EARLY-STAGE ASSESSMENT FOR OFFICE BUILIDINGS CONCERNING THERMAL COMFORT, ENERGY EFFICIENCY AND SUSTAINABILITY

Anja Degens[1], Frank Scholzen[1], Christoph Odenbreit[1]
[1]Faculty of Science, Technology and Communication, Research Unit in Engineering Sciences, ArcelorMittal Chair of Steel and Façade Engineering, University of Luxembourg, Luxembourg

ABSTRACT

This paper shows the influence of relevant design parameters for highly glazed facades and light weight composite structures on energy demand, thermal comfort and environmental quality of office buildings. In detail constructive and technical measures have been identified to optimise this type of building in European climates. The results indicate that the ventilation strategy has a significantly higher influence on the energetic and thermal performance of the building than the structure type or the window-to-wall ratio. However, in case of an adequate ventilation strategy, the structure type becomes more decisive if thermal comfort shall be optimised.

INTRODUCTION

Office buildings account for a large portion of the total energy consumption in Europe. Due to increased comfort requirements almost all new buildings are air-conditioned. The European consumption of electricity for active cooling systems will increase fivefold between 1990 and 2020 according to studies of the European Commission (Maas et al., 2011). Therefore, one aim of European building directives is the energetic optimisation of non-residential buildings.

A tendency towards highly glazed facades for office buildings can be noticed despite their sometimes bad reputation for being a cause of comfort problems (Eicke-Hennig, 2006). In contradiction to that trend, current scientific research results recommend a lower window-to-wall ratio and structures with a high proportion of thermal mass to reduce energy consumption and overheating hours. On the other hand, light weight composite structures are an interesting alternative because of pre-fabrication possibilities and higher design flexibility. In addition, steel load bearing structures with large spans and less weight contribute to less “Grey Energy” and environmental impacts (BFS, 2011). The challenge is to find the “break-even-point” of this higher material effort for energetic and thermal comfort reasons in comparison to the environmental aspects.

The project results present an optimised constructional execution range to meet all requirements mentioned above considering the conflicts and dependencies already in the early design process, when it is crucial for planners to make profound decisions. Guidelines and planning recommendations for office buildings with a focus on highly glazed facades and light weight composite structures will be given. The consideration includes the energy demand and environmental impacts not only of the use phase but also of the entire life cycle of the building.

Existing tools

The majority of existing building performance simulation tools intend to map the building rather completely, which is the reason for high barriers concerning their application in the early design phase. It is a complex, costly and time consuming task which requires steep learning curves (Reichard et al., 2005). As a consequence, these calculations are often carried out in later planning phases, where many important decisions are already irreversible. All decisions during the project starting phase have a major influence on the costs of the construction and the use phase as well as the end-of-life phase of the building (Ritter et al., 2014).

For years computer-assisted design optimisation has relied on a manual “trial and error approach” to analyse relevant input parameters and parameter combinations. Nowadays automatic optimisation tools or platforms are available including advanced techniques for simulation-based design for example design of experiments (DoE), surrogate modeling, optimization and data-mining methods (Cenaero, 2014).

REFERENCE ZONE AND METHOD

The main features of a building can be analysed by using the reference zone method. It allows the estimation of the effects of different facade and structural solutions already in the optimization phase of the building (P881, 2015). The advantage lies in the fact that a rather simple model allows to quantify directly the influence of constructional and technical design parameters on energy demand and indoor climate conditions. The net energy demand of a reference zone shall be representative for the energy demand of the entire building. The generation of heat and cold (end energy) and the Primary Energy will be calculated in the next evaluation stage.

Office building and reference zone

The office building under consideration is a typical low- or medium-rise building of three to seven stories with a rectangular floor plan, which has a large market share (Lange at al., 2009). The selected organisation form is the “combination office concept”, see Figure 1.

All evaluations are based on a representative reference zone which can be applied to different types of building geometry and the commonly used office organisation concepts, for example the single office or open space solution. It is located in an intermediate storey of the building with a floor area of 110 m^2, which provides a work space for about ten persons. The facade grid is 1.35 m and the construction grid for columns, slabs and beams has been designed according to structural calculations. The opaque parts of the exterior wall are highly insulated (u-value of 0,17 W/m^2K) and the climate conditions of the boundary zones are identical to those of the reference zone.

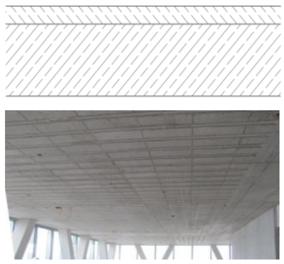
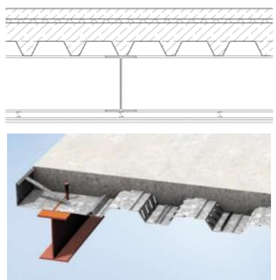
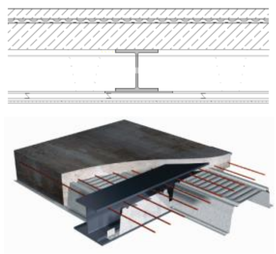
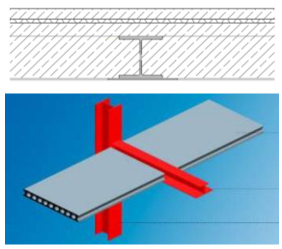
Figure 1 Floor plan and cross section of office building and reference zone

Structure type and Facade system

Typical solid and steel composite structure types of office buildings have been defined for the parametric study. They are optimised in terms of structural and material efficiency. The solid structure consists of reinforced concrete and screed (SOLID 1). The steel composite types are a conventional composite beam and slab with steel sheeting (STEEL 1) and an integrated floor beam system with steel sheeting (STEEL 2a) or precast concrete elements (STEEL 2b). Both systems consist of a floating screed and optional a suspended ceiling, see Table 1.

The facade system is a curtain wall structure as commonly used in office buildings. Three selected window-to-wall ratios represent a punctuated facade with a ratio of 48% (F 48), a band window facade with a ratio of 77% (F 77) and a fully glazed facade (F 100), see Table 2. The window-to-wall ratio calculation is based on the inside surface of the exterior wall and each window area consists of 80% glazing and 20% frame.

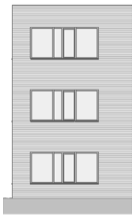
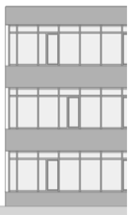
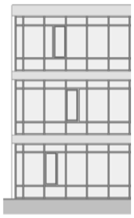
Table 1
Structure types of office building

TYPE	STRUCTURE	SKETCH AND IMAGE
SOLID 1	**solid** reinforced concrete with screed	
STEEL 1	**steel composite** steel beams, profiled sheeting + concrete, floating screed, suspended ceiling	
STEEL 2a	**steel composite** integrated floor beams, profiled sheeting + concrete, floating screed, suspended ceiling	
STEEL 2b	**steel composite** integrated floor beams, precast concrete element, floating screed, (suspended ceiling)	

Climate

The following parametric study is based on the moderate Western European climate of Saarbrücken, Germany. In a next step, the Southern European climate of Madrid, Spain and the Northern climate of Oestersund, Sweden will be part of the study. In Southern Europe the focus is on active cooling systems and in the North on the optimisation of heating demands. In addition, the need of de- and humidification will be analysed.

Table 2
Facade systems of office building

TYPE	F 48	F 77	F 100
SYSTEM			
WINDOW RATIO	48%	77%	100%

Parametric study

To determine the energy demand of the reference zone dynamic thermal simulations have been carried out with TRNSYS Version 17. These evaluations are focussed on the defined structure types and the main facade parameters such as orientation, window-to-wall ratio, shading devices and glazing types. In addition to these constructional parameters, the technical concepts ”controlled lighting system” and “ventilation strategy” have been analysed.

When planning an office building the number of parameters and parameter combinations that influence the energy demand is very high. In the early design phase it is necessary to identify and concentrate on the most important parameters in order to reduce the number of parametric studies and hence the time consumption of the user (Gratia et al., 2002). The parametric study of key parameters has been done by using a manual method where some input parameters are defined as fix or categorical with typical values of office buildings, see Table 3. The analysis will be continued by using an automatic optimisation tool where the key parameters will be more variable but as well defined as continuous, discrete or categorical.

Table 3
Definition of parameters

No.	PARA-METER	DEFINITION
1	Operation time	260 days/a, 2.860 hours/a USE time
2	Occupancy rate	10 Persons, seated, light work
4	Internal loads	12,5 W/m^2 office equipment
3	Lighting system	10 W/m^2, 40% fluorescent tube, light control function
5	Infiltration rate	0,1 h^{-1}
6	Heating	Set point indoor temperature: daytime 22°C, night time 16°C
7	Cooling	Set point indoor temperature: 26°C during USE time (7h-18h)
8	Ventilation strategy	VENT_MECH: Mechanical ventilation, constant air flow during USE, air change rate 1 h^{-1}, constant supply temperature of 18°C, heat recovery 70% VENT_NIGHT: VENT_MECH + optional enhanced night ventilation, air change rate 4 h^{-1} VENT_NAT: Natural ventilation, base rate 0.7 h^{-1} + optional enhanced daytime, air change rate 2 h^{-1} and night ventilation, air change rate 4 h^{-1}
9	Shading devices	SHON: External, radiation controlled, shading factor 0.7 SHOFF: Without external shading ELEC: Electrochromatic glazing, U_g = 0.78 W/m^{2}K, g = 0.407 - 0.05
10	Glazing types	EW1: Triple glazing, U_g = 0.6 W/m^{2}K, g = 0.584 EW2: Double glazing, U_g = 1.24 W/m^{2}K, g = 0.584 EW3: Double glazing, U_g = 1.23 W/m^{2}K, g = 0.436

RESULTS

Orientation

A previous analysis of different facade orientations has shown that the South West orientation in Western European climate is the most critical orientation concerning energy demand and overheating hours, see Figure 2.

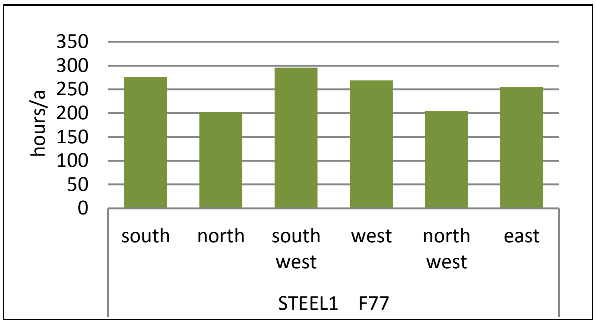


Figure 2 Overheating hours of different orientations

Therefore, the presentation of the further results considers the South West orientation of the reference zone.

Ventilation Strategy

The impact of the ventilation strategy has been analysed based on the structure types SOLID 1 and STEEL 1, the window-to-wall ratios of 48% (F 48), 77% (F 77) and 100% (F 100) and a triple glazing with external shading device.

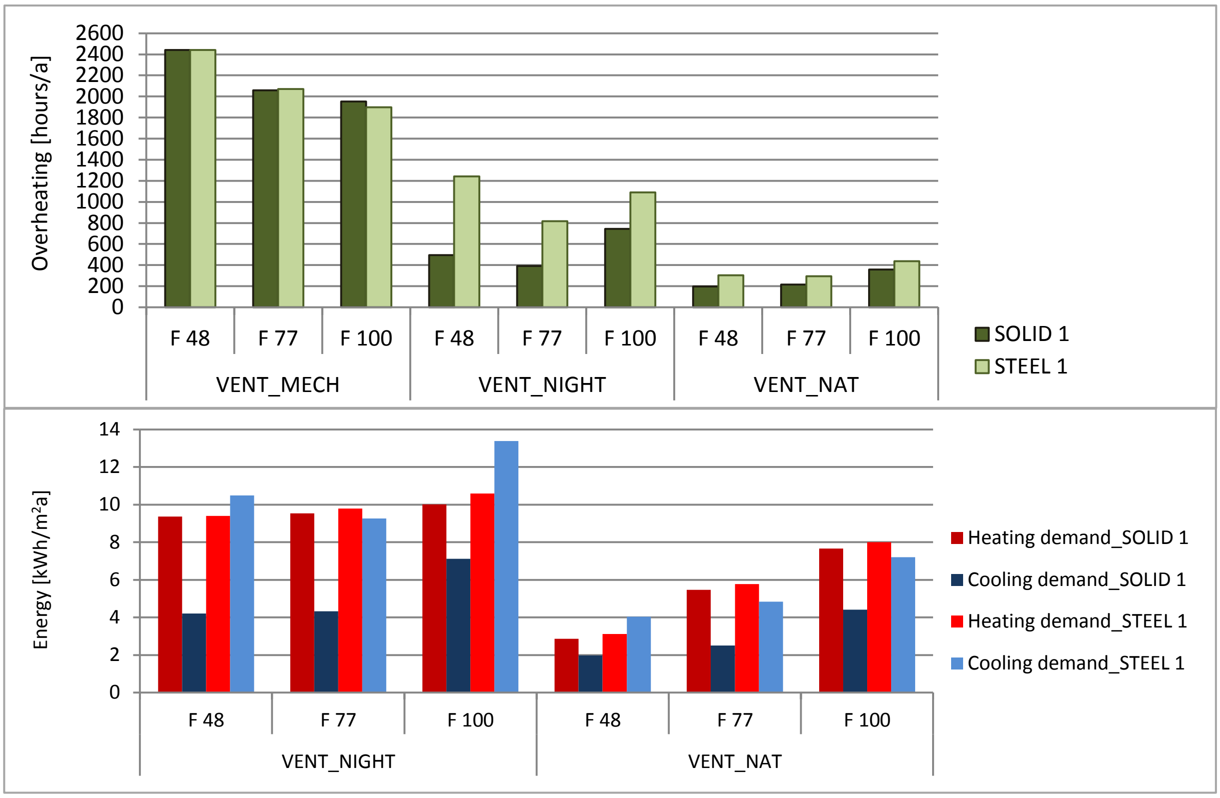


Figure 3 Overheating hours and energy demand of different types of ventilation strategy

The results are presented for the mechanical ventilation system with a constant air supply temperature during USE time and a heat recovery of 70% (VENT_MECH, see Table 3, parameter No.8) and for the system with additional natural night time ventilation (VENT_NIGHT, see Table 3, parameter No.8). The latter system benefits from the cooling effect of outside air during periods of overheating risk. The third system is an entire natural ventilation system (VENT_NAT, see Table 3, parameter No.8) with an air change rate similar to the other two systems and an enhanced day- and night time ventilation. In case of natural air flows, the air supply temperature is set to the outside temperature. The natural ventilation is regulated by upper and lower trigger values of the air temperature of the zone and additionally if it is higher than the outside temperature with a sufficient temperature difference.

Figure 3 shows that the ventilation strategy has a significantly higher influence compared to the parameter window-to-wall ratio and structure type. The system VENT_MECH based on a constant air supply temperature without natural ventilation causes the most overheating hours. The strategy VENT_NIGHT with enhanced natural night time ventilation improves the situation but the amount of overheating hours remains in an uncomfortable range. An acceptable range can be reached with VENT_NAT if a consequent natural day- and night time ventilation for efficient heat removal is applied during periods of overheating. In this case, the reference zone complies almost with general comfort requirements, if a lower window-to-wall ratio is selected. However, both structure types still have a comfort problem, because the user has to accept temperatures above 26°C during more than 200 hours a year, even if 10% overheating hours a year during USE time are standard (approx. 240 hours/a). The advantage of the natural ventilation is the cooler air supply temperature but for the design of air inlets it has to be taken into account that an outside temperature can cause local discomfort.

Structure type

The results indicate that the structure type has only minor influence on the heating demand but a substantial influence on the cooling demand, see Figure 3. The steel composite structure with profiled sheeting, concrete, floating screed and a suspended ceiling (STEEL 1) leads to a higher cooling demand and in case of none air-conditioned building to more overheating hours than the solid structure consisting of reinforced concrete and screed (SOLID 1). Whether the structure type (mass) or the slab type respectively the suspended ceiling (accessibility of the mass) is decisive will be discussed in the next chapter "Influence of slab types".

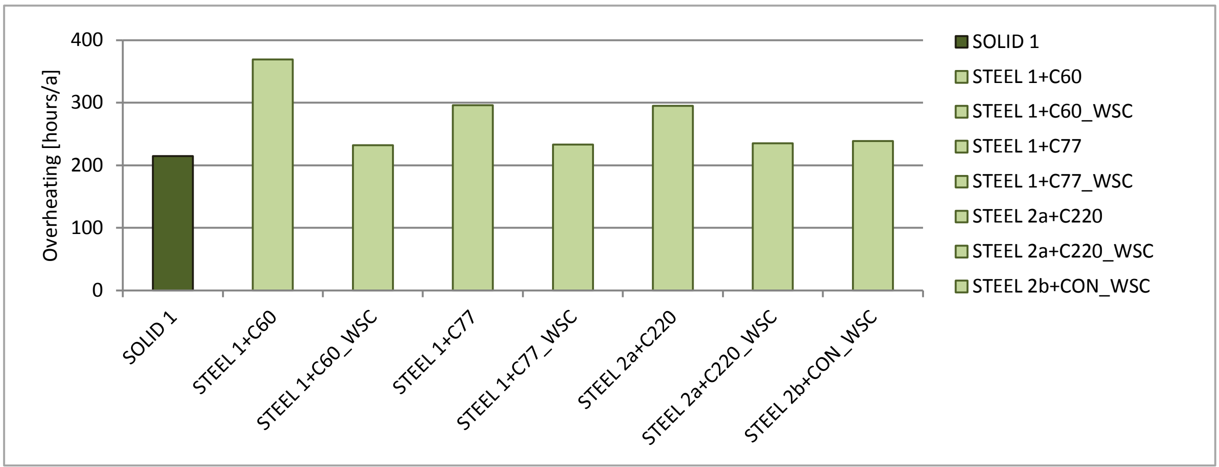


Figure 4 Overheating hours of different slab types of steel composite structure

Influence of slab types

In a first parameter study, the different slab types of the solid structure (SOLID1) have been analysed. The assumption that the energy demand and the overheating hours increase significantly if the thermal storage capacity of the reference zone is reduced for example by adding a false floor (FF) instead of a screed (SR) or a suspended ceiling (SC), has been confirmed, see Figure 5.

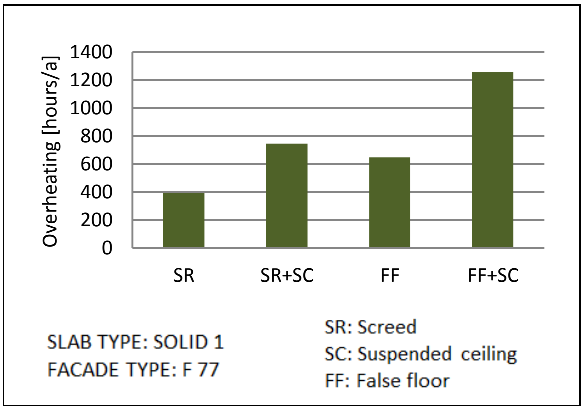


Figure 5 Overheating hours of different slab types of solid structure with VENT_NIGHT

In a second study, the parameters of the steel composite slabs have been varied like the mass of the slab and the accessibility of the mass for example by removing the suspended ceiling and replacing the profiled sheeting with precast concrete elements, see Table 4. The analysis is based on the ventilation strategy VENT_NAT, a window-to-wall ratio of 77%, a triple glazing and an external shading device.

Removing the suspended ceiling (cases marked in Figure 4 as “WSC”) of the steel composite structures has enormous effects on the overheating hours, which can be reduced to similar values as in case of uncovered solid structures, see Figure 4.

The choice of the slab type and the mass have less influence than expected but if an enhanced natural day- and night time ventilation is applied the influence of a suspended ceiling becomes decisive. (Leenknegt et al., 2013) have shown that the accessibility of the thermal mass has a strong influence regarding on the reduction of overheating hours. However, in office buildings slabs are commonly covered with a suspended ceiling to use the space for technical installations or to implement sound insulation elements. An alternative to comply with acoustic and thermal comfort requirements are free hanging sound absorbers or acoustic panels on walls. The simulation of the impact of sound absorbers is not part of this project but of ongoing research studies (Lombard, 2015).

Table 4
Slab types of steel composite structure

SLAB TYPE	NOMEN-CLATURE	DEFINITION
SOLID 1		280 mm concrete, 70 mm screed
STEEL 1	C60	profiled sheeting C60 + 100 mm concrete slab, floating screed and suspended ceiling
STEEL 1	C60_WSC	without suspended ceiling
STEEL 1	C77	profiled sheeting C77 + 130 mm concrete slab, floating screed and suspended ceiling
STEEL 1	C77_WSC	without suspended ceiling
STEEL 2a	C220	profiled sheeting C220 + 190 mm concrete slab, floating screed and suspended ceiling
STEEL 2a	C220_WSC	without suspended ceiling
STEEL 2b	CON_WSC	precast concrete elements 230 mm depht, floating screed

Glazing types and shading devices

Current developments in material science offer new facade technologies, for instance electrochromic switchable glazing technology. It allows the variation of visible light transmission and solar heat gain coefficient (g-value) to adjust heat and light in relation to interior comfort requirements (Meek et al.,

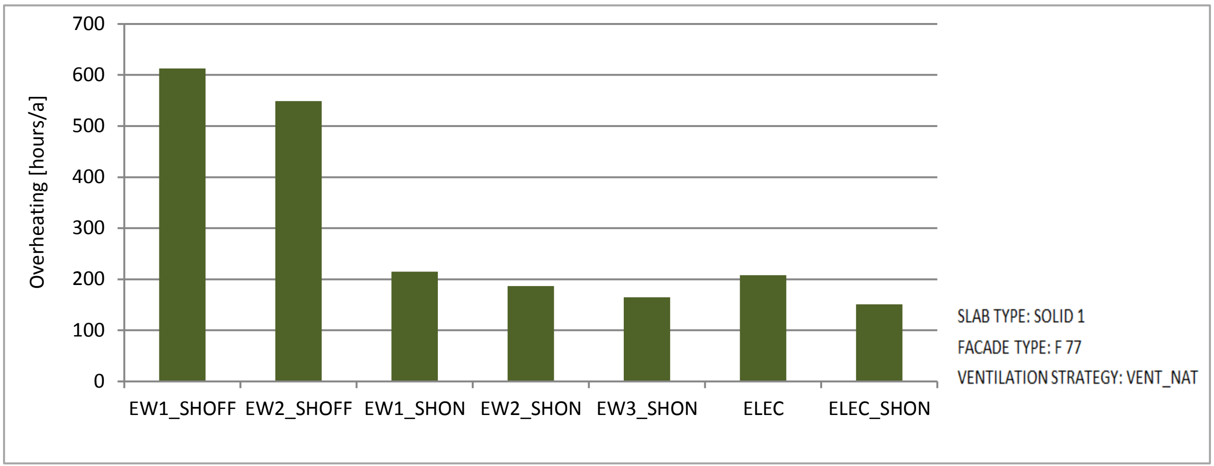


Figure 6 Overheating hours of glazing types and shading devices

2013). The authors (Lee et al., 2006) revealed for instance that the switchable glazing technology has shown a cooling load reduction of the building of about 20% and lighting power savings of 50% or more when combined with a photo-responsive lighting control.

The analysis of different glazing types and shading devices, see Table 5, is based on the solid structure, a window-to-wall ratio of 77% and the ventilation strategy VENT_ NAT.

Table 5
Glazing types and shading devices

NOMEN-CLATURE	DEFINITION
EW1	Triple glazing, U_g = 0.6 W/m^{2}K, g = 0.584
EW2	Double glazing, U_g = 1.24 W/m^{2}K, g = 0.584
EW3	Double glazing, U_g = 1.23 W/m^{2}K, g = 0.436
SHON	External shading device, radiation controlled
SHOFF	Without external shading device
ELEC	Electrochromatic triple glazing, U_g = 0.78 W/m^{2}K, g = 0.407 - 0.05

The comparison of the three glazing types in combi-nation with an external shading device reveal, that the overheating risk is higher when using a triple instead of a double glazing with an equivalent g-value (see EW1_SHON and EW2_SHON, Figure 6). The higher transmission losses of the double glazing are beneficial in this case. The overheating hours decrease due to less solar gains if the g-value of the double glazing is reduced from 0.584 to 0.436 (see EW2_SHON and EW3_SHON, Figure 6).

A radiation controlled external shading device is essential to improve thermal comfort. An interesting alternative to such a conventional device is an electrochromatic glazing (ELEC). Both systems show approximatively the same performance and a combination of them would mean a further small improvement (ELEC_SHON), but of course costs for two systems will arise.

CONCLUSION AND OUTLOOK

The study has investigated the parameters

- Structure type
- Slab type
- Window-to-wall ratio
- Ventilation strategies
- Glazing types
- External shading devices and
- Electrochromatic glazing

and their influence on the energy demand and the overheating hours of a “reference office zone”.

Due to the fact, that the design challenges in moderate Western European climate lie more in the field of cooling respectively overheating than in heating issues the parametric study is focussed on the optimisation of thermal summer comfort. The thermal behaviour of office rooms is more influenced by the internal and external loads than by transmission losses. The results show that a ventilation strategy with enhanced natural day- and night time ventilation is a simple and powerful option for office buildings to reduce overheating by ventilating “away” heat loads. It is more important for the thermal and energetic performance than other building related design parameters like the window-to-wall ratio or the mass of the structure type (solid or steel composite structure). However, if such an adequate ventilation strategy is applied the structure and slab type become decisive to achieve summer comfort and low cooling energy demand.

The differences between the solid and the steel composite structures are not as significant as expected. For both structure types the accessibility of the mass is essential when it comes to use thermal storage capacity. To comply with thermal and acoustic comfort requirements alternatives to a suspended ceiling should be installed like free hanging sound absorbers or acoustic panels on walls.

The window-to-wall ratio has effects on the transmission losses, the solar gains and the daylight use. These three effects influence the energy demand

and an optimum is difficult to predict. For the configuration presented, a band facade with 77% window-to-wall ratio shows a better performance than a punctuated or a fully glazed facade, assuming that a radiation controlled lighting system is used. A lower glazing area leads to more artificial lighting and a larger area to higher solar gains. The standard 3D building project of TRNSYS 17 supports the simulation of illuminance values corresponding to daylight factors but in addition a detailed external daylight simulation will be applied to analyse the visual comfort of the reference zone.

The aim of further research is to extend the range of optimisation steps of the steel composite structures. In this project they have been conducted as flat slabs with or without suspended ceiling but according to (Döring, 2008), it can be assumed that profiled steel sheet deckings have a higher effective thermal capacity than conventional flat slabs. Additional technologies like phase change materials will be integrated into future simulations because they can increase the thermal capacity of light weight systems (Döring, 2008).

For an overall evaluation of the building design parameters not only the energy demand of the use phase but also the energetic and environmental impacts of the whole life cycle including construction and end-of-life phase have to be considered. A life cycle assessment (LCA) of the reference building is an important factor of the investigation.

A systematic sensitivity analysis with statistical methods and an automatic design approach by using an optimisation platform is in progress due to a growing amount of input parameters and thus a large number of thermal simulations required. The aim is to rank the parameters according to their impact and importance on energy demand, thermal comfort and environmental quality and to give easy applicable design guidelines for the early planning phases.

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