	300
X10	dT(coolant) at max power [C]	2.98	4.69	3.76	3.71	3.5
X11	dT(zone air-coolant) at max power [C]	6.14	7.85	7.85	6.38	8
X12	Night set-back temperature [C]	18.79	20.48	18.99	20.23	21.5
X13	Set-point temperature [C]	20.17	20.99	20.33	20.65	21.5
X14	Dead band of the controller [C]	0.43	1.16	0.65	0.52	2
X15	Glazing U-value [W/m2K]	1.24	2.31	1.51	1.57	1
X16	Internal shading relative darkness [ratio]	0.4	0.73	0.73	0.6	0.5
X17	Maximum power of the cooling beam [W]	331.4	536.8	338.7	503.08	510
X18	dT(coolant) at max power [C]	2.49	4.39	3.17	2.72	3.5
X19	dT(zone air-coolant) at max power [C]	6.81	8.44	7.68	7.35	8
X20	Night set-back temperature [C]	18.74	20.84	18.74	19.09	21.5
X21	Set-point temperature [C]	20.42	21.07	20.74	20.69	21.5
X22	Dead band of the controller [C]	0.38	1.29	0.61	0.42	2
X23	Glazing U-value [W/m2K]	1.16	2.11	1.47	1.33	1
X24	Internal shading relative darkness [ratio]	0.06	0.27	0.07	0.2	0.5

No optimal solution is achieved with the minimum acceptable *S*2-thermal comfort requirements (set-point deviations = 10%). Achieving optimal solution with minimum acceptable thermal comfort level requires additional saving in the energy consumption or additional reduction in the cooling equipment size. Manual estimations are performed showing that reducing the cooling equipment size (less than 17.5 and 28.5 W/m^2 at north and south zone respectively) increases significantly the S2-set point deviations. On the other hand, it is very difficult to reduce the primary energy consumption less than the minimum achieved value maintaining acceptable S2-thermal comfort level. Hence, additional optimization step is needed to achieve S2-solution with minimum energy consumption and minimum cooling equipment size.

The solution-space consists of combinations between 24 design variables (from X1 to X24) as shown in Table 1. The optimal ranges of those variables are summarized in Table 2. The optimal ranges give a first impression that realistic ranges are assumed for the problem. However, in-deep analysis shows important notices which can lead to better assumptions for the bounds. The results indicate that some of the design variables (X4, X6, X7, X8, X10, X11, X13, X14, X18, X19, X21, and X22) have insignificant or non influence on the results in some ranges. For instance, X7 (the night ventilation is not allowed X7 hours before the occupied period) is implemented to avoid unsuitable night ventilation at early morning. However X5 (the minimum exhaust air temperature at which the night ventilation is enabled) was sufficient to consider this issue. X5 was important to keeping the building at a reasonable warm temperature. This avoids much of overcooling at early morning. For the same reason (acceptable thermal comfort level at early occupied hours), X3 (minimum outdoor air temperature at which the night ventilation is enabled) is selected with minimum value of 7 ^{o}C. X3 has a small influence on the results. However X5 is the most effective parameter in the night ventilation control strategy.

The previous section shows that the implementation of the night ventilation was limited by acceptable thermal comfort requirements. Higher thermal comfort levels require less night ventilation use.

The maximum power of the cooling beam (X9 and X17) is addressed as design variable. Oversized ranges of cooling beam have insignificant or non influence on the results. However, reducing the cooling beam size increases dramatically the percentage of the set-point temperature deviations. The latter is proportional to number of occupied hours at which set-point-0.5 > T_{op}°C > set-point+0.5. Since a strict tolerance (±0.5 °C) is used, most of optimization simulation-runs are performed trying to achieve high level of thermal comfort. In the other words, less iterations are performed for S2 set-point temperature deviations > 5% (see Fig. 4). X9 and X17 were constrained by a lower bound 200 and 300 W, respectively. The optimal ranges shows that for optimal solution with S2 set-point temperature deviations ≤ 6.2 %, the minimum cooling equipment size is 208.6 and 331.4 W for the north and south zone respectively. This means optimal solutions with 10 % ≥ *S*2 set-point deviations ≥ 6.4 % could be achieved using smaller cooling equipment size. Hence, additional optimization step with a modified upper and lower bounds is needed to achieve minimum energy consumption and minimum cooling equipment size S2-solution.

The maximum power of cooling beam (X9 and X17), the temperature difference between inlet and outlet cooling beam water (X10 and X18), and the temperature difference between the cooling beam temperature surface and mean zone air temperature (X11 and X19) are required to select a suitable cooling beam. Higher temperature differences (X10 and X18) require less flow rate and consequently less pumping power. However lower temperature differences (X10 and X18) lead to lower operative temperature inside the zones. The opposite is true for X11 and X19. Table 2 shows the optimal range of the temperature differences (X18) at the south zone is lower than the optimal range of the temperature differences (X10) at the north one. Since the supply water temperature is constant (14 °C), the lower temperate difference requires lower cooling beam temperature surface. On the other hand, the optimal temperature difference range of X19 at the south zone is high than the optimal range of X11 at the north one. Since same temperature set-point is required inside the studied zone, higher temperature difference requires lower cooling beam temperature surface. From the previous notes, based on the new S2 requirements, it can be concluded that, a lower cooling beam temperature surface is required in the zones which have higher cooling load (e.g., south zones) more than the other zones.

The water radiator set-points (X13 and X21) have optimal range from 20.2 to 21 °C (less than the lowest set-point 21.5 °C). This was to avoid much of overlapping between heating and cooling. For the same reason, accurate PI-controllers with dead bands (X14 and X22) less than 1.3 °C are selected for optimal solutions. Using a very small dead band could be unrealistic. PI-controllers with dead band above 1°C could be acceptable solution.

In order to maximize the daylight (minimize the artificial lighting energy), the optimization algorithm selected relatively light-shading type as a building envelope solution (X24) for the south zone in most of the simulation runs. The north zone is relatively shaded by the building itself (machine room, see Fig. 2). This means the light shading could not help significantly to reduce the artificial lighting in the north zone. As a results dark-shading is selected in most of the simulation runs to reduce the heating energy (i.e., dark shading provides higher window surface temperature). On the other hand, compared with the south zone, higher range of glassing U-value is selected for north one.

In the new classification, *S*2-class requires 21.5 °C operative temperature set-points when the 24hr mean average outdoor temperature is less than 10 °C. Cold outdoor temperatures reduce the cooling demand. However, on the other hand, implementing lower indoor set-point temperature increases the cooling requirements. Finland has a cold climate most of the year. The results show that about 50% of the annual cooling energy was needed while the outdoor temperature is less than 10 °C. This percent could be reduced easily if a free cooling option was implemented.

5. Conclusion

Optimal solutions for high level thermal comfort (Classification-2008) office building are achieved by utilizing a multi-objective optimization scheme. Two phase optimization approach (PR_GA) was performed giving a set of optimal combinations between building envelope and HVAC design parameters. The optimal ranges of the 24 design variables are founded and analyzed. The analysis shows that 12 design variables have a marked influence on the results. However the others have less impact. Compared with a reference design, the simulation-based optimization approach allows 20% energy saving and 34% reduction in cooling equipment size.

In order to achieve *S*2 solutions both cooling and heating sources should be in operation during the whole year. Cooling device with sophisticated controller is needed to trace the *S*2 set-point profile. Since the heating and cooling are required during the whole year, suitable simulation optimization approach is needed to avoid much of overlap between heating and cooling (i.e., many of heating/cooling settings should be addressed as design variables). Office buildings have significant heat gains. Consequently, even in cold climate countries, optimization is required to reduce both heating and cooling energy uses (i.e., high insulation and non-shading solutions could reduce the heating demand; however, additional cooling will be required). Night ventilation is a good solution to reduce the cooling demands in moderate climate countries. However, in cold climate countries, the night ventilation increases the overcooling at early morning hours and/or increases the heating demands (e.g., water radiator size and/or heating energy use). Day lighting cuts much of the electrical energy use. However the day light increases the cooling demands (e.g., cooling beam size and/or cooling energy use) particularly if restricted definition is adopted for high thermal comfort level. Light internal shading could be a compromise solution. Suitable simulation optimization approaches is required necessarily if high level of thermal comfort and sustainable measures are design goals.

The results shows that the cooling equipment size and the primary energy consumption increase dramatically to achieve optimal solutions with *S*2 set-point deviation < 3%. *S*1 Class if adopted would require tighter control and additional heating/cooling demands than *S*2 Class. If very tight thermal comfort requirements do not provide a significant improvement for the performance of occupants, a minimum acceptable thermal comfort level (e.g., *S*2 set-point deviations=10%) could be a unique optimal solution for sustainable communities. No optimal solution with *S*2 set-point deviations > 6.2% is achieved in the current study. Additional optimization step with a modified solution-space and good initial population is proposed for a future work.

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