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by

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Born on 26 February 1972 in Trier, (Germany)

DESIGN GUIDELINES FOR HIGHLY GLAZED OFFICE BUILDINGS IN STEEL COMPOSITE CONSTRUCTION DEVELOPED BY USING DYNAMIC THERMAL SIMULATIONS, OPTIMISATION METHODS AND LIFE CYCLE ASSESSMENT

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Abstract

Since the middle of the past century a trend towards highly glazed office buildings has been gaining ground throughout nearly all regions of the world. The control of the indoor climate has been achieved by an increased level of facility technology. This is the reason why many of these buildings are equipped with full climate control. Now that the scarceness of resources and climatic change, are increasingly recognised with a rising awareness, a return to climate-adapted architecture and low-tech concepts can be noticed. Research works and planning recommendations in this area, however, set boundaries to the design flexibility e.g. by standard definitions of ratios of window area or the structure type. As a consequence, the research issue of this project is focused on the development of design guidelines and optimisation steps for the early planning phase of office buildings. The central point of interest is on the question if and to what extent highly glazed office buildings in steel composite construction can be implemented in terms of energy efficiency, comfort requirements and environmental quality. The project is divided into four different fields of analysis: a parameter study based on thermal simulations, a sensitivity analysis, measurements and a life cycle assessment. The sensitivity analysis helps to evaluate the simulation results by using multivariate statistical methods. The establishment of energy and emission characteristic values of various case studies and the direct comparison of these values offers the possibility to evaluate different designs related to facade, structure type and the selection of materials. The results have illustrated that the steel composite structure can compete with solid structures with regard to the above mentioned requirements, especially when taking into account the high recycling potential of steel. In addition large spans are offered by a high flexibility of floor plans, the possibility of alternative use in future and thus a prolongation of the potential use life of office buildings. From an energetic point of view, the ratio of window area, shading devices and type of glazing require a very differentiated approach and the consideration of the orientation during the process of the facade design. A band window facade is the most suitable compromise for the optimisation of the heating and cooling energy requirements as well as for the efficient use of daylight. Further potential for optimisation is provided by the lighting being the decisive parameter for the primary energy demand. In our temperate European climate zone, office buildings with low-tech concepts can be easily implemented, which may lead to a primary energy demand of less than 100 kWh/(m^2a) for heating, cooling, ventilation and lighting without considering office equipment and further auxiliary energy demand. Key parameters are the accessibility of the slabs and the fine-tuning of the natural ventilation strategies using passive cooling effects. The limits of such concepts, however, are represented by the risk of overheating, especially in the context of increased daytime temperatures caused by e.g. urban planning factors or also climatic changes. In Northern or Southern Europe the implementation of low-tech concepts is recommended only under certain conditions.

Zusammenfassung

Seit Mitte des letzten Jahrhunderts hat sich ein Trend hin zu hochverglasten Bürogebäuden in nahezu allen Regionen der Welt durchgesetzt. Die Kontrolle des Raumklimas wurde durch zunehmende Gebäudetechnik erreicht. Aus diesem Grund sind viele dieser Gebäude mit einer Vollklimatisierung ausgestattet. Durch die Erkenntnis und das Bewusstsein von Ressourcenknappheit und Klimaveränderungen lässt sich jedoch eine Rückbesinnung auf eine an das Klima angepasste Architektur und sogenannte „low-tech“ Konzepte erkennen. Forschungsarbeiten und Planungsempfehlungen in diesem Bereich schränken jedoch die Gestaltungsfreiheit ein, z.B. durch pauschale Festlegungen des Fensterflächenanteils oder der Bauweise. Aus diesem Grund konzentriert sich die Forschungsarbeit darauf, Planungsempfehlungen und Optimierungsschritte für die frühe Planungsphase von Bürogebäuden zu entwickeln. Die Frage, ob und in welcher Hinsicht hochverglaste Bürogebäude in Stahlverbundbauweise in Bezug auf Energieeffizienz, Komfortanforderungen and ökologische Qualität umsetzbar sind, steht dabei im Mittelpunkt der Untersuchungen. Die Forschungsarbeit gliedert sich in vier verschiedene Untersuchungsgebiete: eine Parameterstudie basierend auf thermischen Simulationen, eine Sensitivitätsanalyse, messtechnische Untersuchungen und eine Lebenszyklusanalyse. Durch die Sensitivitätsanalyse können die Simulationsergebnisse unter Anwendung multivariater statistischer Methoden ausgewertet werden. Die Entwicklung von Energie- und Emissionskennwerten verschiedener Fallstudien und ein direkter Bezug dieser Werte zueinander, bieten die Möglichkeit verschiedene Entwürfe in Bezug auf die Fassade, die Bauweise und die Materialauswahl zu bewerten. Die Ergebnisse zeigen, dass die Stahlverbundbauweise in Bezug auf die oben genannten Anforderungen konkurrenzfähig ist gegenüber einer Massivbauweise, vor allem unter Berücksichtigung des hohen Recyclingpotentials von Stahl. Hohe Spannweiten bieten zudem flexibel nutzbare Grundrisse, größere Umnutzungsmöglichkeiten und damit eine Verlängerung der potentiellen Lebensdauer von Bürogebäuden. Das Fassadendesign ist in Bezug auf die drei Parameter Fensterflächenanteil, Sonnenschutz und Verglasungsart aus energetischer Sicht sehr differenziert und unter Berücksichtigung der Gebäudeorientierung zu entwerfen. Eine Bandfassade ist der beste Kompromis zur Optimierung des Heiz- und Kühlenergiebedarfs sowie einer effizienten Nutzung des Tageslichtes. Weiteres Optimierungspotential bietet die Beleuchtung, da sie der entscheidende Parameter für den Primärenergiebedarf ist. In der gemässigten Klimazone Europas ist die Umsetzung von Bürogebäuden mit „low-tech“ Konzepten gut möglich und kann zu einem Gesamtprimärenergiebedarf von unter 100 kWh/(m^{2}a) für Beheizung, Kühlung, Lüftung und Beleuchtung führen, ohne Berücksichtigung von zusätzlichem Bedarf für Hilfsenergie und Büroausstattung. Schlüsselparameter sind die Zugänglichkeit und damit die thermische Nutzbarkeit der Deckensysteme und die Feinabstimmung natürlicher Lüftungsstrategien zur Nutzung von passiven Kühleffekten. Es zeigen sich jedoch auch die Grenzen dieser Konzepte im Bereich des Ueberhitzungsrisikos, vor allem im Hinblick auf steigende Tagestemperaturen z.B. durch städtebauliche Randbedingungen oder auch Klimaveränderungen. In Nord- und Südeuropa ist die Umsetzung von „low-tech“ Konzepten nur eingeschränkt empfehlenswert.

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1 Introduction

1.1 Background

The architectural design is understood to be a process of transforming a room programme into a spatial shape and its integration in an urban planning situation [Hönger]. In this context, the freedom of design and the possibilities to exercise controlling influence on the building are greatest in the planning phase and any modifications in a later work phase mostly imply huge efforts, see figure 1.

« Was nicht von Anfang an einbezogen wird, lässt sich nicht nachträglich implementieren[1]. »
[Hönger]

Already in the early planning phase climatic, resource and energetic aspects should have a significant influence on the typology, construction and the selection of materials [Hönger]. Over the past decades the aspects of a climate-adapted architecture began their gradual descent into almost total oblivion in our regions due to the availability of cheap and seemingly unlimited fossil fuels [Hube]. When looking at new office buildings all over the world, this is not only a European problem. An international style detached from climatic aspects leads to unbalanced solutions, which as a consequence are the reason for high demand of electricity and fossil fuels [Hausladen, 2012]. High comfort requirements are met by means of the so-called "compensation method" according to [Hönger] in the form of highly developed building service engineering (full climate control). The high energy demand of the existing buildings reflects these developments. On the other hand new findings related to the scarcity of resources and climatic change have already initiated a return to so-called low-tech concepts [Hube]. In our temperate climate zone the aims of sustainable building design can be achieved by means of building shape and interior concept as well as passive utilisation of building elements combined with a reduced building technology. In this design process the attempt is to match the economical, ecological and socio-cultural requirements of various national sustainability certification systems (LEED, BREAM, DGNB).

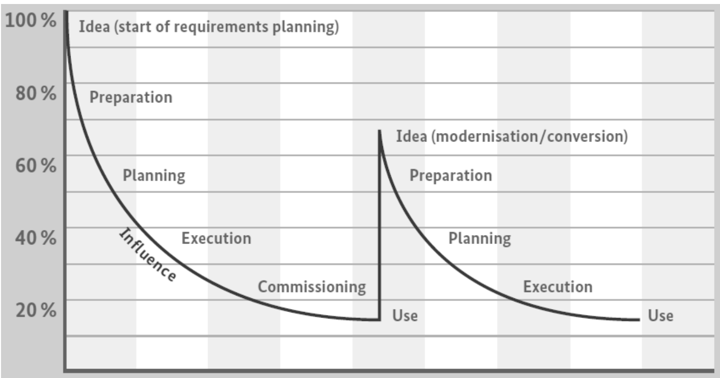


Figure 1: Options for a direct influence on a building during the life cycle [BMUB-1]

Employments in the field of administration and service have increased with the effect that people spend most of their working time in so-called "office buildings". As a result, aspects of socio-cultural quality, which evaluate the factual circumstances related to well-being and

[1] What we failed to include from the very beginning, cannot be implemented belatedly.

productivity, have gained a growing importance. In this context, the focus is nowadays on the quality of physical working criteria such as thermal, visual and acoustic comfort and indoor climate. In future, further aspects of ergonomic science and environmental psychology as well as the evaluation of the conceptual approach of building design should be given greater consideration in the certification systems. Significant points to provide a good working environment are very good acoustic qualities, natural light conditions and the option for a direct control of the technical installations by the user as well as a personal protective atmosphere [FOSTA].

1.1.1 Office buildings

Recent developments in the field of office and administration buildings reflect a trend towards highly glazed and fully air-conditioned buildings. The call of property owners and investors for buildings with a light and “modern” appearance and a transparent design, which put a stamp on a location due to their public image, have been responded to, see figure 2. On the other hand, the results of numerous scientific examinations and studies on the topic of energy efficiency recommend a building concept with a low proportion of window area and a solid structure in order to increase the thermal storage capacity, see chapter 2. The possible environmental advantages of a lightweight construction and the major flexibility of steel and steel composite structures are often neglected.

Figure 2: Example for a building that put a stamp on a location, Berlin Potsdamer Platz [Flickr]

A closer look at the energy balance of office buildings reveal that considerable progress has been achieved in recent years owing to national thermal insulation regulations. The energy required for cooling and ventilation systems as well as the lighting of a building are increasingly the focal point especially in combination with the objectives defined by the European Directive 2010/31/EU related to the energy performance of buildings [Döring]. A previous study of the University of Luxembourg on the real energy consumption of schools and office buildings is a further proof of the fact that heating requirements influence the high primary energy demand of office buildings to a lesser extent than the electricity required for the air-conditioning and the artificial lighting of the buildings [Thewes].

1.1.2 Facade design

The facade system, consisting of opaque and transparent parts, is the structural element with the highest impact on the energetic and environmental quality of a building. Energy demand

and room comfort, e.g. thermal, acoustic, visual comfort as well as air quality, are mainly determined by the structure of the opaque exterior wall element, the choice of the window ratio, the selected shading device and types of glazing. Since climatic conditions are constantly changing, the requirements placed on facade systems are manifold and alternating. During the heating period the aim is to reduce heat losses to a minimum and obtain high energy inputs. When there is a risk of overheating (cooling mode), the goal is to achieve high heat losses and low energy input [FOSTA]. In addition, the design of the facade system is directly linked to the efficient use of daylight and the planning of natural ventilation strategies.

1.1.3 Structure types

In many European countries a lot of office and administration buildings remain unoccupied, not only as a result of the banking and financial crisis of 2008, but this is also a clear signal for structural problems [Eisele]. Many existing buildings cannot be adapted to the technical and spatial requirements of new forms of office organisations such as e.g. non-territorial office structures, the business club or combi-office. In the meantime sustainability aspects related to flexibility, adaptive capacity and conversion feasibility of a building have gained considerable importance for investors. They can be considered as a positive factor in terms of market value and constitute an important part of several sustainability certifications. However, no suitable methods exist for a monetary evaluation of these sustainability aspects of office buildings [Eisele].

In Germany and Luxembourg the standard solution for new office buildings mostly consists of solid concrete structures. Steel or steel composite structures are usually not taken into account by building owners and planners [Eisele]. Potential advantages such as e.g. the high degree of prefabrication, the little construction weight and potentially large spans are often excluded from consideration. These aspects, however, might contribute to a higher flexibility of the building [Eisele].

1.1.4 Early planning phase and practicable tools

Especially in the early planning phase, before an engineering or interdisciplinary planning team has taken over responsibility, building designers are confronted with the reconciliation of the latest developments on the real estate market, recommendations from science and research as well as increasingly severe national and European legislations. Nevertheless, all crucial decisions concerning the construction type, architectural style and facade design are taken in this planning phase. The problem lies in the lack of practicable tools suitable to verify the direct influence of different design parameters on the energetic, environmental and economic quality of the building concept. 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 design phase. It is a complex, costly and time-consuming task, which requires steep learning curves [Reichard]. As a consequence, these calculations are often carried out in later planning phases, where many important decisions are already irreversible.

The status of current developments underlines the necessity to supply all the planners actively involved in practice with the scientific expertise already in the design phase.

1.2 Aim of research

The tendency towards solid structures in Western Europe has various reasons. Planners and building owners mostly rely on conventional standard solutions [FOSTA] and lightweight or steel composite structures are often assumed to be the reason for comfort problems. In Luxembourg e.g. planning guidelines for public buildings [ABP] suggest to opt for solid structures and a low ratio of window area considering the whole life cycle of the building. These and further recommendations of scientific studies which propose lower ratios of window area (described in chapter 2.7.2) set limits to the planner's design flexibility.

Therefore the focus of this research project is on highly glazed facades and steel composite structures. The aim is to clearly identify the impact of design decisions on energy efficiency, thermal comfort and environmental quality and to give answers to the following questions:

In which way is it possible to optimise energetic and environmental quality of a highly glazed building with a ratio of window area of more than 70% in steel composite structure?
Whether and in what respect are steel composite structures able to compete with solid structures?
Which constructive and technical possibilities are offered by low-tech concepts and where are the limits of this approach?

The central points of the examinations consist of

- the thermal storage capacity of slab systems combined with various ventilation strategies and of
- the facade design in connection with the use of daylight and comfort requirements.

The main objective of this study is the development of general planning recommendations and design guidelines for the early planning phase and to extend the range of optimisation steps for highly glazed office buildings in steel composite structure. The analysis will be carried out taking into account an overall, life cycle oriented and sustainable building design.
Therefore a reliable database is required and in consequence a huge amount of design parameters and several structure types has to be integrated into the analysis. The guidelines are supposed to contain information referring to the choice of building materials, the construction type and facade design. They will be corroborated by the application of statistical methods and the results of comparable studies. A planning instrument that is easy to handle ought to be developed with the further possibility to evaluate different concept scenarios in terms of their energetic and environmental impacts. For this purpose the most important design parameters are to be identified and quantified as they form the basis of the graphical presentation of so-called "rules of thumb".

Energy and emission characteristic values relating to the whole life cycle of a building serve as the database that allows the development of a professional planning tool. Within the scope of this project energetic and environmental characteristics for office buildings shall be developed and reflect scientific evidence. A cost analysis is not an integral part of this study, instead reference is made e.g. to the interdisciplinary research project [FOSTA], in which these aspects are explained in detail as well as the ergonomic and statistical requirements set on office buildings.

1.3 Research Methodology

Subject of this study is a theoretical, expertise-based parameter study supposed to analyse various architectural concept decisions that are typical for office buildings. This justifies the necessity to develop a reference office building as a working basis in line with future requirements on energy-efficient and sustainable new buildings. In order to be representative for diverse forms of office organisation, a high level of flexibility in terms of floor plan layout and supporting structure is to be achieved. Part of the building will be defined as the so-called “office zone” according to the reference zone method, see chapter 3. Within the scope of this project this reference zone serves as a basis for all energetic and environmental evaluations.

This study is divided into four areas of examination. First part is an expertise-based parameter study whose subject is the evaluation of energy efficiency and thermal comfort with the help of dynamic, thermal building simulation software. Result of this part is the net energy demand for heating and cooling and the number of overheating hours during the period of one year. The statistical review of the simulation results demand a sensitivity analysis, the second part, which is carried out by means of an optimisation tool and the use of multivariate, statistical methods of analysis. The objective is to identify and quantify energy-relevant key parameters and to develop optimisation steps for highly glazed buildings in steel composite structure. Therefore, the tool will also be used for the design of experiments (DoE) and the optimisation process. The focus of evaluations lies on the following design parameters:

- orientation
- window area (window-to-wall ratio)
- structure type (thermal storage capacity and material selection)
- slab type
- shading devices
- glazing type (Ug-value and g-value)
- ventilation strategies
- lighting strategies

Supplementary to the theoretical analyses, a series of measurements, the third part, is performed in an office of the University of Luxembourg aiming at the metrological verification of the actual thermal storage capacity of a solid slab and its impact on the indoor climate and the subsequent evaluation in comparison to the theoretical simulation results of the same room.

The fourth part, a comparative environmental evaluation of the office zone based on the methodology of life cycle assessment (LCA) illustrates the environmental impacts of design decisions with regard to building materials and structure type on material, component and building level. Energy and emission characteristic values related to the primary energy demand and the global warming potential of the product phase will be developed and set in a direct relation to the values related to the operational energy use of the office zone. The consideration of the end-of-life scenarios and of the recycling potential plays a decisive role particularly for the important building materials concrete and steel.

Finally, the results will be summarised in the shape of generalisable planning recommendations and design guidelines for the early planning phase. Optimisation steps for highly glazed buildings in steel composite and solid structure will be pointed out in a clear manner. The graphical presentation of the “rules of thumb” developed and the verification of the design guidelines by means of the application of selected case studies form the conclusion of these evaluations. The following chapters of this study reflect the procedure described herein.

2 State Of The Art

This project is located in the context of many divergent aspects that are crucial for the planning and construction of future office buildings. In the early design phase, in which all decisions with relevance for the building in terms of energetic and environmental impacts have to be taken, the planner is faced with conflicting goals as follows:

- trend in the property market and clients requests vs. scientific research
- highly glazed facades vs. low ratio of window area or punctuated facade
- solid structure vs. lightweight structure
- supporting structure of concrete vs. steel-, or steel composite construction
- low-tech concept vs. high-tech building control
- passive cooling vs. air-conditioning to fulfil comfort requirements
- self-efficacy of users and user satisfaction vs. control of the technical installations e.g. shading devices and lighting control
- optimisation of thermal comfort in summer vs. thermal comfort in winter.

Based on these concept decisions the following chapter gives an overview of the most important principles and key parameters for a sustainable building planning.

2.1 Energy efficiency

When talking about office buildings of the future, the focus lies on the present developments in the field of zero-energy and plus-energy buildings. The implementation of the European Directive “Energy Performance of Buildings EPBD, 2010” seeks to ensure that all new buildings to be nearly zero-energy by the end of 2020 and all new public buildings must be nearly zero-energy by 2018 [EU 2010/31/EU]. Apart from high overall energy efficiency, based on the passive house standard, a major part of the energy demand is supposed to be covered by renewable energies. Furthermore, some EU Member States aim at the elimination of greenhouse gas emissions by the year 2050. Also the energy demand of the existing buildings is expected to be further reduced with the remaining demand to be covered by renewable energies [Voss, 2016].

For the planning of office buildings the implementation of these targets means:

- a further reduction of the energy demand especially of electrictiy consumption
- energy efficiency in operation and during the whole life cycle
- a minimum of emissions
- energy demand covered by renewable energies

However, it is not necessary to operate office buildings with an autonomous power supply because e.g. the roof area covered by photovoltaic panels would have to correspond to the floor space [Leibundgut]. In contrast, [Voss, 2016] is of the opinion that the objective is the continued development of energy and facility management concepts whose subject is the energy generation and storage on site and/or the buildings’ optimum convenience to the network. The buildings should have a connection to an energy supply network plus flexible concepts operating in conformity with this network [Voss, 2016]. In case of zero-energy buildings in the future the focus will be directed primarily on the resources required during the whole life cycle, especially concerning product phase, end-of-life and recycling potential of the materials.

The results of a study of the German Federal Ministry of Economics and Technology (BMWi), research field for energy-optimised buildings (EnOB), state that the importance of electricity consumption has increased in the total energy balance of a building by the increasing insulation measures in the last years. The energy saving potential in today's office buildings is particularly in the primary energy demand for electricity consumption, e.g. for ventilation, air-conditioning and lighting equipment. Optimised or even passive cooling concepts can significantly reduce electrical energy consumption. In consequence a primary energy demand for heating, cooling, ventilation, lighting and auxiliary power up to 100 kWh/(m^{2}a), based on the net floor area, should be achieved according to the funding requirements "energy-optimised construction" [EnOB]. The examination of 18 administration buildings within the scope of the EnOB study clearly demonstrates that characteristic values of electricity consumption of less than 100 kWh/(m^{2}a) of primary energy can be achieved but it also illustrates the problems particularly in terms of property renovation. In average the existing buildings have a higher demand of 129 kWh/(m^{2}a) whereas new buildings reach values of 54 kWh/(m^{2}a) [Voss, 2016]. Figure 3 shows the specific primary energy consumption and greenhouse gas emissions for heating, cooling, lighting and ventilation of the administration buildings under examination.

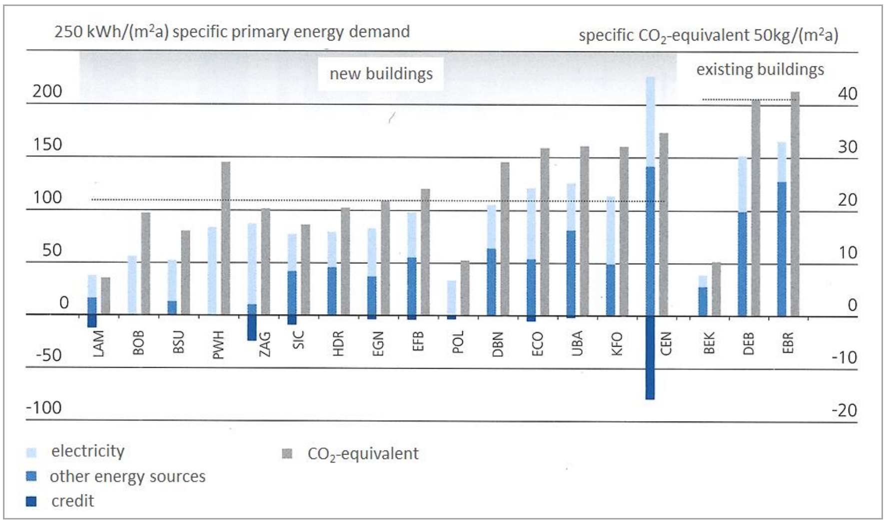


Figure 3: Primary energy demand of 18 office buildings of a German research study [Voss,2016]

A field study of 38 existing office buildings in Luxembourg, however, shows the discrepancy between research efforts and the constructional reality. The primary energy demand of the buildings examined leads to an average value of approx. 677 kWh/(m^{2}a) [Thewes]. Partially these data, however, include the user electricity for office equipment, servers etc., which is usually left out in the calculations of other studies. Therefore, a direct comparison is hardly possible. The problem when capturing the data is that frequently separate measuring devices are not available in order to carry out an accurate energy monitoring.

The energy characteristic values of the buildings examined in Luxembourg und comparable values from other European countries demonstrate that the buildings' high level of technology leads to an increase in primary energy demand. The consumption in fully air-conditioned offices exceeds that of not or partially air-conditioned buildings by the factor 2 or 3 [Thewes]. Reason for this is the high demand for electricity and cooling production, see figure 4.

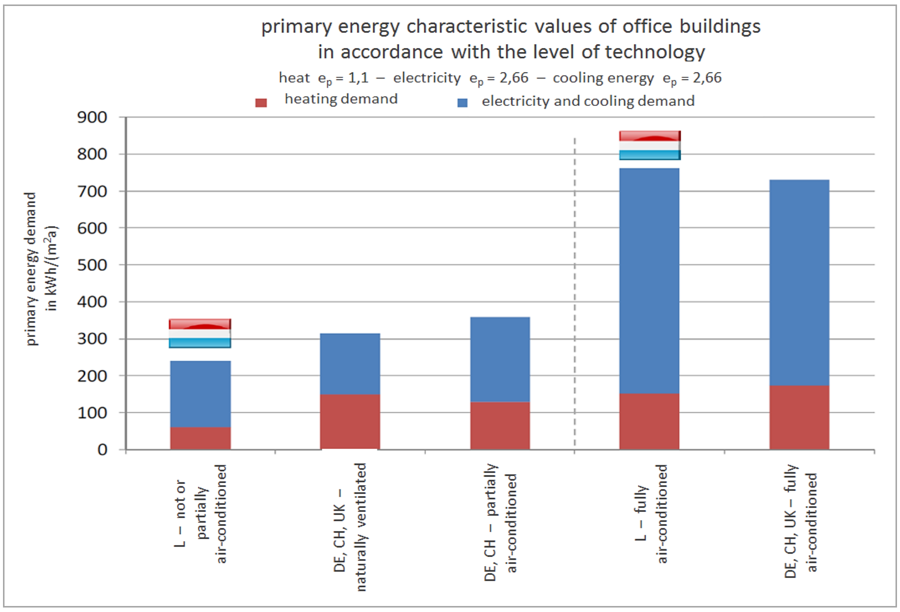


Figure 4: Primary energy characteristic values of office buildings in accordance with the level of technology [Thewes]

The energy characteristic values presented show the large spans and the enormous potential for saving of future office buildings. The growing complexity of the building task offers a great variety of possibilities for optimisation. The objective is to develop optimised energy and technology concepts on the basis of renewable energies and not a further technological upgrading of buildings. Crucial point is the energy and CO_2 balance of the entire building system [Leibundgut].

Above all, energy-efficient planning signifies climate-adapted planning, which means to create the basis for a low energy demand of the building by means of constructive measures. This basis in combination with simple energy and technology concepts finally leads to a low energy demand, which can be covered by renewable energies and is thus environmentally compatible, sustainable building planning.

2.2 Office organisations

The different tasks of nowadays office work such as single, team and process work as well as communication require specific spatial allocations of workplaces. Closed spaces for tranquillity and concentration, open spaces for interdependent working stages and communications sectors require a high degree of flexibility and opportunity for interaction in the field of office organisation. Ideal solution would be a working environment, which can be adapted to the various activities in terms of space and atmosphere. This so-called „morphing office“ may still be utopia today but offices with varying spatial situations, flexible workplaces in connection with non-territorial forms of work seem to be most suitable for the present office and knowledge work [Hascher]. Tendencies towards decentralised, more flexible technical equipment increase comfort and well-being of the user. A higher degree of user acceptance can be reached due to enhanced influence possibilities. These aspects should be taken into account when planning future office buildings.

An ergonomic study of [Eisele] and their summary of various studies lead to the conclusion that the attractiveness of a workplace and the productivity of the employees can be improved by reducing the number of office units and people in one room. According to [Eisele] the well-being of the staff is influenced by the following parameters in descending order of importance:

Importance (high → low)

- acoustics
- materiality
- lighting
- quality of integration of technology
- sense of security
- visual connections
- indoor air quality.

Good acoustic qualities, natural light conditions and individually adaptable settings for heating and cooling met wide approval. A personal protective atmosphere, workplaces alongside of window fronts and the use of high quality materials was also entirely rated positively. Since the 1990s the popularity of the office organisations combi office and business club increases, see figure 5. The time period of introduction and typical floor plans of office organisations can be seen in figure 6.

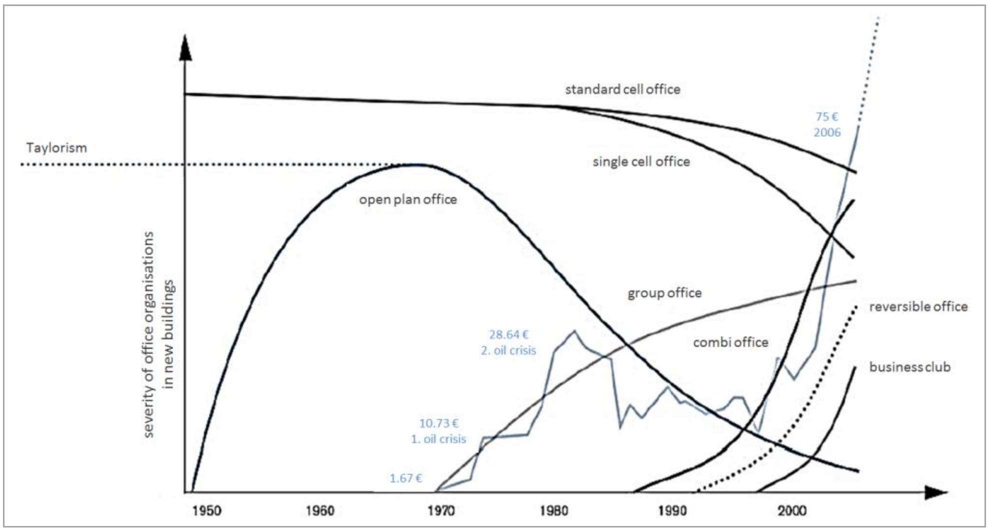


Figure 5: Severity of office organisations in new office buildings [FOSTA]

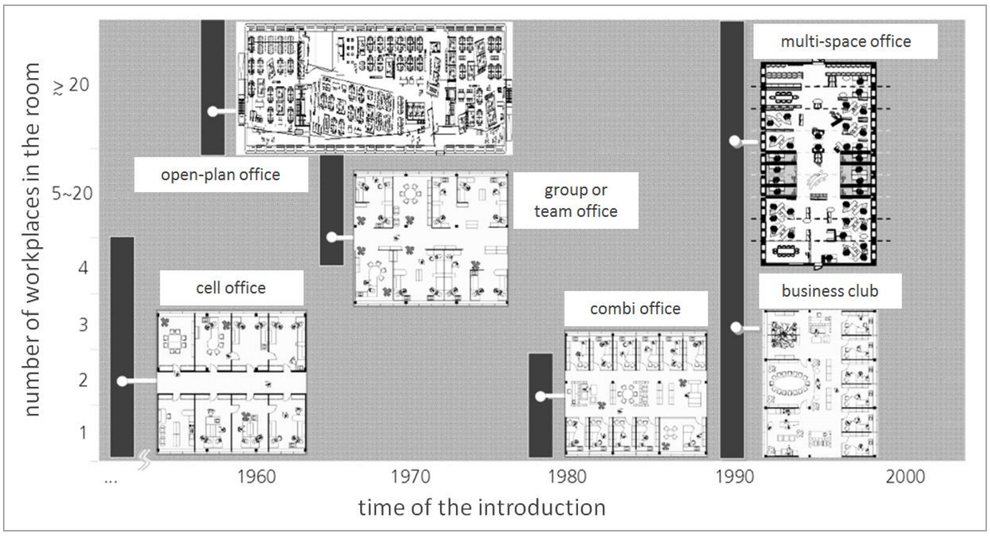


Figure 6: Introduction of office organisations in the last 50 years [Rieck]

The implementation of various office organisation concepts from the single office right up to the open-space area are made possible by a high flexibility of the floor plans. The capacity of office buildings to adapt to changing entrepreneurial organisation structures offers better opportunities to re-let and thus preserves the value of the building. If these buildings also fulfil representative functions and can be classified as energy- and emission-efficient then their long-term survival on the market is ensured for the future [Eisele].

2.3 Design process

The planning process of a building is an iterative process which equally involves architects, engineers, professionals and building owners. The early design phase (concept phase) represents the most decision-intensive part, in which all relevant decisions regarding the shape of the building, structure type and facade design are taken. During the subsequent planning phases of approval and implementation planning, the possibilities for influence and amendments become restricted due to the growing complexity and the specifications required for the implementation of the project. The challenge for architects and the engineering team already in the concept phase is to find the best solution taking into account:

- urban principles
- building geometry and dimensions
- floor plan design and choice of supporting structure
- facade design and
- suggestion of technical installations.

The meaning of sustainable building planning is that the economic, environmental and socio-cultural requirements placed on a building are met. When talking about integrated planning this refers to an interdisciplinary team involved in the project right from the start of the planning and linked to a common network of electronical information [Hascher]. The use of the latest design methods and information technology programmes, e.g. building information modelling (BIM) or building performance simulation (BPS), forms the basis for efficient work. The evaluation criteria to measure the success of a project as a whole are e.g. aesthetics, compliance with time schedule and budget, profitability, user satisfaction, energy efficiency and environmental compatibility [Hascher]. Architects and project managers assume the function of coordination, organisation and communication while the task of the building owner is to define the demand (clarification of requirements) as well as the occupancy planning and space efficiency of the areas available. The methodological preparation of the occupancy planning [DIN18205] and of an energetic performance specification [BMUB-2] serve as the basis for the design process.

The increased demand for sustainability certifications of office buildings of private investors as well as of public authorities increasingly calls for this type of integrated planning.

2.4 Sustainability certification

Various national certification systems for buildings have been developed to evaluate the energetic, economic and environmental quality of buildings due to the global efforts in terms of sustainability and climate change. In the nineties of the last century in the UK the system “Building Research Establishment Environmental Assessment Method (BREEAM)”, in the US the “Leadership in Energy and Environmental Design (LEED)” and in France the system “Haute

Qualité Environmentale (HQE)" were established. All other certification systems have been developed during the last 10 years. In Germany the system "Deutsches Gütesiegel für Nachhaltiges Bauen (DGNB)" is available on market since 2008 [Ebert]. In recent years in Belgium and Luxembourg developments on the systems VALIDEO and LENOZ are ongoing.

The variety of systems and the differences between them, affected by national architecture, standards and legal requirements, leads to uncertainties and ambiguities among planning teams and clients. However, the current developments of the well-known systems BREEAM, LEED and DGNB clearly indicate an internationalisation process and a steady convergence in the definition of the core criteria. In future this trend will allow a better comparability of the results [Ebert]. Additionally, in the European Union a new building assessment methodology has been developed based on a research project "OpenHouse" (Seventh Framework Programme, FP7). The objective is to complement existing systems for planning and constructing sustainable buildings. Involved were organisations from eleven countries, companies, research organisations, end users and policy makers [OpenHouse]. Within this project the tool "Sustainable Building Specifier (SBS)" was developed, which is available by Fraunhofer IBP, Germany, to support the user by creating life cycle assessment (LCA) studies.

2.5 Climate conditions

Climate is a key parameter for the implementation of climate-adapted architecture. The interactions between temperature, solar radiation, absolute air humidity and wind velocity have a decisive influence on the constructive design parameters and the choice of the room conditioning. The orientation and the form of the building play a crucial role in the various climate zones of the earth, see figure 7.

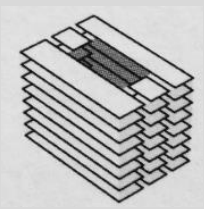
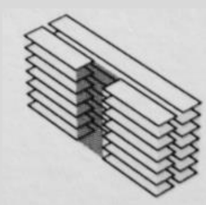
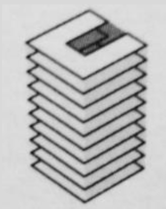
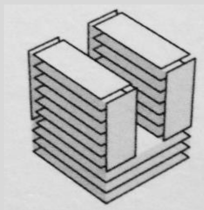
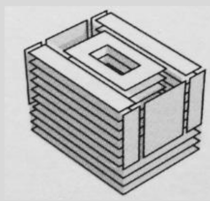
Building design in climate zones				
cool	temperate	subtropical	tropical	desert
				
- north-south orientated - compact - inside atrium	- north-south orientated - bar structure - outside atrium	- block tower - access zone north orientated	- north-south orientated - subdivided structure	- north-south orientated - including yards

Figure 7: Building design recommended for different climate zones [Hausladen, 2012]

In the temperate climate zone of Western Europe[2], the seasons are defined by long transition periods without extreme fluctuations of temperature and humidity. The solar radiation varies considerably over the year. The climate is determined by warm temperatures in summer and cool temperatures in winter. In continental locations the temperature fluctuations during the year are higher than in coastal areas. Heating is more decisive than cooling demand and in summer time passive cooling measures, such as night cooling, can ensure a comfortable

[2] Definition of Western, Southern and Northern Europe based on the information of the German "Deutsche Gesellschaft für Staatenkunde e.V."

indoor climate if solar radiation is limited. Natural ventilation is possible during the whole year. The need of de- and/or humidification is very low. To reach a compromise between compactness, transmission losses, daylight use and natural ventilation a north-south orientation, a moderate depth of the building and a window area of 50% to 70% (except north orientation with 40%) are recommended [Hausladen, 2012]. In continental areas of Southern Europe, e.g. in Madrid, Spain, the building design could be similar but with respect to higher temperatures and more solar radiation.

In the cool climate zone of Northern Europe the seasons are clearly defined with cold winter and warm summer temperatures and the solar radiation shows strong fluctuations over the year. Low temperatures in winter reduce the possibilities of natural ventilation while it is possible in summer and night cooling is efficient. Heating demand is decisive and humidification could be necessary in continental areas. In consequence the building design should lead to less transmission losses. A north-south orientation, compactness and a window area of 30% to 40% (except south orientation with 50%) is advisable [Hausladen, 2012].

Monitoring studies of office buildings, however, have illustrated that in the temperate climate zone an active cooling is necessary to avoid a loss of comfort [Voss, 2016]. The authors refer to international climate research activities and stress that this problem will be aggravated due to climate changes in the years to come with an increase of summer days with a daily maximum temperature of more than 25 °C, see figure 8.

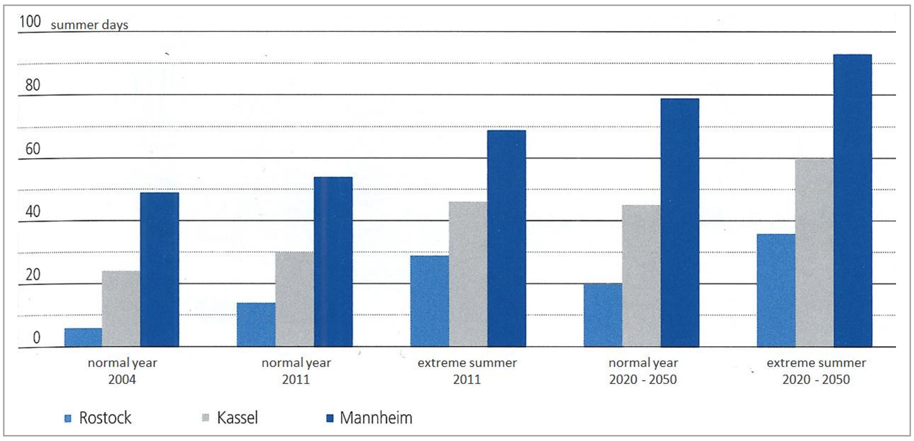


Figure 8: Frequency of summer days on the basis of different climate data records [Voss, 2016]

2.6 Structure type

The structural problems of existing buildings are mostly the missing flexibility of floor plans and adaptive capacity of the primary structure even though office buildings should allow short-term adjustments of the office organisation without fundamental changes of the supporting structure [Eisele].

2.6.1 Supporting structure

In office buildings the supporting structure is implemented mostly in the shape of a frame or skeletal structure. For the columns and slabs a concrete, steel or steel composite structure can be chosen. In this case the columns of the supporting structure are allocated independently of the exterior wall and the usually non load-bearing facade elements are fixed in front of the structure, the so-called “curtain wall” [Knaack]. The choice of the structure type and the material selection determine the energetic and environmental impacts of the building due to massivity and thermal storage capacity.

The grid structure has been adapted over the last years to allow more flexible office organisations and the major depth of the buildings, with more than 13 m - 14 m, not only allows a two-wing but also a three-wing allocation. An optimum allocation of the intermediate columns (central post) or their complete absence then permits a maximum flexibility of floor plans [Eisele].

2.6.2 Building materials and components

The product phase of a building causes a significant part of the total primary energy demand. An appropriate material selection in terms of energetic but also environmental aspects is becoming increasingly important due to a trend towards shorter life cycles and the reuse of building materials or components. The percentage of energy required in the product phase is decisive in energetically optimised buildings compared to the total energy consumption of the whole life cycle. In a passive house, for example, this percentage could be up to 50% of the total energy consumption considered over a period of 50 years [Hegger]. Especially the erection of the supporting structure has a strong impact on the entire primary energy demand of a building, see figure 9

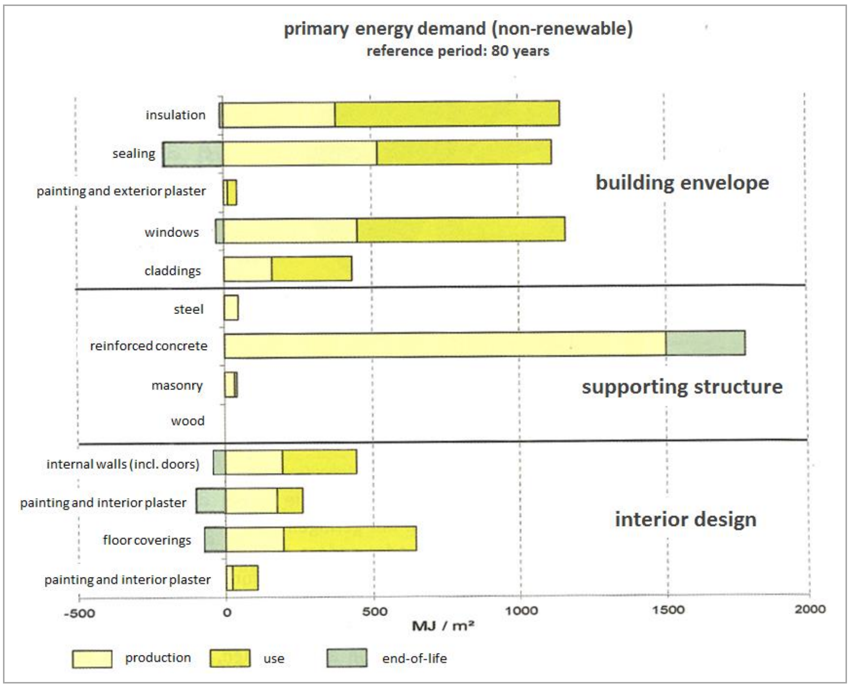


Figure 9: Primary energy demand of product, use and end-of-life phase of building components [Bauer]

In multi-storey buildings the slabs account for a proportion of 60% – 80% of the entire shell construction volume of the building. The choice of the slab system thus has far-reaching consequences in terms of economy and ecology [Claßen]. Recent developments in the area of slab systems are supposed to improve the flexibility of floor plans but also the environmental impacts. The objective is to develop material-saving and recyclable systems of large spans and low construction heights. In the field of steel composite structures e.g. the system „InaDeck" of the research project NASTA P879 or the CoSFB system of ArcelorMittal has been established, see figure 10.

The study of the „InaDeck“ has pointed out that although the environmental impacts are higher compared to a standard steel beam system, e.g. Holorib compound slab system, beneficial aspects result from the possibility to omit suspended ceilings and floor constructions. The technical installations can be integrated into the supporting structure and thus allow maintenance from above. Due to this integration the total slab thickness is smaller, the volume of the building can be reduced and the lower weight of the slab results in a more slender supporting structure [Claßen].

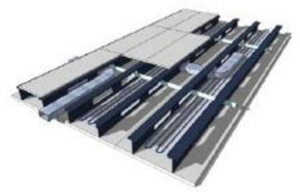
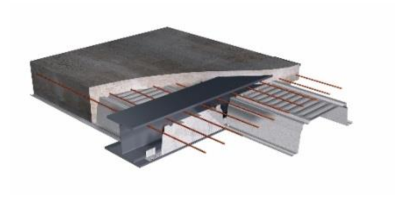
	
InaDeck [Claßen]	CoSFB [Braun]

Figure 10: New developments of steel composite slab systems

The CoSFB is also a lightweight system and leads to a reduction of primary energy demand and CO_2 emissions per square meter due to the efficient material input [Braun]. A comparison with a traditional concrete slab system for two construction grids, 8.1 m x 8.1 m and 12 m x 8.1 m, has shown a reduction of the global warming potential of 40% [Hechler].

2.6.3 Life cycle assessment of supporting structures

A study concerning the ecological efficiency of office buildings deals with the comparison of five different construction systems for a six-storey building, four steel composite structures and one reinforced concrete structure as reference case. All types follow the same basics for functionality and dimensions. They have a dimension of 32.40 m x 13.70 m, a skeleton structure and a curtain wall facade of steel and stainless steel with transparent and opaque fillings. A bracing core is not included. The authors investigated the position of a central post and compared different slabs and columns. The evaluations are based on the product phase, the end-of-life phase and include the recycling potential [Siebers].

The steel composite structure with a central post cause less primary energy than the structure with a wider span. The fact that reinforcing steel does not get any benefit for recycling because it is made of steel scrap in the electric furnace route, leads to a high primary energy demand of the concrete solution in case of identical construction grid (5.40 m x 5.50 m). The authors reveal that besides the facade elements the slabs are responsible for about 70% of the entire mass of the building including base plate and roof system. The steel composite slabs have an average weight of about 500 kg/m^2 in comparison to the concrete variant with 700 kg/m^2. However, the non-renewable primary energy demand of all structural systems tend to the same level, between 400-600 MJ/per m^2 gross floor area. The calculations performed show that the mass portions are not automatically indicative for the primary energy demand [Siebers].

Another study highlights the fact that a composite steel and concrete structure allows decreasing the total environmental footprint of an office building. The evaluation is based on a nine-storey office building with a dimension of 42 m x 24 m including two sublevels. The authors have compared three structural systems of columns and slabs: a concrete structure with a concrete core, a composite structure with a concrete core and an optimised composite structure with a steel core. The results show that the best choice is the latter system. The authors stress the positive effect of considering the recycling potential (Module D of EN 15804) of materials at the end-of-life phase [Vassart].

2.6.4 Building concept for public office buildings

In Luxembourg planning guidelines for public office buildings exist based on a study by consulting engineers from Switzerland [ABP]. The concept gives constructional and technical recommendations to achieve energy efficiency and comfort requirements, see figure 11.

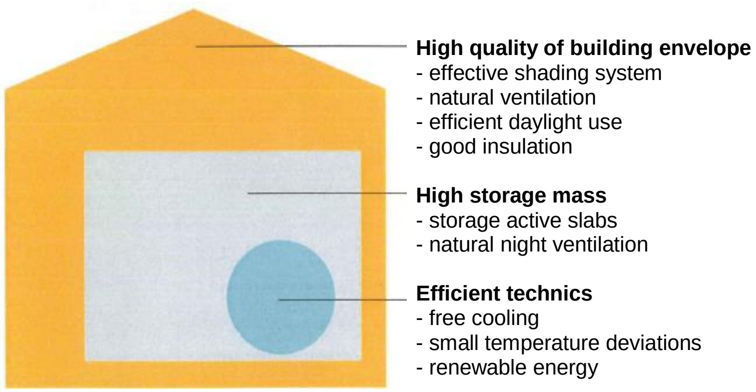


Figure 11: Main recommendations of office building concept in Luxembourg [ABP]

The philosophy is to build at least medium-weight constructions with a high proportion of thermal active mass of approximately > 350 kg/m^2_{NGF}. Slabs should have a minimum of 70% free surface without suspended ceilings or acoustic insulation to use thermal storage capacity. To avoid acoustic problems an increase of massivity (thickness) is recommended. The building envelope should be well insulated and have a U-value < 0.20 $W/(m^2K)$. The ratio of the window area should be lower than 60% and the U-value of glazing between 0.6 - 0.8 $W/(m^2K)$. The window elements should not have a lintel and a parapet of at least 60 cm height. Thermal activated elements (TAB) are not recommended due to high inertia. Priority should be given to low - tech concepts with quick response systems and components and a combination of natural and mechanical ventilation systems. Concerning the aspects of “Grey Energy” less glazing area with a minimal part of window frame is recommended. Furthermore, it is stated that for claddings the content of “Grey Energy” is low when there is wood, medium when there is a solid construction and high if metal is chosen.

2.6.5 Thermal storage capacity

A slab with a thickness of 20 cm can be thermally activated down to its core as far as no cladding has been installed on any side assuming that the storage mass of buildings elements only has to extent to a maximum depth of 10 cm [ABP]. According to the authors a suspended ceiling reduces the thermal storage capacity of a concrete slab from approx. 250 kg/m^2 to approx. 40 kg/m^2. The mass that can be thermally activated amounts to approx. 2 cm within an hour, approx. 10 cm in the course of a day and approx. 25 cm in a week [Roulet]. Chapter 6 will further analyse the impact of the thermal storage capacity in relation to passive cooling concepts.

2.7 Facade design

The facade design is of major importance in view of thermal protection, particularly during the summer months. Adapting a building to the climate conditions of its surroundings and the interaction of facades and room conditioning is therefore a crucial factor [Hascher]. The main aspects in office buildings are the protection from overheating (thermal comfort in summer), the reduction of transmission losses (thermal comfort in winter), transparency (visibility), usage of daylight and sun protection, see figure 12.

The facade system includes movable components, which are subject to the control of the user. In the concept phase functional, structural and design specifications have to be considered besides high standards, user and building-specific requirements in terms of climate control, environmental protection, health and user comfort.

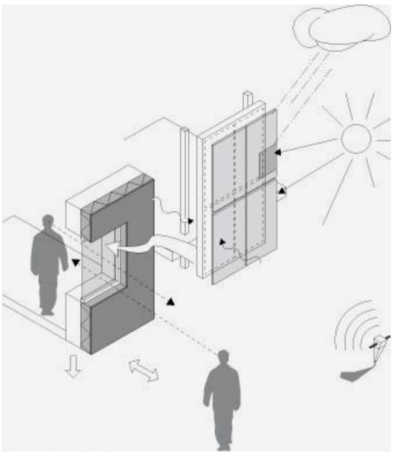
	**Local, climate conditions:**	**Facade functions:**	**Comfort requirements:**
Facade as interface [BauNetz-1]	- orientation - solar radiation - ambient temperature - air humidity - air quality / pollution - wind, rainfall - noise - socio-cultural context	- daylight directing - insulating - storage capacity - natural ventilation - noise protection - wind damping **Design parameter:** - window area - type of glazing - shading devices - material choice and construction	- thermal comfort - visual comfort - room air quality - acoustic comfort - fire and mechanical protection

Figure 12: Facade system as interface between exterior and interior climate conditons[3]

2.7.1 Construction principles

The construction of the opaque part of the exterior wall as a load or non-load-bearing element depends on the supporting structure of the building. In case of a skeletal structure, which is mainly used for office buildings, the exterior walls are commonly non load-bearing facade elements. The construction can be a solid (e.g. masonry, concrete) or a frame structure (e.g. steel, wood). It consists of a primary and secondary structure and a space filling element, see figure 13.

Finishing inside, the insulation layer and the cladding outside, with or without ventilated air layer, complete the element. The arrangement in front of the structure without ventilated air layer is called “curtain wall” or warm facade according to DIN EN 13830 [BauNetz-2]. This should not be mixed up with “curtain, ventilated facade systems” or cold facades according to EN 13119 and DIN 18516, although they are also arranged in front of the structure [BauNetz-2].

[3] This table makes no claim to be complete.

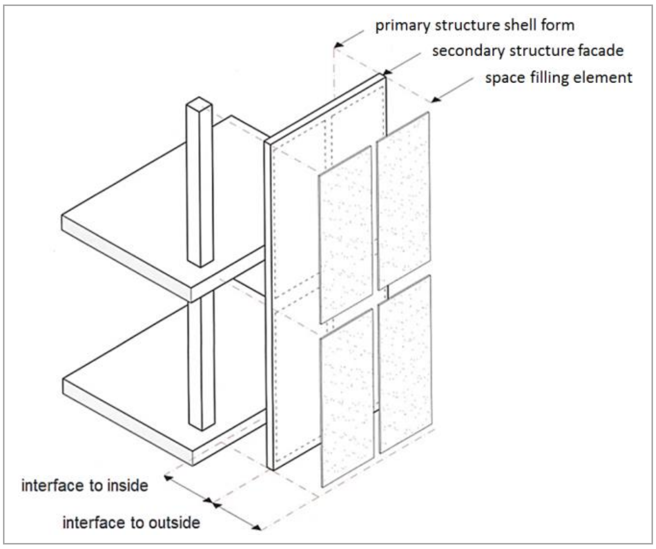


Figure 13: Facade construction principle [Knaack]

Depending on the type of construction and mainly the ratio of the window area a difference is made between punctuated-, band window- or fully glazed facades. Essential for the design of the elements are in addition the three functional zones with specific requirements:

- top section: daylight zone for light control, ventilation
- middle section: view zone and natural lighting
- bottom section: parapet zone for ventilation and energy.

Facade systems can be divided into single-, multi-layer, combination, component or integral facades. In single-layer facades, for example the element facade, opaque and transparent components are assembled in one layer. Functional elements of sun protection, ventilation, energy and light control are usually situated next to each other. Multi-layer facades, for example double skin facade systems have a secondary glass layer which is set in front of the primary construction. The opaque and transparent components are arranged in different layers. Component or integral facades are systems with integrated additional elements for different functions like heating, cooling, ventilation, light guidance, shadings or elements for energy production. These systems are available on market and can be installed as element facades, for example the “E^2 Facade” of Schüco [Schüco, 2013], see figure 14, or the “closed cavity facade” of Gartner [Bornemann].

Figure 14: Integral „E^2 facade“ system [Schüco, 2013]

2.7.2 Window area

The ratio of window area has a considerable influence on the indoor room climate due to the interaction of the absorbing areas in the interior of the building. The absorption of solar radiation at an opaque area, the conversion into thermal parts and their return flow to the outside are crucial factors [Leibundgut]. The challenge for a planner is to find an optimum ratio of window area. The tendency towards highly-glazed buildings on the real estate market is inconsistent with many findings of scientific studies. Hereinafter various recommendations and statements concerning the temperate climate zone will be compared.

As mentioned in chapter 2.6.4, special planning guidelines for office buildings in Luxembourg recommend a ratio of the window area lower than 60%, the waiving of a lintel and a parapet of at least 60 cm high [ABP]. In addition the author of a field study of the existing building stock in Luxembourg, who additionally has evaluated the influence of energy relevant parameters, recommends a window-to-wall ratio of maximum 45% (corresponding to the outer facade area) [Thewes]. Other studies go a step further and take into account also the differences of the solar radiation in various orientations of the facade. In his study related to the use of daylight and artificial lighting in office buildings [de Boer] recommends the technical optimisation of lighting during the concept phase, a facade design adapted to the orientation, control strategies for indoor lighting and light-directing facade systems in south, east or west orientation. He points out that with a ratio of window area of more than 60% the energy demand for lighting can only be reduced to a small extent. An increase of the ratio of window area to 100% only causes an improvement of the effective exposure to light of 6% on average for all models examined. Double-glazed facades noticeably deteriorate the indoor lighting conditions [de Boer].

The author of another study also recommends a ratio of the window area depending on the orientation, based on the presumption that the operative temperature does not exceed 28°C for more than 100 hours per year during the working period [Hausladen, 2006], see figure15.

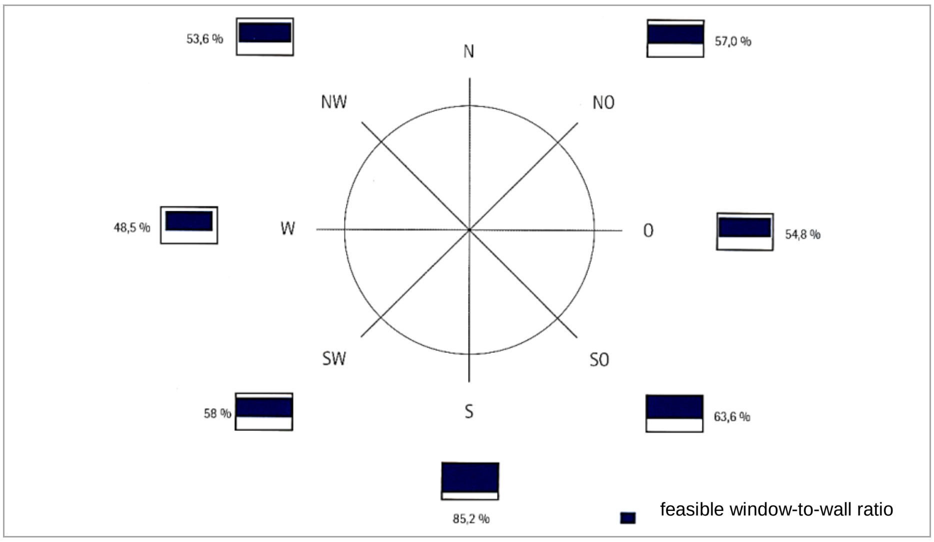


Figure 15: Recommendations for a window-to-wall ratio depending on the orientation [Hausladen, 2006]

A contrary point of view is that depending on a good insulation standard respectively a high facade quality the specific primary energy demand of an office building in Central Europe is lower in case of a highly glazed facade and allows a more efficient building operation [Knaack].

The prerequisite is that the energy demand for heating and cooling is low due to the high quality of the facade in terms of thermal insulation and sun protection, and artificial lighting is more decisive. Figure 16 shows the energy demand in case of a triple-glazing and an external shading device.

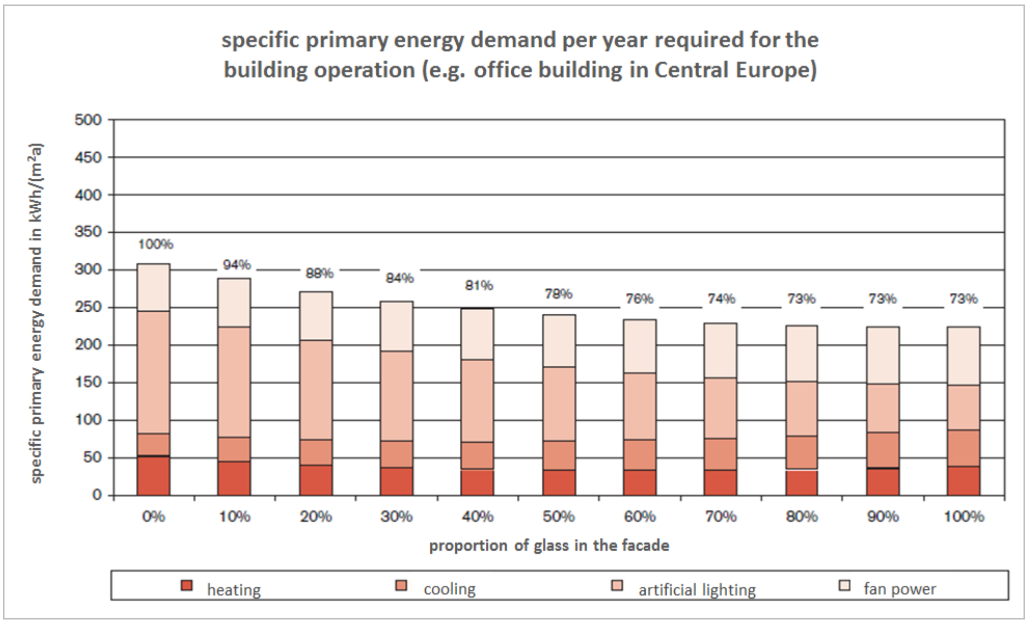


Figure 16: Specific primary energy demand per year with different window-to-wall ratio [Knaack]

2.7.3 Type of glazing

Due to the risk of overheating of office buildings in summer, solar loads need to be reduced while introducing the optimum effect of daylight especially with high ratios of window area. In the heating mode high transmission losses should be avoided as well as a drop in temperature in front of the window pane. The choice of the glazing depends on the climate conditions, the orientation and the combination with shading devices. In dependency of their thermal, visual and lighting parameters glasses can be subdivided into thermal insulation glass and solar protection glass.

The insulation standard of glazing is indicated by the thermal transmittance (U_g-value). The solar energy transmittance (g-value) specifies the percentage of solar radiation that reaches the room, a value of 0.4 thus means 40% of solar loads. The absorption coefficient (α), the level of reflection (ρ) and the light transmission factor (τ or Tvis) of the glazing as well as the secondary thermal emission play a crucial role [Voss, 2006]. The g-value is calculated by the summarisation of the transmitted solar radiation and the secondary thermal emission from the inner windowpane. The thermal emission results of the absorption of solar radiation within the window pane and subsequently releasing it to the immediate surroundings in the form of longwave radiation and convection [Wagner].

The technical values presented in table 1 illustrate the broad range of the thermal and optical qualities of the glazings. The selectivity allows the evaluation of the quality of a glazing in terms of daylight usage and energetical properties. The selectivity (S) is determined by the relation between the light transmission factor (Tvis) and the solar energy transmittance (g-value) [Wagner], see equation 1.

$S = \frac{Tvis}{g}$ (Equation 1)

A selection of typical types of thermal insulation and solar protection glasses available on the market [Wagner] is summarised in table 1.

Table 1: Technical parameter of typical thermal insulation and solar protection glasses

Type of glazing	Structure	Thermal transmittance (U_g-value in $W/(m^2K)$)	Solar energy transmittance (g-value)	Visible light transmittance (Tvis)	Selectivity (S)
Thermal insulation glass (argon)	triple	0.8 - 0.5	0.61 - 0.35	0.73 - 0.57	1.2 - 1.60
Thermal insulation glass (argon)	double	1.3 - 1.0	0.62 - 0.48	0.80 - 0.70	1.3 - 1.46
Solar protection glass (argon)	triple	0.7 - 0.6	0.43 - 0.20	0.66 - 0.36	1.53 - 1.80
Solar protection glass (argon)	double	1.1 - 1.0	0.43 - 0.20	0.42 - 0.17	1.69 - 1.76

In general, a high transparency (Tvis) within the visible part spectrum of the solar radiation is desired. In order to reduce the energy demand for heating, however, a very low or no selectivity (S ± 1.0) with a high Tvis-value and in the cooling mode a high selectivity S >1.8 is an advantage [Leibundgut]. In case of a high selectivity the energy input is reduced and a high transparency reduces the annual number of hours which require artificial lighting. The selectivity of typical solar protection glasses is illustrated in figure 17.

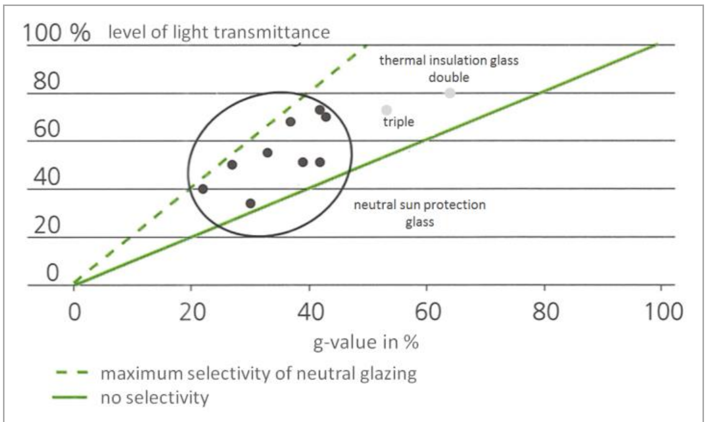


Figure 17: Selectivity of typical solar protection and two thermal insulation glasses [Voss, 2006]

In winter, however, the use of solar protection glasses might considerably reduce passive solar inputs and thus increase the heating energy demand by approx. 10%-15%. Also externally installed blinds can cause such an increase especially when used as glare protection [Voss, 2016].

In addition the choice of the glazing directly influences human biorhythm. Scientific evidence has demonstrated the positive effect of the high colour rendering of natural light. A double thermal insulation glass with a higher g-value can be preferred to a triple solar protection glass because the light quality is closer to the natural daylight [Voss, 2016]. Researchers of the Fraunhofer Institute for Silicate Research (ISC) with the collaboration of the company Uniglas, achieved an increase in light transmission in the whole range from 380 to 580 nanometres, namely in the range of the vitalising spectrum of natural light (higher proportion of blue light) with a new coating on the interior side of the window panes. At 460 nanometres the light transmission stands at 79% without negative effects for the insulation properties [Fraunhofer ISC].

2.7.4 Shading devices

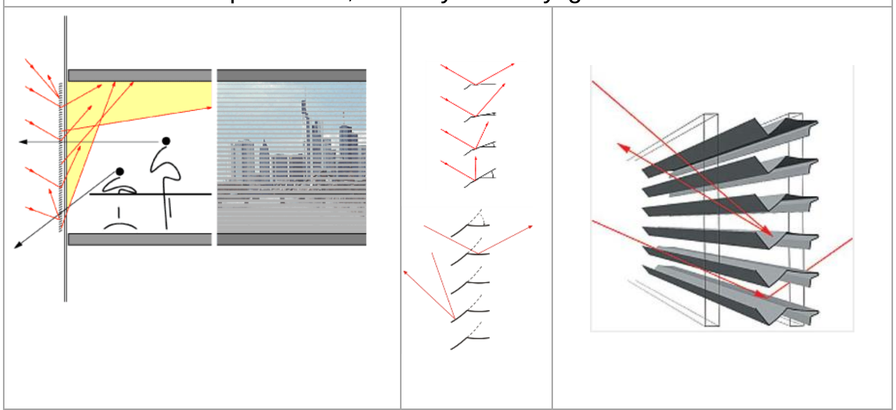
Essential for the thermal protection in summer is the effectiveness of the sun protection systems which depends on the position of the shading devices (exterior, intermediate or interior) and the choice of the glazing, e.g. solar protection glass or switchable glazing systems. The solar heat gain coefficient of glass and shading device (g_{tot}) can be calculated with a simplified method in dependence of the g-value of the glazing and the reduction factor of the shading devices (F_c-value according to the German standard DIN 4108-2) [Wagner], see equation 2.

$$g_{tot} = g * F_c \quad \text{(Equation 2)}$$

For exterior systems common F_c-values lie between 0.1 and 0.5 and in case of interior installation the values usually vary from 0.65 to 0.9. The lower the reduction factor F_c, the more efficient is the shading device [Voss, 2016].

The problems caused by big glazings especially in combination with unfavourable implementations of the facade design become evident in existing buildings with the shading devices mostly shut to avoid glare and direct solar radiation at the workplace. For the occupant these measures represent significant restrictions of transmittance (visibility) [Hoffmann]. Various measures tend to provide a remedy such as e.g. the „cut-off" position of the venetian blinds where the inclined position of the slats block the sun while it offers the possibility of light transmission. Additionally two-part hangings with a daylight use in the upper sector and sunscreening in the visible sector are interesting alternatives as well as developments in the field of slats geometry, see figure 18.

Sun protection, visibility and daylight reflection



In the outdoor area | In the space between the window panes

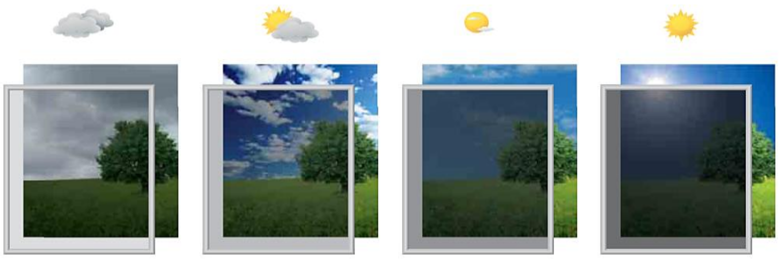
Figure 18: Developments of shading systems for sun protection, transmittance and daylight reflection [Koester]

Switchable glazing technologies to control solar radiation and light transmission are an additional alternative. An important objective of such glazings is the high transmittance of the entire solar radiation in the transparent state and a high dynamic selectivity in order to lower the solar thermal loads during the process of tinting. The technologies can be subdivided into passive (thermochromic, photochromic and thermotropic) and active (gaschromic and electrochromic) systems [Wagner]. Only thermotropic and electrochromic glazings are currently available on the market for the building sector.

2.7.4.1 Electrochromic glazing

The electrochromic switchable glazing technology allows the variation of the visible light transmission and the solar energy transmission (g-value) to adjust heat and light in relation to interior comfort requirements [Meek]. The authors [Lee] revealed that the switchable glazing technology has shown a cooling load reduction of the building of about 20% and lighting power savings of more than 50% when combined with a photo-responsive lighting control.

The system works with a thin solid electrochromic film of nanostructured coating which is sandwiched between two layers of glass and activated with low voltage to change colour from clear to dark [Uni Cambridge]. The electrical voltage, which provides for the dark tinting of the coating, is generated according to the solar radiation on the facade or depending on the room temperature [Voss, 2016]. The system varies between four to five states of tinting from clear to fully tinted. The g-value varies between 0.3 to 0.03, Tvis in percent between 55% to less than 1% and corresponding to these values the selectivity S of the glazing system, see figure 19.



Lichttransmission* Light transmission*	54 %	16 %	5 %	<1 %
G-Wert* g-value*	0,36	0,09	0,06	0,03

*Werte eines Dreifach-Isolierglases. *Values of a triple insulating glass unit.

Figure 19: Tinting states of electrochromic glazing system [Schüco, 2015]

In case of glass sizes of 1 m x 1 m the completely tinting process takes approx. 12 minutes. Also in the tinted state, mostly deep blue, the transmittance is preserved. The potential for development lies in the increase of selectivity when switched off and the reduction of the switching time (transition from one phase to another) [Wagner].

A study carried out at the Science College Overbach has shown that the thermal protection in summer has been complied with and that the occupants did not find the obscuration of the glass to be disturbing because the visual contact has not been negatively affected. Further measurements in a data-processing center have illustrated that in terms of temperature progression and solar loads an electrochromic glazing can lead to similar results like an external shading device [Voss, 2016]. The cost of an electrochromic standard glass with an U_g-value of 1.1 W/(m^{2}K) amounts to approx. 500 €/m^2 until 600 €/m^2 net. According to [Voss, 2016] they are thus able to compete with a thermal insulation glass plus external, mobile shading device. The cost of a thermal insulation glass amounts to approx. 300 €/m^2 and the cost of an external shading device to approx. 150 €/m^2 until 200 €/m^2.

The topic of a study by [Ajaji] is the development of a suitable control strategy depending on the vertical outdoor illuminance and the outdoor temperature for a highly glazed office building in

Brussels. First the authors summarise the results of several studies (Zini, 2006; Clear et al. 2006; Lee et al. 2006; Köhl et al. 2006) and occupant surveys in recent years and indicate advantages and disadvantages especially in dependence of the control strategy to find a compromise between visual comfort and energy efficiency:

advantages

- uniform level of daylight in the room
- no discomfort due to overheating
- continuous view to outside
- reduction of cooling power

disadvantages

- period of the switch
- glare problems.

The occupants have preferred the possibility of manual controlling and no automatic mode. The best strategy for temperate and cool climate is that the glazing is dark when the need is for cooling and clear during heating period [Lee]. Based on this information [Ajaji] used thermal simulations to assess the vertical diffuse outdoor and the average indoor illuminance taking into account the fact that the building is equipped with a dimmable lighting system. He integrated additionally the switching dynamic of the electrochromic glazing into his control strategy. In his project the primary energy consumption due to heating, ventilation and air-conditioning (HVAC) and artificial lighting and the risk of overheating has been evaluated. The author comes to the conclusion that electrochromic glazing combined with a low rate of night ventilation reduces overheating and allows avoiding mechanical cooling without increasing the demand for lighting and heating so that the impact on the building energy demand is less decisive. The primary energy demand could strongly be reduced due to less cooling demands. The risk of over illuminance in the rooms (more than 1,000 lx is uncomfortable, more than 3,000 lx unacceptable) is very low in comparison to a clear glazing type [Ajaji].

2.7.4.2 Glare protection

An additive glare protection and thus the separation of sun and glare protection have an energetic advantage especially when the sun protection is mobile or switchable. Important feature for the user's comfort is to guarantee the individual controllability and transmittance (visual contact to the outside). In general, functional combinations of glare and sun protection as well as light guidance have to be optimised in a harmonised and coordinated manner [Voss, 2016].

2.8 Energy concepts

The performance of employees is considerably influenced by the indoor climate conditions of office buildings. This correlation and the improvement of occupational health and safety is a central point of scientific research and the basis to determine standards and climatic guidelines. Over the past decades a global standard has evolved with the consequence that workplaces have been equipped with substantial technical expenditure to reach the required level regardless of the respective climate zone [Leibundgut]. In nearly all climatic zones of the world the commitment to a specific indoor temperature between 20 °C and 27 °C and humidity between 3.5 g and 12 g water per kg air necessitates the installation of air-conditioning systems. A consequence of this again is that due to the high technical level of the buildings also the comfort requirements of the users have grown and in consequence the energy demand of the building.

2.8.1 Nearly zero emission standard

Many concepts have been developed in order to increase energy efficiency and to decrease emissions of office buildings. One approach is to assume that in future the central point is not the saving of energy but the aim should be a zero emission standard. Buildings are supposed to emit less than 1 $kgCO_2/(m^2a)$. Such an emission-free building requires a highly sophisticated architecture and can be implemented according to the present state of the art and considered environmentally reasonable [Leibundgut]. Objective of the author`s concept is to supply heat no longer by means of the combustion of primary fossil fuels such as coal, oil and natural gas and by a limited extent of wood, but e.g. with heat pumps in combination with solar energy systems (hybrid collectors) and seasonal underground storage tanks and photovoltaic systems. Smaller decentralised components of facility technology with new control systems should help to reduce the generation of emissions caused by the necessary exergy supplied (mechanical work) to zero [Leibundgut].

2.8.2 Passive and low tech concepts

Other studies came to the conclusion that effective actions involve the optimisation of energy efficiency and the use of passive measures. In our temperate climate zone active cooling measures can be neglected. A comfortable indoor climate indeed can be achieved by natural ventilation and passive cooling concepts such as efficient night ventilation in combination with high thermal inertia of solid building elements [Thewes, ABP]. The omission of an active cooling system influences the architecture, structure type and facility technology. Essential factors are the reduction of internal and solar heat loads, the thermal storage capacity of the building and heat losses during the night because the required comfort cannot be regulated by an air-conditioning system, neither in case of future changes in use nor in case of unfavourable user behaviour. Presuppositions are significant temperature differences between night and day and nighttime temperatures below the target value fixed for the interior of the building [Voss, 2006].

[Leenknegt] has evaluated the influence of the parameters air change rate, internal gains, accessibility of the thermal mass and convective heat transfer coefficient on night cooling strategies. They indicated the positive effect of enhanced night ventilation to decrease overheating (ventilation rate tested from 4 h^{-1} up to 12 h^{-1}) and found out that for example in case of internal gains of 15 W/m^2 the reduction is higher by a change of the ventilation rate from 4 h^{-1} to 5 h^{-1} (approx. 22%) as by a change from 11 h^{-1} to 12 h^{-1} (approx. 11%). The evaluation of the accessibility of the mass has shown that thermal comfort is substantially worse if the thermal mass is covered up. The authors also investigated different convective heat transfer coefficients (CHTC) and found out that the influence is more obvious if the accessibility of the mass is given. They came to the conclusion that during night ventilation periods a mixed convection correlation (surface convection) is more appropriate than the standard of the building simulation models. Although the influence of the air change rate and the internal gains on thermal comfort is higher, an appropriate choice of the CHTC is important and will further be analysed [Leenknegt].

Apart from the use of passive cooling the planners of the office building “Concept 2226” in Austria went one step further. Studies related to their planning of a six-storey building without active heating, cooling or ventilation systems found out that it can be operated in an energy-efficient mode and that it complies with legal requirements in terms of thermal comfort. Compared to zero net emission buildings it needs no cost intensive high efficient HVAC systems and does not depend on onsite or grid storage systems [Junghans]. The building has an envelope with a very low heat transfer and extremely high air tightness. The exterior walls have a cavity wall structure consisting of bricks with a thickness of 72 cm and have an U-value of 0.08 - 0.1 W/(m^{2}K). The windows exist of a triple glazing and a high performance window frame. They have an U-value of 0.6 W/(m^{2}K). Besides the performance of the envelope a new building automation system is core of the concept. It controls natural ventilation openings for each room depending on the indoor air quality based on temperature and humidity, the weather conditions outside and the user demand. The indoor temperatures targeted are between 20 °C and 26 °C and the maximal acceptable CO_2 concentration is 1200 ppm. In the planning and optimisation process a variety of thermal and computational fluid dynamics (CFD) simulations was carried out using TRNSYS, COMIS and TRNFLOW. The results have shown that the optimal temperature set points are between 22 °C and 26 °C for daytime operation and between 600 ppm and 1000 ppm for the CO_2 concentration. The author concluded that the simulations have given useful recommendations for the planning process to find optimal control set points and that the tools can be used to test a novel building automation algorithm. The results indicate that the predictions of the room temperatures simulated are close to the measured data [Junghans].

2.8.3 Decentralised concepts

Constantly changing office organisation forms and the tendency towards flexible workplaces without predefined user specifications also require a high level of adaptive capacity of the technological concepts to the individual comfort requirements of the users. Latest research projects reveal aspirations to adapt the workplace to the type of work and individual needs. The decentralised control of the technical equipment plays an important role and it can be expected that also a reduction of the energy demand will be possible [TU Kaiserslautern]. An experimental room was set up to test, on the basis of metrological data and user surveys, the impact of office chairs with heating and cooling function, the adjustment of illuminance to the type of activity (sensors attached to the chairs), LED illuminance with changing colours in adjustment to biorhythm, an obscuration of floor-to-ceiling glass elements by electrochromic systems and external shading devices as well as their control in connection with artificial lighting.

2.9 Comfort requirements

People spend 90% of their life indoor, more than half of which is attributable to the workplace. Important factors for health and well-being as well as for the productivity are a high thermal comfort and a good indoor climate [Hascher]. The user’s acceptance in terms of thermal comfort, indoor air quality, noise and lighting significantly contributes to the satisfaction with the workplace. High comfort in office buildings in combination with a low energy demand can be achieved by an early integral planning of passive and active measures. The evaluation of these criteria can be carried out according to the German standard DIN EN 15251 [BNB].

2.9.1 Thermal comfort

Many studies of the last years underline the importance of thermal comfort, on the one hand in the field of assessing the user‘s satisfaction on the basis of observations of existing buildings by means of measurements and user surveys as done e.g. [Gossauer] and on the other hand in the field of developing models or tools to evaluate the thermal comfort of people also in case of complex indoor climate conditions. A study of the Center for the Built Environment, US Berkeley, evaluates the effect of solar radiation loads onto the thermal comfort of occupants in a building, their physiological reaction and how it influences the perception of thermal comfort [Hoffmann]. The study has shown that the user comfort level in a building is higher in case of diffusing shading systems, especially in case of highly glazed buildings and unfavourable orientations. The reduction of direct radiation on sensitive parts of the user`s body avoids local discomfort. A new developed software-tool allows to quantify the effects of different shading and fenestration systems, e.g. exterior or interior venetian blinds or coatings, on the occupant`s perception of thermal comfort [Hoffmann].

The German standard [DIN EN 15251] is based on the requirements of the EU Directive 202/91/EG:2002 and defines design criteria for the dimensioning of building technology as well as input parameters to be used for building simulation and the evaluation of the indoor climate. One special feature is that this standard, contrary to other standards related to the dimensioning of building technology, does not determine specific criteria for the thermal indoor climate during the heating and cooling period, but there is a distinction between naturally ventilated and air-conditioned buildings. The standard points out, that recent findings have shown that the requirements occupants placed on buildings with natural ventilation may differ from those placed on air-conditioned buildings [DIN EN 15251].

In case of rooms with natural ventilation by windows that can be opened to outside air, DIN EN 15251 specifies design criteria pertaining to indoor temperature for the energy calculation. In case of a medium comfort standard temperatures between 20 °C and 24 °C are recommended for the heating period and during the cooling period a temperature between 23 °C and 26 °C is recommended (high comfort standard: heating period 21 °C until 23 °C, cooling 23.5°C until 25.5 °C). For buildings with air-conditioning systems design criteria pertaining to indoor temperature to a medium standard should lie above 20 °C in winter and should not exceed 26 °C in summer (high standard between 21 °C and 25.5 °C).

2.9.2 Indoor air quality

The indoor air quality is supposed to guarantee olfactory and hygienic safety. The choice of low-emission building products and the securing of an adequate air exchange with the help of natural (ventilation openings that can be adjusted by the occupant), mechanical or combined systems the indoor air quality can also be ensured with regard to CO_2 concentration [BNB]. In [DIN EN 15251] the air volume flow is defined in dependence of building emissions and indoor air quality. In case of high quality requirements and a low-emission building an area-related value of 3.6 $m^3/(h_m^2)$ is mandatory in a single office based on 10 m^2 per person and 2.5 $m^3/(h_m^2)$ in an open plan office based on 15 m^2 per person [DIN EN 15251].

According to recommendations of the German [DIN 18599-10] in a group office the area-related fresh air flow rate should be at least 4 $m^3/(h_m^2)$ or person-related 40 $m^3/(h_pers)$. The recommended air exchange rate in group offices stands at 2-3 h^{-1} and in full cooling function through the air at 4-8 h^{-1}. According to [DIN EN 13779] values of 45 $m^3/(h_pers)$ and 3 $m^3/(h_m^2)$ can be considered to provide good indoor air quality.

2.9.3 Visual comfort

Visual comfort strongly depends on the ratio of window area, the choice of the glazing type and of the externally or internally mounted shading device. In an office building these parameters determine the use of daylight and thus the potential for saving artificial lighting and the energy demand for cooling [BNB]. The users' satisfaction is determined by the possibilities to exercise control and the light conditions at the workplace (visual contact to the outside, glare protection, light distribution and the colour of light in the room). The appropriate illuminance depending on the visual tasks according to [DIN EN 15251] can be complied with by means of daylight, artificial light or a combination of both. This German standard requires an optimal use of daylight and window areas that are neither too small nor too big and unprotected to avoid overheating. For office workplaces the design criteria pertaining to the illuminance level or intensity of illuminance should amount to 500 lx (measured on the height of the working plane at 0.8 m) [DIN EN 15251].

A study on the impact of light on the human biorhythm, however, reveals that occupants of office buildings prefer an average level of illuminance of 800 lx of artificial lighting depending on the time of day and season. In rooms with artificial lighting the need for light is thus higher than the value of 500 lx, which is mandatory for workplace lighting according to the German standard. It is known that daylight has a positive impact on people but when observing the use of daylight from an economic point of view there are different perceptions. Artificial light is dimmed or switched off once 500 lx have been reached at the workplace. However, this level of illuminance is often regarded as being insufficient because with the level of available daylight also the desire for light in the room increases. If the light outside is very bright then the occupants will try to balance the lack of light inside [Hascher]. The users' acceptance of the lighting systems is the decisive factor that determines the annual number of artificial hours in an office building. Developments to individualise workplace illumination and to adapt it to the various activities underline this assumption, see above decentralised concepts.

An examination of administration buildings in the course of the research initiative EnOB has illustrated that the share of lighting in the area-related electricity consumption of office buildings adds up to a median value of 10 $kWh/(m^2a)$ final energy. The value ranged between 5 $kWh/(m^2a)$ and 23 $kWh/(m^2a)$ in dependence of the level and type of illuminance, efficiency and the illuminant [Voss, 2016]. The author cites (Reinhart) who comes to the conclusion that artificial light control systems in office buildings that depend on the time of day can bring huge savings of up to 70%. The potential for saving due to a daylight-dependent dimming is most efficient when the supply of daylight is medium or good which corresponds to a daylight factor between 1.5% and 6% [Voss, 2016]. In case of deep rooms or a low ratio of window area, however, a good supply of daylight is hardly possible [Eisele]. When the ceiling is e.g. 2.8 m high and built without lintel the maximum room depth that can be illuminated to a sufficient extent is 5 m. Window areas below the work plane do hardly contribute to the supply with daylight [Eisele]. In case of a highly glazed building with a ratio of window area of 75% and a light transmission value of 72% of the glazing even room depths of 4m still achieve a sufficient daylight factor of more than 2% [Voss, 2006]. In order to achieve a good distribution of daylight in office buildings the daylight factor should exceed 7% even beyond a room depth of 2.5 m [ABP]. With the installation of external shading device and a thermal insulation glass only a maximum daylight factor between 4% and 5% can be achieved at a room depth of less than 2.5 m and a maximum value lower than 3% at a room depth of 5 m despite a high proportion of glazing of 90% [Hascher, Eisele].

2.9.4 Possibility of user influence

The satisfaction of the user and the possibilities to exercise control are further criteria of sustainable building design because the future occupant has a significant influence on the actual energy consumption of the building. Depending on the user profile the average consumption can vary from 15% below or 60% above the reference value of the standards [Hegger]. The broad spectrum of this assessment illustrates the difficulty to map and to take into account the user’s influence during the planning and simulation of office buildings to a sufficient degree.

2.10 Building performance simulation

The fact that national and international legislation related to the energy performance of buildings according to the European directive [EU 2010/31/EU] is constantly being tightened especially in view of net zero energy buildings and the increasing demand for building certifications force the planner to verify the direct influence of various key parameters on the energetical, environmental and economic quality of the building concept already in the concept phase. The workload involved and the increased complexity of the design task can only be solved by means of tools suitable for daily praxis.

The problem, however, consists in the fact that the majority of building performance simulation (BPS) or building thermal simulation (BTS) tools are not suitable for an early design phase and for the optimisation of design alternatives due to the level of detail required. Furthermore, the technical knowledge gained by scientific research as well as a huge number of recently developed tools does not achieve a breakthrough into the daily work of architects and engineers. They usually work with software products for design and implementation, the so-called CAD programmes (computer-aided design). In the future an efficient coordination of the complex planning process can possibly be taken over by the building information modelling (BIM), which is able to build upon the frequently used CAD systems. It is an approach to optimise integrated building planning, construction, administration and facility management of buildings with the help of 3D modelling. This method digitally captures, combines and links all relevant data of the building over the whole life cycle (integral planning), see figure 20. However, CAD and BIM tools do commonly not offer any information regarding the energetic, economic and environmental impacts of the design.

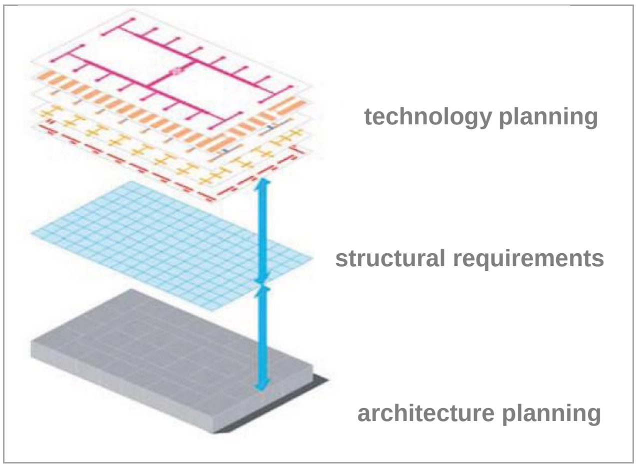


Figure 20: Principle of building information modeling (BIM) [Holvestadt]

A variety of other assessment or evaluation tools available on market are focused on energetic or environmental aspects. There are almost no practicable tools for an entire life cycle analysis and suitable for the optimisation process in the concept phase. A study of [Attia, 2012] focused on thermal comfort and energy performance reveals that there is a need for decision support tools for designers to rapidly assess alternatives especially for low and net zero energy buildings. The majority of existing building performance simulation (BPS) tools is used after the decision-making. Despite the proliferation of these tools there are still high barriers for their application in the concept phase because in practice it is a complex, costly and tedious task, time consuming and it requires a high level of expertise. On the DOE website of the US Department of Energy [IBPSA] in 2011 392 BPS tools are listed and only less than 40 tools are targeting architects during the early design phase. In the iterative design process generally planners start with “rules of thumb” to create a design. Then they model it to verify its compliance with performance goals and if the proposed design does not meet the goals, the designer will go back and start again [Attia, 2012]. The author concludes in a second study concerning this topic that more effective and efficient informative and evaluative tools are needed. Tool developers should provide tools that additionally focus on carbon besides energy, allow the simulation of passive design strategies and more detailed evaluation of comfort and the design and optimisation of renewable energy potential [Attia, 2011].

A selection of various tools and developments over the recent years will be presented hereinafter. The University Catholique of Louvain for example has created a design tool for low energy office buildings called “OPTI-bureaux”. The objective is to obtain the best adequacy between the climate, the building and the occupants` behaviour. The tool can be used for parametric studies of design choices on energy consumption during the design process with a minimum of data [Gratia, 2002, Gratia, 2003]. Their studies are published in the book “Thermique des immeubles de bureaux” [Gratia, 2006]. At ETH Zurich the “Design Performance Viewer” (DPV) has been developed to record the building energy and the associated material flows and CO_2 emissions of a building. This software is based on the information provided by digital BIM and can be connected with it in order to evaluate the structural physics of different building concepts. The tool is supposed to enable the architect as a “non-expert” to analyse energy, exergy, emissions and cost in the early design phase and it offers various possibilities of visualisation [Schlüter-1, Schlüter-2]. Objective is the use of this software as a planning tool and not as an expert tool, see figure 21.

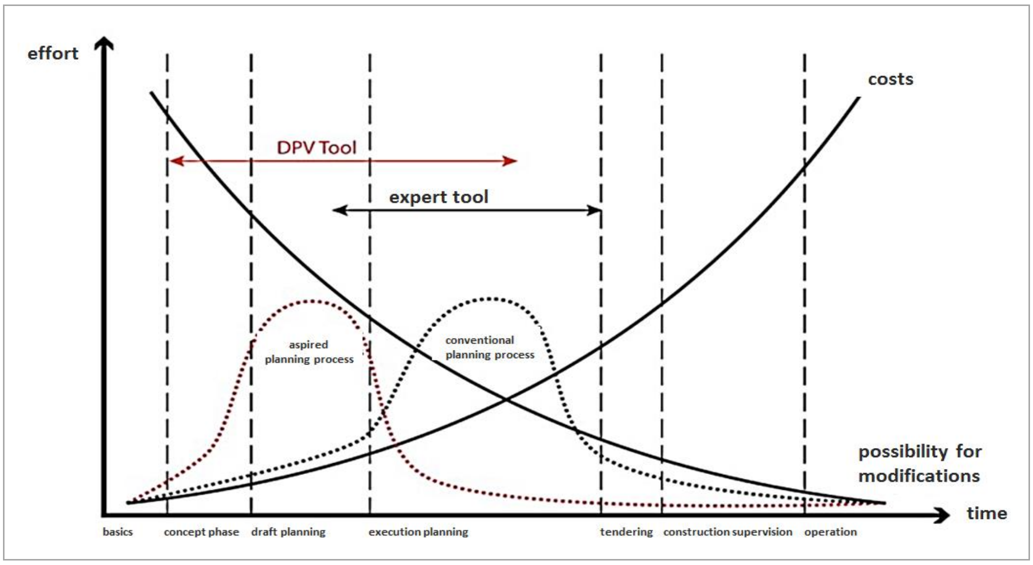


Figure 21: Applicability of the Design Performance Viewer (DPV) in the planning process [Schlüter-1]

Within the scope of the research project Nasta FOSTA a new tool, the so-called “Sustainable Office Designer” (SOD) of the Technical University of Munich has been developed with reference to the optimisation of the supporting structure for office buildings in steel composite structure. It is a CAD-based tool for early concept designs drawn up for the environmental and economic evaluation of structural solutions with a focus on the frequent case of rectangular floor plans and buildings with a maximum of seven storeys. On the basis of the architectural design model a parametric structure model and a preliminary static calculation are established. The optimisation method consists of a genetic algorithm. Future aim in the course of its further development is to integrate additional structure types and design criteria such as e.g. an overall energy balance including operating energy. The developers would like to mention that until now no use is being made of this type of optimisation computer technologies during the concept phase of buildings and supporting structures in the field of commercial application software designed for civil engineering. This tool shall give an impulse to integrate optimisation methods to a greater extent [Eisele, Hascher]. One application and the exemplary visualisation are illustrated in figure 22.

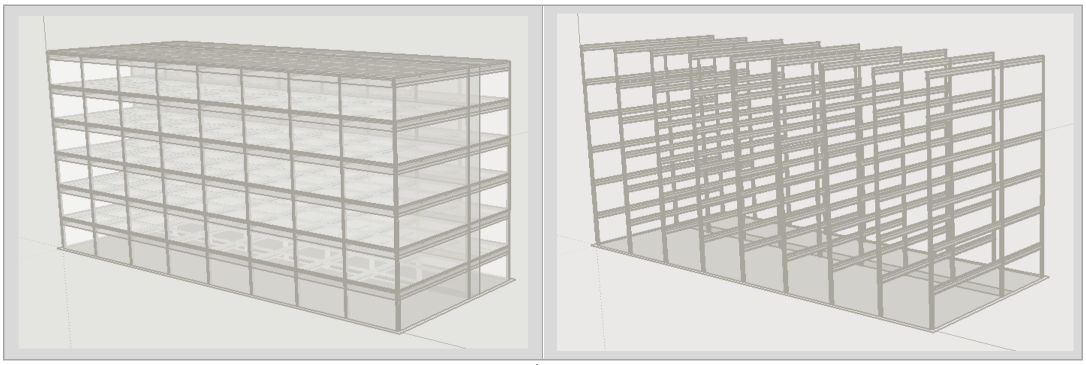


Figure 22: SOD model of reference office building[4]

[4] test with the reference office building, see chapter 3

Not only in the area of civil engineering does the problem of missing optimisation tools arise but also in the field of building technology and particularly in architecture because the vast number of potential parameter combinations and their impact on the energy and environmental balance of a building are difficult to predict with the help of a “trial-and-error” method or an expertise-based decision-making. Recent developments have shown that frequently used optimisation methods can be introduced e.g. in industrial applications in the area of building optimisation. These tools offer advanced techniques for a simulation-based design of experiments (DoE), surrogate modelling, optimisation and data-mining methods such as e.g. “Minamo” of the applied research centre “Cenaero”, which will be explained in detail in chapter 5.1 and “DesParO” of the Fraunhofer Institute for Algorithms and Scientific Computing [Fraunhofer SCAI].

2.10.1 Information about the selected tools

In this project the most relevant design parameters of office buildings will be analysed in terms of energetic as well as environmental aspects. The environmental evaluation will be carried out on the basis of a life cycle analysis (LCA). A comparative ecobalance study will be conducted to illustrate on material and component level the environmental impacts of concept decisions. The methodology applied as well as the approach chosen will be clarified in chapter 7.1 to 7.3.

Basis of the energetic calculations are the standards and comfort requirements presented above. The impact of energy-relevant parameters on energy efficiency and thermal comfort will be determined by means of the dynamically calculating, thermal building simulation software TRNSYS (TRaNsient SYstem Simulation Program), Version 17.01 (2012). The expertise-based parameter study will be completed by the application of an optimisation tool and the performance of a sensitivity analysis, see chapter 5.

2.10.2 Background of TRNSYS

TRNSYS belongs to the most widespread and scientifically recognised building simulation programmes. Starting from version 17.01 it is possible to import data of a 3D model and automatically establish a new 3D multi-zone building project. In order to be able to use this function, with the aid of a software tool for example “SketchUp” or in future also “Rhino”, first a model has to be created with the definition of the following design parameters:

- geometry
- window-to-wall ratio
- boundary conditions of the envelope components to adjacent zones or the outside
- shadings caused by neighbouring buildings.

The main interface of TRNSYS is the simulation studio where all components, referred to as types, of the simulation model are linked. For the 3D file imported the settings of the weather data (e.g. based on Meteonorm data files), the azimuth angles of the model and the control systems of the shading devices and the lighting control have to be adjusted. These types are connected to the important “Type 56” (TRNBuild) which offers a specific interface to setup the characteristics of the building, e.g. material choice, definition of wall and window types, and its technical performance such as e.g. ventilation, heating and cooling systems, infiltration, internal gains and schedule. A daylight simulation is not supported at the moment of the current investigations but ongoing developments lead to a new integrated daylight model to allow the calculation of daylight factor, autonomy, useful daylight, illuminance level and energy use for electric lighting [Transsolar-2] during the thermal simulation run.

The use of a multi-zone model allows the detailed simulation of single zones of the building. The time steps for the simulations (TIMESTEP) can be chosen at will and the outputs defined can be released via so-called „plotters“. TRNSYS offers the possibility to calculate the idealised heating and cooling demand of each zone without indicating the type of generation, the distribution or the transfer within the building. The amount of heating and cooling energy demand to achieve the desired target temperature and thresholds that are defined by TRNBuild, is determined at the end of each simulation time step. The heating and cooling energy flows are connected directly with the zone temperature nodes [Solar Energy Lab].

Solar radiation model

In TRNSYS two models can be used for the distribution of radiation, the first is based on “geosurf-factors” (percentage share) that can be inserted by the user. The second model is based on “view factor matrices” of each surface, which are calculated on the basis of the geometrical data of the 3D model [Schmidt]. The connections of horizontal solar radiation and onto the facades with TRNBuild can be done automatically based on the selected orientation and the weather data (internal calculation of radiation data) or by the user himself in the TRNSYS studio (external). If an automatic connection is chosen, the setting “integrated radiation control” according to the window type should be chosen to define the external shading factor in TRNBuild. The shading control and the F_c-value are then connected with the settings in the simulation studio (MaxEshade).

Shading of direct solar radiation

In case of shading caused by neighbouring buildings or fixed shading, a shading matrix of the direct sky radiation based on 3D geometry data is being established. The hemisphere is being subdivided into so-called patches (Tregenza model) and each one is represented by a centre point, see figure 23.

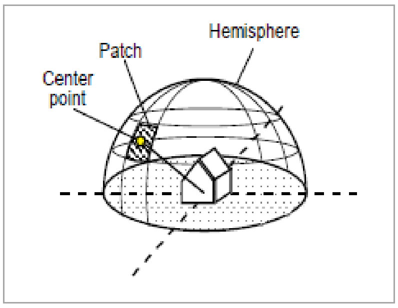


Figure 23: Subdivision of the hemisphere into patches [Transsolar-1]

The beam radiation distribution in case of the external windows is based on geometric distribution.

Shading of diffuse solar radiation

Analogue to the direct solar radiation the calculation is founded on the 3D geometric data. Under the assumption of an isotropic distribution, which means a uniformly radiation distribution in all directions of the three-dimensional room, of the diffuse radiation, those patches that are located in front of the area are integrated into the calculation. The calculation leads to a reduction of direct radiation onto a surface.

Direct distribution of radiation within a zone

Based on the 3D geometric data the total input of direct shortwave radiation is distributed geometrically within the zone, see figure 24.

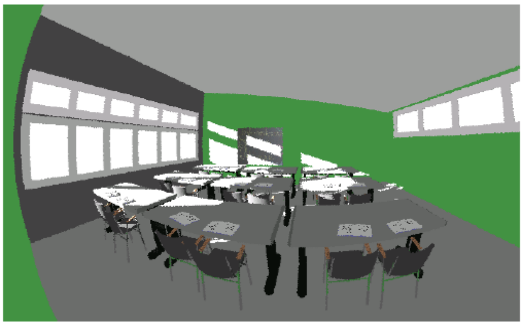


Figure 24: Direct distribution of radiation within a zone [Transsolar-1]

The creation of a matrix for the distribution of direct radiation takes place in the same way as the shading matrix by means of the subdivision of the hemisphere into patches.

Diffuse and longwave radiation distribution within a zone

On the basis of the 3D geometric data diffuse radiation is distributed onto all surfaces of a zone except for the window areas. The longwave radiation exchange is carried out accordingly.

Detailed model

If a 3D model is used, then a detailed model, integrated in version 17.01, can be used in TRNSYS for the calculation of the longwave radiation exchange and the convective heat flow between walls (wall nodes) and the thermal zones (air nodes). Subsequently the air nodes (T_{air}), wall nodes of the surfaces (T_{surf}) and the long-wave radiation exchange between the surfaces are exactly calculated with a separate calculation of the convective and the longwave radiative resistance. For each building component the solar absorptance coefficient is determined as well as the longwave emission coefficient and the convective heat transfer coefficient. When creating a 2-node model apart from the air node also a radiation node (T_{rad}) is being calculated, see figure 25.

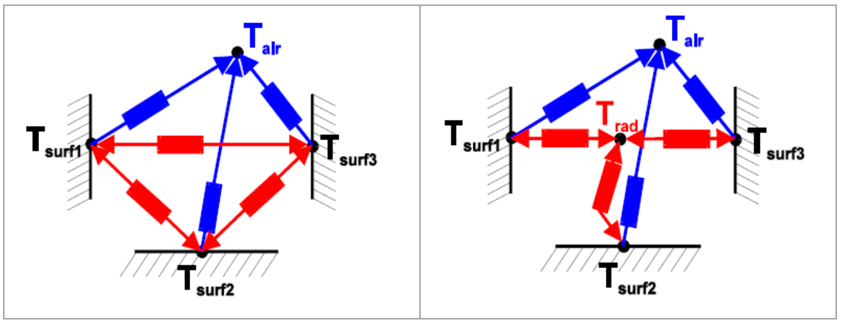
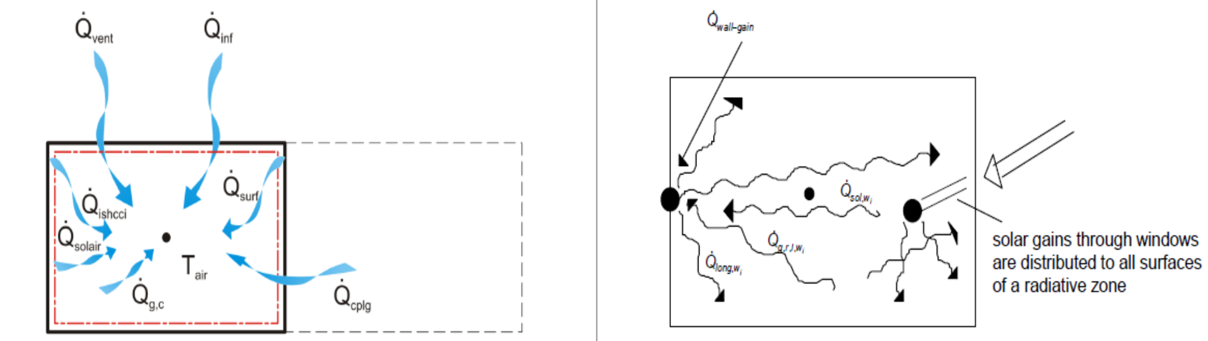


Figure 25: Distribution of radiation of the detailed model with one (left) and two nodes (right side) [Transsolar-1]

The advantages of the detailed model lie in the fact that the user can enter material-specific emissivities, include several air nodes in one radiative (longwave) zone and evaluate comfort values depending on the chosen position. Disadvantage is the increased effort for the manual input and higher computing capacities.

TRNSYS does not indicate an exact distribution of indoor temperatures in the three-dimensional room but due to the distinction between air and wall nodes it is possible to take into account the convective and radiative heat gains. The definition of the convective and radiative shares of the internal loads is important because the convective shares are directly used for the balancing of the air node. In case of the wall node also the radiation and the solar gains are taken into account [Thewes], see figure 26.



Heat balance on the air node

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} + \dot{Q}_{solair,i} + \dot{Q}_{ISHCCI,i}$$

with

$\dot{Q}_{surf,i}$	$= U_{w,i} \cdot A_{w,i} \cdot (T_{w,i} - T_{air})$	Convective heat from surfaces
$\dot{Q}_{inf,i}$	$= \dot{V} \cdot \rho \cdot c_p (T_{OA} - T_{air})$	Infiltration gains (air flow only from outside)
$\dot{Q}_{vent,i}$	$= \dot{V} \cdot \rho \cdot c_p (T_{vent} - T_{air})$	Ventilation gains (air flow from a user-defined source)
$\dot{Q}_{g,c,i}$		Internal convective gains (people, equipment, illumination, radiators, etc.)
$\dot{Q}_{cplg,i}$	$= \dot{V} \cdot \rho \cdot c_p (T_{zone,i} - T_{air})$	Gains due to air flow from zone i or boundary condition
$\dot{Q}_{solair,i}$	$= f_{solair,i} \cdot (I_{trans,dif,i} + I_{trans,dir,i})$	fraction of solar radiation entering an airnode through external windows which is immediately transferred as a convective gain to the internal ai
$\dot{Q}_{ISHCCI,i}$		absorbed solar radiation on all internal shading devices of zone and directly transferred as a convective gain to the internal air

Heat balance on the wall node

$$\dot{Q}_{r,w_i} = \dot{Q}_{g,r,i,w_i} + \dot{Q}_{sol,w_i} + \dot{Q}_{long,w_i} + \dot{Q}_{wall-gain}$$

with

$\dot{Q}_{wall-gain}$	user-specified heat flow to the wall or window surface
$\dot{Q}_{r,w_i}$	radiative gains for the wall surface temperature node
$\dot{Q}_{g,r,i,w_i}$	wall specified ratio of the radiative part of internal gains
$\dot{Q}_{sol,w_i}$	wall specified ratio of the solar gains through all windows
$\dot{Q}_{long,w_i}$	longwave radiation exchange between this wall and all other walls, windows

Figure 26: Heat balance on the air node (left side) and on the wall node (right side) [Transsolar-1]

Heat transfer function through building components

The heat transfer through a building component is described by the surface temperatures (T_{surf}) and the heat flows ($\dot{q}$) from inside to the outside. TRNSYS automatically calculates the heat flow on the basis of the conduction transfer function method (one-dimensional heat transfer function) while taking into consideration the material data such as thickness, conductivity, capacity and density of one- or multi-layer elements. However, the wall is considered as a black box model [Solar Energy Lab], see figure 27.

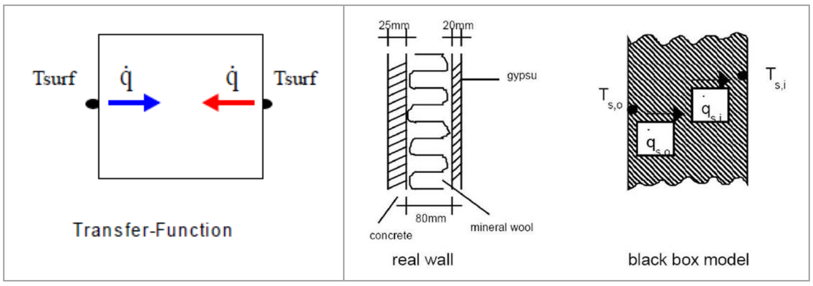


Figure 27: Heat transfer function [Transsolar-1]

The material properties are considered independent of temperature and the temperatures are regarded dependent from place and time. For each wall the internal and external heat flows are calculated with the aid of coefficients, surface temperatures of the wall as well as the heat flows resulting from the previous time step. The convective heat transfer coefficients[5] can be defined by oneself or by means of internal calculation, which also includes the temporal and thermal change of the wall. It is not possible to indicate the temperature progression inside the wall [Solar Energy Lab]. The heat flows and temperatures on the interior and exterior wall surfaces are illustrated in the following figure 28.

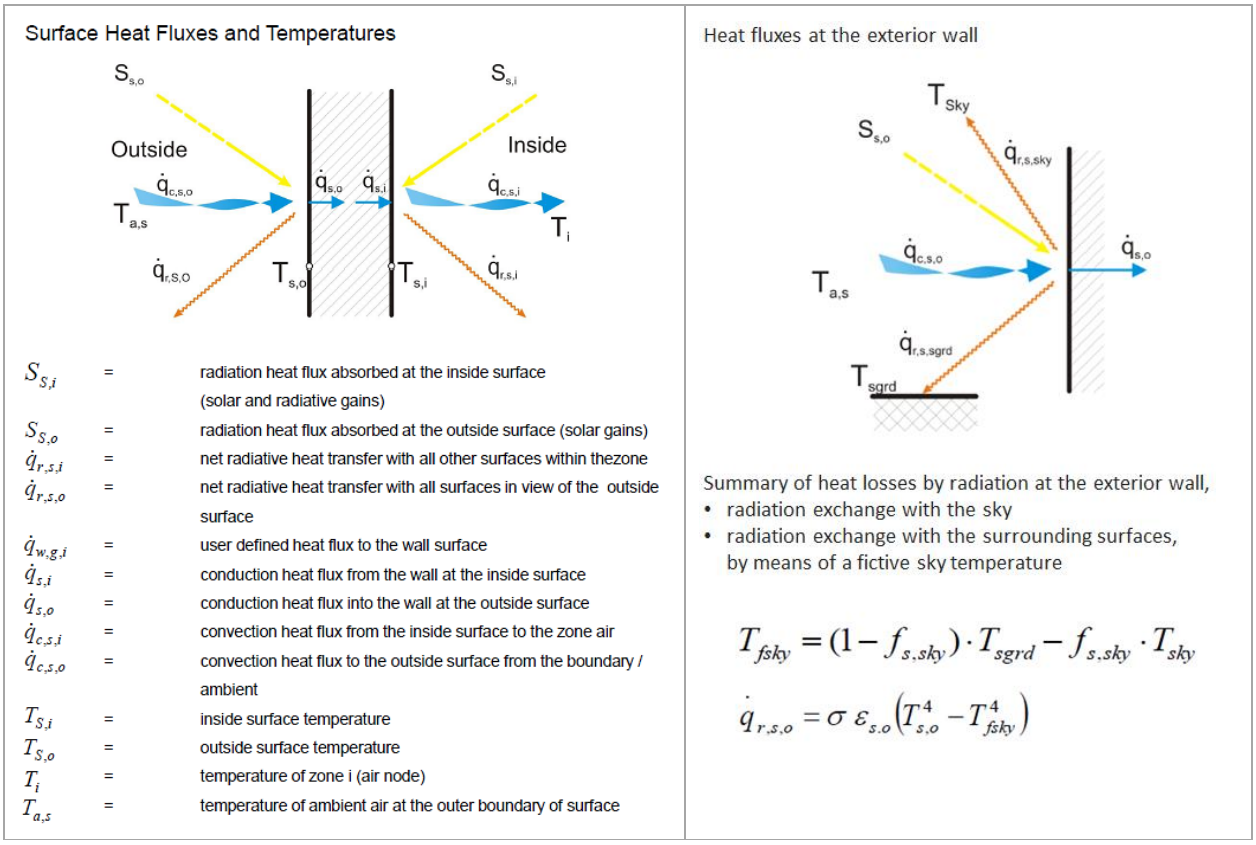


Figure 28: Heat flows and temperatures on the interior and exterior wall surfaces [Transsolar-1]

Originally the calculation method described for the multi-zone models to calculate the heat conduction was developed for annual energy balances with the typical resolution of one hour. In case of very small time steps (less than 5 minutes) and very heavy, well-insulated walls this approach almost reaches its limits. Consequently, for the calculation of the conduction transfer

[5] In this project the heat transfer h is defined as 11 kJ/h m² K inside and 64 kJ/h m² K outside.

function a separate time interval is used (TIMEBASE), which has to be an integer multiple of the TIMESTEP [Jungwirth]. Various studies by [Delcroix] use a calculation method that was established for that purpose, especially for simulations of phase-change materials with very small time steps.

Calculation window and shading

Glazings can be created with the software WINDOW and imported or taken from the data base of TRNSYS. The simulation is accompanied by a detailed calculation of transmission, absorption and reflection for direct and diffuse radiation and also of the heat transfer by means of convection and longwave radiation of the window element as well as a calculation of the longwave radiation exchange with the surroundings by means of the fictitious sky temperature ($T_{f,sky}$). In TRNBuild also the reduction of radiation with the help of the external shading device can be calculated by defining the shading factor (F_c), see figure 29.

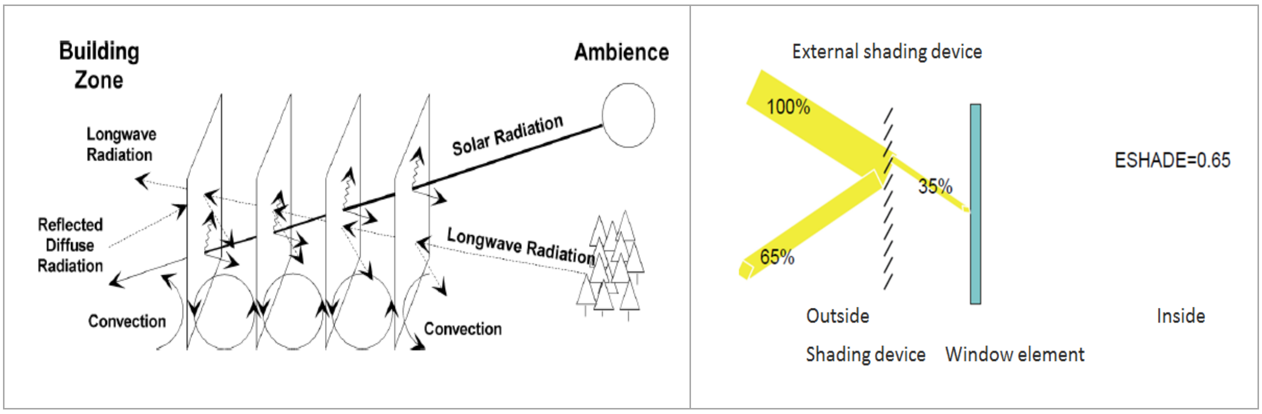


Figure 29: Simulation method of glazings and external shading devices [Transsolar-1]

For the planned version TRNSYS 18 also a new detailed window model is integrated to simulate complex fenestration systems for example a shading device that lies between the window panes, using the software WINDOW, Version 7 according to ISO 15099 (Thermal performance of windows, doors and shading devices - Detailed calculations). A new bidirectional scattering distribution function (BSDF), which characterises light transmission, reflection and directional distribution of a surface, has been developed and it allows the import of the data into TRNSYS by means of BSDF data files [Transsolar-2].

3 The Reference Building

A reference office building has been developed with a choice of building components which are commonly used in office buildings and which meet the technical, structural and physical building requirements of sustainable building design. The materials chosen have a high market share in Western Europe and are suitable for use in office buildings. The design of the reference building and the office zone, which are presented in this chapter, are considered to be representative for similar, typical office building constructions.

An important criterion of sustainable building design is the flexibility of the building structure so that the value of the property is maintained and the vacancy rate of office buildings lowered [FOSTA]. The structure should be adaptable to meet the demands of present-day and future office users due to the continual evolution of the working environment. Different certification systems, for example the DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen), have criteria for flexibility, variability, space efficiency and low operating costs to evaluate the economic quality. Already in the design process, many requirements have to be fulfilled to achieve high economic, ecological and socio-cultural quality. The challenge for the planner is to find the best solution taking into account the following parameters in the iterative design process:

- **Urban principles**
  - site-related factors
  - building and planning legislation
- **Building geometry and dimensions**
  - typological concept
  - double or triple sequence
  - building height and depth, storey height, clear height
- **Floor plan design**
  - choice of structure type (supporting structure)
  - choice of office organisation concept and its requirements for the supporting structure
  - facade and structural grid, construction grid
  - position and dimension of the structure core
  - choice of ceiling structure with and without support (columns, beams, central post)
  - choice of floor construction, position of partition walls
  - fire protection and sound insulation
  - specific areas (e.g. underground parking, entrance hall)
- **Facade design**
  - facade type and construction
  - window area
  - type of glazing
  - sun protection and shading devices
- **Technical installations**
  - choice of heating, ventilation and air-conditioning (HVAC), sanitation
  - electricity supply, choice of lighting systems
  - space required and distribution

To evaluate the impact of these parameters on the energy balance of the whole building, two methods can be applied:

- a static calculation with commonly used monthly energy balances, based on standards such as the German [DIN V 18599] or the Luxembourgish [RGD 173] or
- a detailed analysis using dynamic thermal simulation software with a detailed time representation of typically one hour.

The reference zone method is recommended for the detailed analysis. The advantage lies in the fact that with a fairly simple model it is possible to quantify the impact of different solutions for the facade and structure as early as the optimisation phase of the building [FOSTA]. The net energy demands of a reference zone will be representative of the energy demands of the entire building.

This method has been applied in this project and the so-called “office zone” has therefore been abstracted from the reference building, see figure 30.

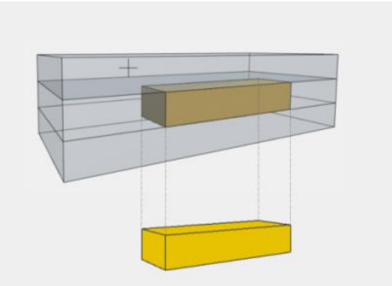


Figure 30: Image of reference zone method

All the project’s energetic and environmental evaluations are based on this representative office zone. The aim of the evaluations is to identify and quantify the impact of key parameters that have been analysed in detail, for example the:

- orientation
- ratio of window area
- structure type (thermal storage capacity and material selection)
- slab type
- shading devices
- thermal transmittance of the type of glazing
- solar energy transmittance of the type of glazing
- ventilation strategies
- lighting strategies.

3.1 The geometry of the reference building

The office building developed is a typical low- or medium-rise building of three to six stories with a rectangular floor plan. A geometry based on a square or bar-shaped structure is mainly used for office buildings and represents a large market share [Lange], see figure 31.

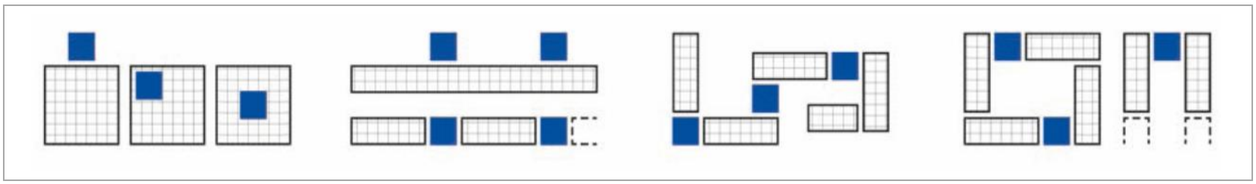


Figure 31: Typological conceptions (point, bar, band or meander and courtyard or atrium)[6] [Eisele]

3.1.1 Floor plan design

The building consists of a triple sequence and the form of organisation concept is the “combi-office”. It is a popular type of office layout which can be found in many office buildings and has high user acceptance. The implementation of other office organisation designs, such as the “business club” or “open space” solutions, are also possible due to the design of geometry and supporting structure, see Figure 32.

Figure 32: Floor plan, section and image of the reference office building[7]

Work stations are located along the facade of the building to take advantage of natural light and natural ventilation. The combi-zone and service rooms are arranged centrally. The cores with the stairwells act as the static bracing at the gable end of the building where the main entrance is located on one side.

The facade and structure grid of office buildings is commonly between 1.20 m and 1.50 m. The facade grid selected for the reference building is 1.35 m, which is the most appropriate grid for an efficient office organisation concept and additionally it is compatible with the grid for

6 typology: the grey parts represent the office zones, the blue parts the construction cores and vertical access/circulation

7 In the general floor plan, the section “office zone” is marked in orange.

underground parking [Eisele]. In almost all designs, the facade and the structure grid are identical, but independent grids are also possible as are staggered arrangements of main and facade grids [Knaack].

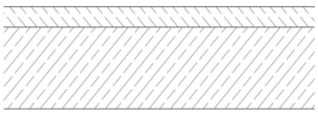
The construction grid is based on the structural grid and normally a multiple of it. The grids should be congruent and aligned [Eisele]. They depend on the choice of slab construction, supporting structure and the appropriate position of the columns and, if needed, the central posts. The aim is to reach a high level of flexibility to allow different office organisation concepts. The basic design of the reference building has a construction grid of 5.40 m along the facade and one of 5m/6m/5m in the depth of the building. However, different construction grids have been applied for the steel composite structure (columns, slabs and beams) according to previous structural calculations. The aim is to find a best solution not from a structural but from an energetic and environmental point of view.

3.1.2 Building dimension

The reference building has a compact geometry and a surface-to-volume ratio (A/V ratio) of 0.34. It has a depth of 16 m based on the construction grid, which is an efficient depth for the office organisation concept of combi-offices, business club or group offices. If the depth of a building is higher than 18 m, it can result in an increase in energy demand for artificial lighting and ventilation [Eisele]. A storey height between 3.25 m and 3.50 m is optimal for a six-storey building to avoid a building level higher than the high-rise-building level of 22 m, calculated from the level outside to the upper face of the finished floor. If a building level is above this height more requirements have to be fulfilled, especially concerning fire protection. In addition, the choice of 3.35 m for the reference building allows scope for different heights of slab constructions because the recommended clear height is 2.75 m [Eisele].

Structure and slab type

In the context of this work, typical solid and steel composite structure types of office buildings have been defined for the reference office building. They are already 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 an optional suspended ceiling, see figure 33.

Type	Structure	Sketch and image
SOLID 1	solid system reinforced concrete with screed	 

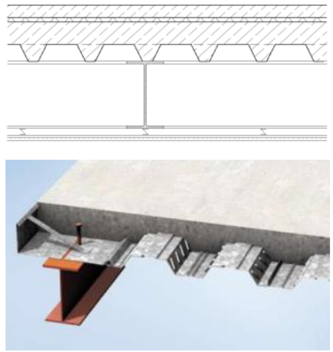
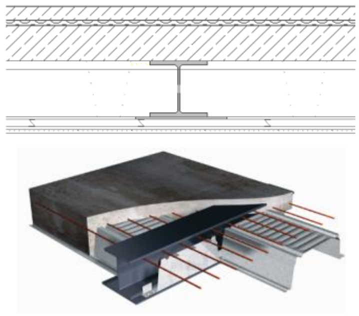
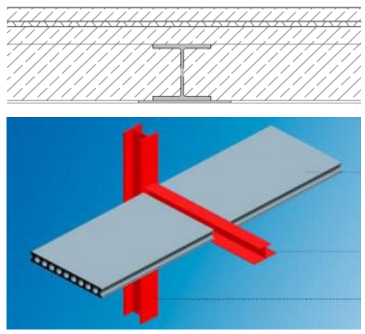
STEEL 1	steel beam system, profiled sheeting + concrete, floating screed, suspended ceiling	
STEEL 2a	integrated floor beam system, profiled sheeting + concrete, floating screed, suspended ceiling	
STEEL 2b	integrated floor beam system, precast concrete element, floating screed, (suspended ceiling)	

Figure 33: Different structure types of reference building

The structural calculations of the steel structure types[8] recommend solutions with various column grids, with and without a central post, and slab. For further details please refer to appendix 4.

The architectural decisions regarding the ceiling and floor constructions and choice of materials have a high impact on the energy requirements and the room conditions, e.g. thermal, acoustic, and visual comfort. The installation, for example, of a false floor or a suspended ceiling decreases the thermal capacity of the slab structure, but on the other hand it makes a simple distribution of the technical installations possible. The aim is to find an optimal solution for both structure types from an energetic and environmental point of view.

3.2 Facade design

The facade system, consisting of opaque and transparent parts, is the building component that unifies the concept and design aspects with the constructive and climate conditions [FOSTA]. It plays an important role in the planning of energy-efficient office buildings because its design influences the air-conditioned space and energy consumption. Additionally, the facade is the

[8] calculated by M. Braun of ArcelorMittal

building component which gives a company an identifiable, attractive address and it projects the image of the site, see figure 34.

Figure 34: Images of different facade designs and window areas[9]

3.2.1 Window area

Facade systems for office buildings are divided in three types depending on their window-to-wall ratio. In this project a punctuated facade with a ratio of 48% (F48), a band window facade with a ratio of 77% (F77) and a fully glazed facade with a ratio of 100% (F100) have been designed, see figure 35. The window-to-wall ratio calculation is based on the inside surface of the exterior wall and each window element consisting of 80% glazing and 20% frame.

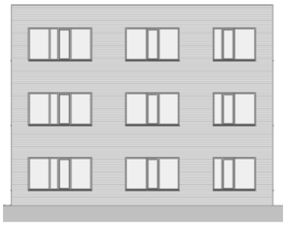
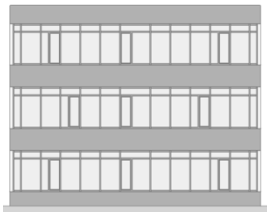
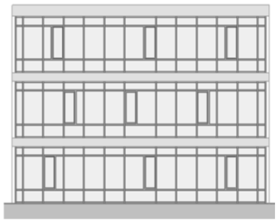
TYPE	F48	F77	F100
Facade design			
Window ratio	48%	77%	100%

Figure 35: Facade types for the reference office building

The following table 2 shows the window area calculation.

Table 2: Window area for the office zone

Window area F48	
Window-to-wall ratio (calculated from outside)	43%
Window-to-wall ratio (calculated from inside)	48%
Window area F77	
Window-to-wall ratio (calculated from outside)	69%
Window-to-wall ratio (calculated from inside)	77%
Window area F100	
Window-to-wall ratio (calculated from outside)	89%
Window-to-wall ratio (calculated from inside)	100%

[9] images from baunetzwissen

3.2.2 Construction types

The opaque element of the exterior wall is a non-bearing, ventilated curtain wall structure, referred to as cold facade, which determines most of the types of construction for office buildings. It consists of the wall element, the insulation material, an internal finishing and external, ventilated cladding. Window elements are commonly used in punctuated or band window facade systems. However, in highly glazed office buildings non-bearing curtain wall systems are installed in almost all cases. These could be element facade with transparent and opaque parts, see figure 36, or self-supporting frame constructions (post and beam systems) made of steel or aluminium profiles. Detailed information about facade constructions is to be found in chapter 2.7.1. The types of glazing selected are triple, double and electrochromic glazing. They have a function either as heat protection or solar glass depending on the choice of the thermal (U_g-value) and solar energy transmittance (g-value), please refer to chapter 2.7.3.

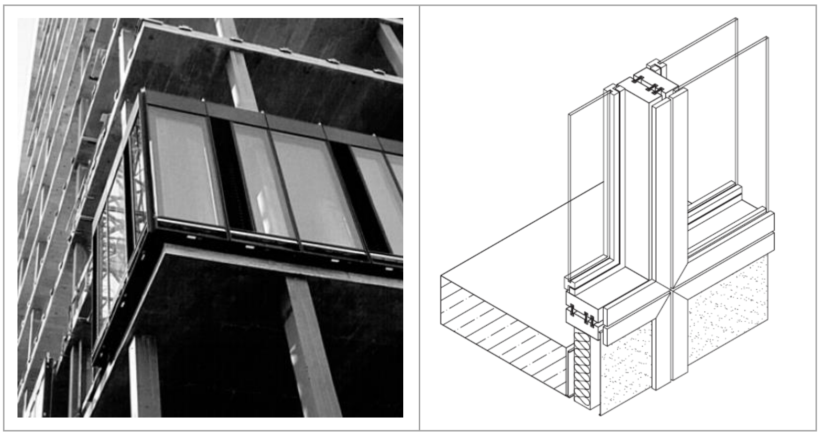


Figure 36: Typical element facade and construction principle [Knaack]

3.3 Office zone

The office zone can be applied to different types of building geometry and commonly used office organisation concepts, for example the cellular office, combi-office or open space solutions. It is located in an intermediate storey of the reference building with a net floor area of 110 m^2, which provides a work space for about ten people. The opaque parts of the exterior wall are highly insulated and have an U-value of 0.17 W/(m^{2}K). The climate conditions of the boundary zones are identical to those of the office zone, see figure 37.

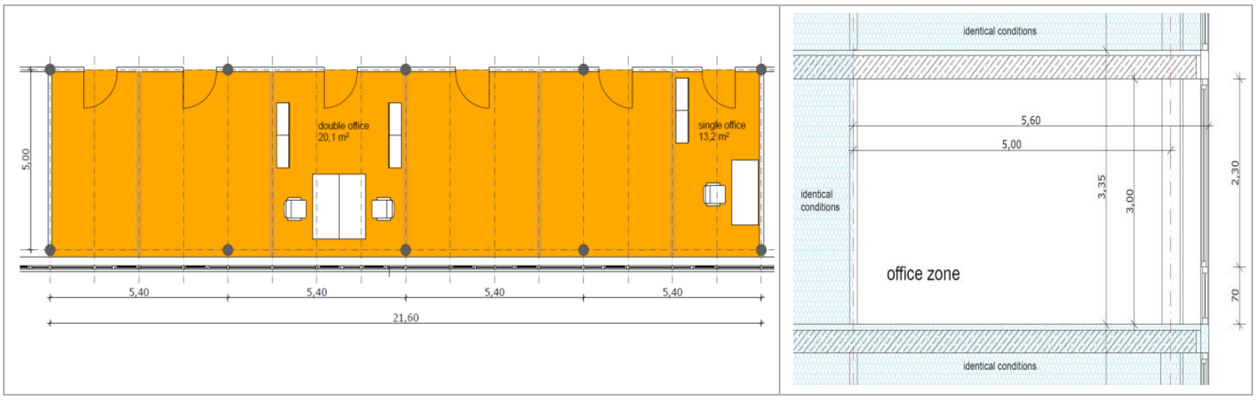


Figure 37: Floor plan and section of the office zone

The following table 3 shows the main properties of the office zone.

Table 3: Properties of the office zone

Reference office zone	Dimension	Unit
Length	21.60	m
Width	5.56	m
Gross floor area	120.10	m^2
Net floor area/energy relevant area	110.38	m^2
Gross volume	402.32	m^3
Net volume	331.14	m^3
Area of exterior wall (calculated from outside)	72.36	m^2
Area of exterior wall (calculated from inside)	64.43	m^2
Gypsum plasterboard wall inside	79.85	m^2
U-value of opaque exterior wall	0.17	$W/(m^2K)$

3.4 General requirements

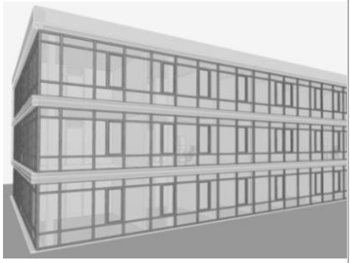
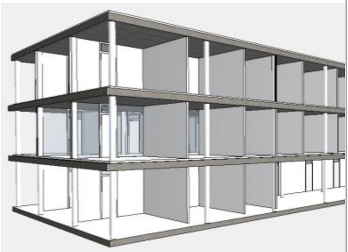
For comparing the results of the energetic and environmental evaluations are necessary, equal general requirements (basic parameters) for the office zone. The following technical, structural and building physical properties have been defined identically for all building materials, components or structure types:

- dimensions
- thermal transmittance and insulation standard
- thermal conditions of boundary zone
- facade and construction grid
- structural design/static analysis and load assumptions
- fire protection and sound insulation
- technical building services
- design of the interior

3.5 Design parameters investigated

The following table 4 gives an overview of the constructive and technical design parameters analysed in the course of the project.

Table 4: Overview of the constructive and technical design parameters and the outputs of the project

Constructive and technical design parameters		NOM	Parameter	Nomen-clature	Definition	See chapter
	Site	**OR**	Orientation of facade	/	south + south-west north west + east (optional)	4.1.2 + 4.2.1
	Facade design	**WA**	Ratio of window area	F48	punctuated facade (48%)	4.1.3
				F77	band window facade (77%)	
				F100	fully glazed facade (100%)	
		**SD**	Shading devices	SHON	external shading device (F_c=0.3) switched on	4.1.4 + 4.2.4
				SHOFF	shading switched off	
		GU **GG**	Type of glazing - U_g-value - g-value	EW1	triple, thermal insulation	4.1.4 + 4.2.4
				EW2	double, thermal insulation	
				EW3	double, solar control	
				EW4	triple, solar control	
				EW6	double, thermal insulation	4.2.6.3
				ELEC2 + ELEC3	electrochromic glazings	4.2.4.2
	Structure/construction	**ST**	Structure type (slabs + columns + exterior wall)	SOLID1	solid structure	4.1.5 + 4.2.3
				STEEL1	steel beam system	
				STEEL2a	integrated floor beam system	
				STEEL2b	integrated floor beam + pref. concrete elements	
		SL	Slab type	SC	suspended ceiling	4.1.5 + 4.2.3.1
				WSC	without suspended ceiling	
				FF	false floor	
	Building technology	**VS**	Ventilation strategy	VENT_MECH	mechanical ventilation strategy	4.1.6.1 + 4.2.2
				VENT_NIGHT	mechanical strategy incl. night ventilation	
				VENT_NAT	natural ventilation strategy	
		/	Lighting strategy	/	control system, solar radiation controlled	4.1.6.2
Simulation results (outputs): HD = Heating demand CD = Cooling demand OH = Overheating hours/a (≥ 26°C) PE = Primary energy demand			Cooling strategy	Case1	cooling, switched on, 26 °C	4.1.6
				Case2	cooling off, calculation of overheating hours	
				Case3	cooling, switched on, 24 °C	4.2.6.2
			Heating	/	fixed	4.1.6
			Schedule Occupancy rate	/	fixed	4.1.6

4 Expertise-Based Parameter Study

The parameter study was started using expertise-based decision-making and continued by applying an automatic optimisation tool, see chapter 5. For the expertise-based study, the design parameters have been determined using typical values for office buildings and their choice is based on architectural experience and literature review. The aim is to identify and quantify the impact that relevant design parameters (see table 4) have on net energy demand for heating and cooling and on thermal comfort. The focus is on the facade design of highly glazed buildings and the thermal storage capacity of solid and in particular steel composite structures. The parameter combinations presented are low-tech concepts which comply with energy efficiency and comfort requirements. The approach of the parameter study is shown in figure 38.

The energetic evaluations are based on the office zone using the reference zone method, see chapter 3. Using dynamic, thermal simulations for the reference office zone, it is possible to directly quantify the influence of different facade designs, structural solutions and technical strategies [FOSTA]. The method is efficient and timesaving for parametric studies where a large amount of data and a range of simulation results are required. The results are representative for the reference building presented, and for office buildings whose construction and floor plan arrangement are similar to the principle of the office zone. If buildings or zones strongly deviate from this principle, for example corner spaces, additional calculations will have to be made.

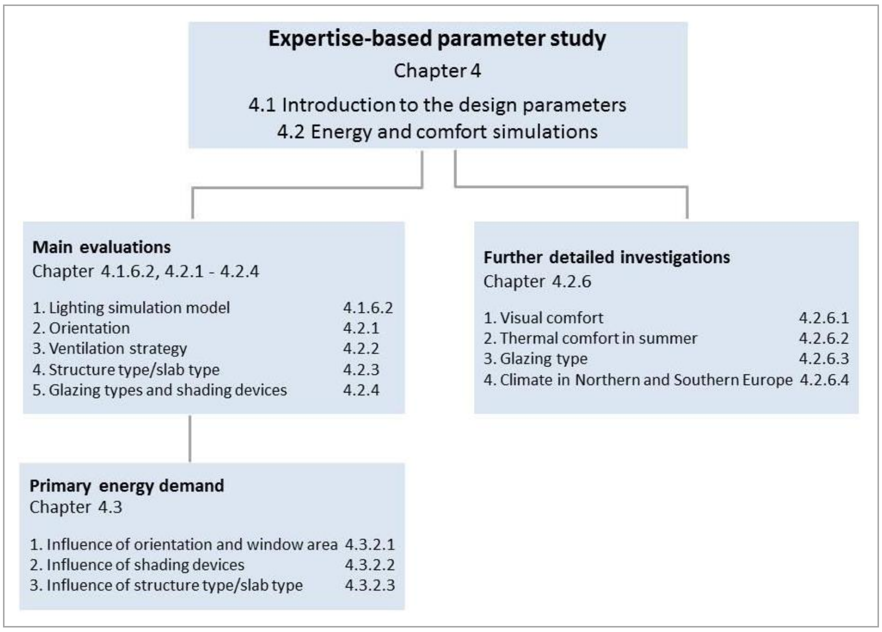


Figure 38: Approach of the expertise-based parameter study

4.1 Introduction to the design parameters

The number of design parameters that can influence an office building's energy demand and the climate conditions in its space is very high. To identify and concentrate on the most important parameters and also to limit the number of simulations required, several of them need to be defined as fixed, discrete or categorical. In this project, selected design parameters concerning the facade design (e.g. window area, glazing type), structure type and ventilation strategy have been varied. This approach is considered acceptable because the aim is to develop design recommendations and a range of optimisation measures for the concept phase when many details still remain undefined. The results should show impacts and tendencies of parameter combinations for highly glazed buildings in steel composite construction. The detailed analysis of a special design parameter which includes several sub-parameters, for example different temperature trigger values for ventilation strategies, does not form part of the project. A further objective is to analyse the influence of new technologies, for example, electrochromic glazings. Definitions and specifications for these design parameters are presented in the following chapter.

4.1.1 Climate conditions

The parameter study is based on the temperate climate of Western Europe in Saarbrücken, Germany (Meteonorm/Europe database). In this climate, the seasons are defined by long transition periods and the solar radiation varies considerably over the year. Temperature fluctuations throughout the year are higher in continental locations than in coastal areas. During the winter heating is required. During the summer passive cooling measures can ensure a comfortable indoor climate if solar radiation is limited. In a moderate climate de- and/or humidification are not necessary [Hausladen, 2012].

In addition, the influence of the warmer Southern European climate of Madrid, Spain, and the cool Northern climate of Östersund, Sweden, on energy demand and thermal comfort of the office zone has been analysed. In Southern Europe the focus is on passive and active cooling systems and in Northern Europe on optimising heating demand.

4.1.2 Orientation

As early on as the concept phase, the site’s climatic and surrounding conditions should have an influence on the building and facade design. Whether a building is north-south or east-west oriented has a great influence on its energy demand and the climatic conditions in its space. The intensity of the solar radiation varies depending on the orientation and azimuth as well as the altitude angles of the sun to the facade.

In a moderate climate, office buildings should be oriented with a north-south orientation. East- and west-oriented facades are more critical as regards the risk of overheating because the period of solar radiation on the facade is approximately 75% identical to the time during which office buildings are used [Hausladen, 2006]. In this project, the focus is on north, south and south-west orientation, which is most critical in the summer. However, the results of all orientations have been analysed for case studies selected.

4.1.3 Window area

The window-to-wall ratio has a high impact on transmission losses, solar gains and daylight use. These three effects influence energy demand and visual and thermal room comfort. The internal loads depend on how much visible light is gained due to the worklight hours from artificial lighting.

In this project a punctuated facade with a ratio of 48% (F48), a band window facade with 77% (F77) and a fully glazed facade with 100% (F100) have been designed for the office zone, see chapter 3. A 3D building model of the office zone for each facade design (SketchUp, Version 8) is the basis for all the thermal simulations, see figure 39.

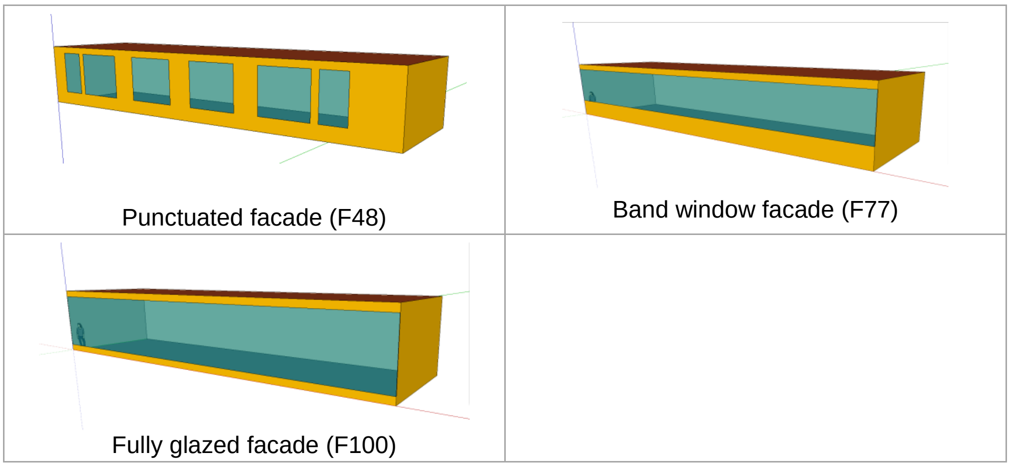


Figure 39: 3D models of the office zone with different window-to-wall ratio

4.1.4 Glazing types and shading devices

Depending on the orientation and the window area, the choice of glazing type and solar shading is crucial, particularly so that improved thermal comfort in highly glazed buildings can be ensured. Various types of thermal insulation (EW1) and solar control glass (EW3, EW4) have been investigated in combination with (SHON) and without (SHOFF) a radiation-controlled external shading device, see table 6. An interesting alternative to such a conventional device is electrochromic glazing (ELEC), see table 5.

Table 5: Defining glazing types

Nomen-clature	Definition	Thermal transmittance (U_g-value in $W/(m^2K)$)	Solar energy transmittance (g-value)	Visible light transmittance (Tvis)	Selectivity (S)
EW1	Triple glazing, insulation glass unit	0.59	0.58	0.74	1.27
EW2	Double glazing, insulation glass unit	1.24	0.58	0.76	1.30
EW3	Double glazing, solar control glass	1.23	0.44	0.62	1.41
EW4	Triple glazing, solar control glass	0.59	0.45	0.66	1.46
ELEC2	Electrochromic triple glazing, radiation-controlled	0.78	0.41 - 0.05	0.41 - 0.01	1.00 - 0.16
ELEC3	Electrochromic triple glazing, radiation-controlled	0.74	0.37 - 0.03	0.55 - 0.01	1.48 - 0.32

Table 6: Defining shading devices

Nomen-clature	Definition	Opaque fraction	Close if	Open when
SHON	External shading device, radiation-controlled, all times	70% (50%)[10]	total radiation on facade >140 W/m^2	total radiation on facade <120 W/m^2
SHOFF	No external shading device			

[10] identical with F_c-value, shutters or venetian blinds 0.3 or 0.25, fixed slats or single slats 0.5 according to DIN 4108-2

4.1.4.1 Glazing types

The heat transfer coefficient (U_g-value), energy transmission coefficient (g-value), light transmission factor (Tvis) and selectivity (S) are the relevant specific values for a type of glazing, see chapter 2.7.3. The challenge for the planner is to find a glazing type which provides an optimal and technically feasible combination of these values. Due to the high internal loads in office buildings, solar gains should be reduced, especially in the summer, without decreasing the use of daylight. During the winter, high transmission losses and cold draughts in front of the glazing should be avoided. The key question is whether the right choice is: thermal insulation glass or solar control glass.

Electrochromic glazing as presented varies the visible light (Tvis) and the solar energy transmittance (g-value) in five states. The glazing ranges from being clear in the first state to fully tinted in the fifth state. The control system depends on total solar radiation on the facade in W/m^2. An optimal control algorithm should avoid high solar gains and in addition an increase in worklight hours during the period when the building is being used. Two electrochromic glazing systems have been devised using the WINDOW, Version 7.2 (2014) software tool. They contain different optical and technical data and respond to variable thresholds of solar radiation on the facade. The effects of the slow transition from one stage to another stage have not been taken into consideration in the simulation process.

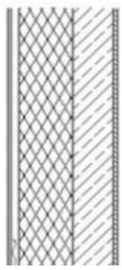
4.1.4.2 Shading devices

The external shading device presented has an opaque fraction of 70% which is similar to an F_c-value[11] of 0.3 (shutters or venetian blinds). Additionally, a shading device with a fraction of 50% (fixed, e.g. single slats or an overhang) has been investigated. The control system is based on the total solar radiation on the facade. The shading device will close if total solar radiation on the facade exceeds 140 W/m^2.

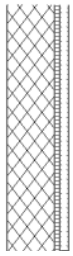
4.1.5 Structure and slab type

The opaque part of the external wall and the slab type play a decisive role due to transmission losses and thermal storage capacity. The exterior walls of solid and steel composite structure types are highly insulated and have an U-value of 0.17 $W/(m^2K)$[12], see table 7.

Table 7: Exterior wall (opaque elements) of solid and steel composite structure

Exterior wall	Definition of opaque element	Sketch
SOLID	015 mm gypsum 150 mm concrete 200 mm insulation 030 mm air layer/sub-structure ventilated + cladding	

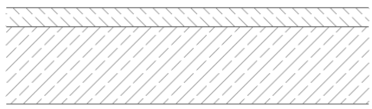
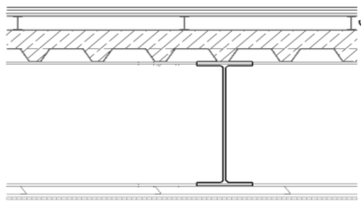
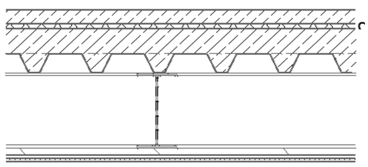
[11] The F_c-value is the reduction factor of the solar shading according to DIN 4108-2. A value of 0.3 indicates that 30% of solar energy can penetrate inside a building.
[12] U-value calculation according to DIN EN ISO 6946

Table 7: continued		
STEEL	025 mm gypsum plaster board 015 mm oriented strand board (OSB) 140 mm steel construction & insulation (optional 200 mm) + cladding	

The slab system of the solid structure consists of reinforced concrete and screed (SOLID 1). The steel composite types are a conventional composite beam and slab system with steel sheeting (STEEL 1) and an integrated floor beam system with steel sheeting (STEEL 2a) or precast concrete elements (STEEL 2b). Structural calculations of the steel composite structure types[13] recommend solutions with various column grids, with and without a central post, and various slab types. For structural calculations and quantities see appendix 4 and 2.

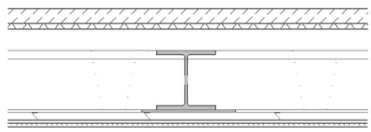
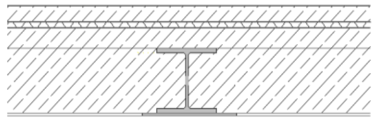
The massivity of the slab and the accessibility of the mass of both structure types have been varied, for example, by removing the suspended ceiling, replacing the floating screed with a false floor or replacing the profiled sheeting with precast concrete elements, see table 8.

Table 8: Slab types of solid and steel composite structure

Structure type	Nomen-clature	Definition	Sketch
SOLID STRUCTURE			
SOLID 1	SO_WSC	280 (240) mm concrete, 70 mm screed	
SOLID 2	SO_SC (FF)	280 (240) mm concrete, 70 mm screed + suspended ceiling (SC), optional false floor (FF)	
STEEL COMPOSITE STRUCTURE_STEEL BEAM SYSTEMS			
STEEL 1	C60	profiled sheeting C60 + 100 mm concrete slab, 55 mm floating screed[14] and suspended ceiling	
STEEL 1	C60_WSC	without suspended ceiling (WSC)	
STEEL 1	C77	profiled sheeting C77 + 130 mm concrete slab, 55 mm floating screed and suspended ceiling	
STEEL 1	C77_WSC	without suspended ceiling (WSC)	

[13] calculated by M. Braun of ArcelorMittal
[14] 55 mm floating screed + 20 mm sound insulation

Table 8: continued

STEEL COMPOSITE STRUCTURE_INTEGRATED FLOOR BEAM SYSTEMS			
STEEL 2a	C220	profiled sheeting C220 + 190 mm concrete slab, 55 mm floating screed and suspended ceiling	
STEEL 2a	C220_WSC	without suspended ceiling (WSC)	
STEEL 2b	CON_WSC	230 mm precast concrete elements, 55 mm floating screed	

Whether the structure type (mass) or the slab type e.g. a suspended ceiling (accessibility of the mass) are decisive will be answered in the next chapter 4.2. In this project, the steel composite slabs with profiled sheeting have been simulated as flat slabs, but according to [Döring], it can be assumed that a profiled steel sheet decking has a higher effective thermal capacity than conventional flat slabs.

The non-bearing interior walls are metal stud partitions which have 100 mm mineral wool inside and a double gypsum plasterboard finishing. All the building components presented have a practicable, technically feasible construction.

4.1.6 Technical strategies

Office buildings with low-tech concepts should have a high proportion of thermal mass, a low ratio of window area and a combination of natural and mechanical ventilation systems to decrease the energy demand for cooling systems (electricity demand) [ABP]. The technical complexity and the possibility for errors are usually lower (robustness of the system) and user acceptance is higher for simple energy concepts [Hausladen, 2012].

In this project, different ventilation strategies have been compared in order to find an optimal solution with natural ventilation and maximum use of passive cooling. Other technical parameters, such as the schedule, set points and heating and cooling control strategies, have been defined as fixed for all the thermal simulations, see table 9.

Table 9: Defining the technical parameters

NO.	Parameter	Definition
1	Schedule/ Operation time (USE)	260 days/a, 7:00 am - 6:00 pm => 2.860 hours/a
2	Occupancy rate	10 people, seated, light work (ISO 7730), 75 W/person[15], 6.8 W/person and m^2 during USE

[15] people are not determined with 150 W, but with 75 W; 150 W including 75 W latent (thermal conduction, cannot be measured) and 75 W sensible (convective + radiative); approx. 7 W/m^2 in single office per person [Dentel]

Table 9: continued		
3	Internal loads	11 W/m^2 office equipment during USE + 2 W/m^2 office equipment at all times/stand-by
4	Heating	Set point indoor temperature: 22 °C daytime, 16 °C nighttime, all season, unlimited heat power, no humidification
5	Cooling	*Case 1*: cooling set point indoor temperature: 26 °C at all times, unlimited cooling power, no dehumidification *Case 2*: no cooling

The specific values presented in table 9 have been determined according to the German [DIN V 18599-10], the Luxembourgish [RGD 173] and the comfort requirements set out in [DIN EN 15251]. The office zone provides a work space which can be defined as a group (two to six work stations) or open plan office (more than seven work stations) corresponding to [DIN V 18599-10]. The recommendations of both user profiles have been included in this project. An 11-hour daily operational period (5 days a week) and an occupancy rate of 10 m^2 per person have been defined. Including the office equipment, a constant value of 19.5 W/m^2 represents the internal loads. According to DIN V 18599-10, this value is in a medium to high range. Maximum occupancy time and density have been selected to evaluate the risk of overheating in the summer and compliance with thermal comfort requirements with a focus on low-tech concepts.

The performance of the heating system ensures that air temperature in the office zone is greater than or equal to 22 °C during the heating period. If in cooling mode the cooling system is switched on (*Case1*), it ensures that the room air temperature is lower than or equal to 26 °C at all times throughout the year. If the cooling system is switched off (*Case2*) the amount of hours per year greater than 26 °C can be determined, the so-called "overheating hours". The aim is to analyse if a low-tech concept without active cooling achieves thermal comfort in summer. The comfort requirements in the standards define that room temperature should not exceed 26 °C without using active cooling for 10% of the operational time (USE) [RGD 173, DIN 4108-2] which is equivalent to approximately 240 hours per year. The adjacent zones have identical climate conditions and no heat flow. The energy demand for the production of domestic hot water is not included in this study.

4.1.6.1 Ventilation and infiltration rate

The air change rates of the natural infiltration and ventilation systems greatly influence energy demand and thermal comfort.

In this project, a mechanical ventilation system with heat recovery, a controlled, constant air supply temperature during USE time (VENT_MECH) and an identical system but with additional natural night-time ventilation (VENT_NIGHT) have been studied. The latter system benefits from the cooling effect of outside air during periods when there is a risk of overheating. The third system is an entirely natural ventilation system (VENT_NAT) with an air-change rate similar to the other two systems and enhanced daytime and nighttime ventilation, see table 10.

Table 10: Defining ventilation strategies

NO.	Parameter	Definition
6	Infiltration rate	0,1 h^{-1} (24h, 7 days a week), high quality air-tightness of the envelope
7	Ventilation strategy	**VENT_MECH**: mechanical ventilation system controlled, constant air flow during USE (7:00 am - 6:00 pm) supply temperature of 18 °C air change rate 1 h^{-1} and heat recovery rate of 70%
		VENT_NIGHT: identical to VENT_MECH + enhanced night ventilation controlled **night-time ventilation** (natural cooling by automated facade flaps) air change rate 4 h^{-1} ventilation is switched on if room air temperature is ≥ 25 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 20 °C
		VENT_NAT: natural ventilation by enhanced daytime-nighttime ventilation hygienic base change rate 0,7 h^{-1} during USE (7:00 am - 6:00 pm), low polluting building, equates to approx. 30 m^3/person controlled **daytime ventilation** (automated windows and/or users) air change rate 2 h^{-1} ventilation is switched on if room air temperature is ≥ 25 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 23.5 °C controlled **night-time ventilation** (automated facade flaps) air change rate 4 h^{-1} ventilation is switched on if room air temperature is ≥ 25 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 21 °C

The air change rates presented in the table are based on the gross volume of the office zone.[16] Humidification or dehumidification has not been considered in this study.

The net energy demand Q for conditioning the outside air to the supply air condition (pre-heating and pre-cooling) is based on the temperature difference.

$$Q = \sum^{USE\ time} V * \rho * c_p * \left(T_{supply} - T_{amb}\right) * (1 - hr) \qquad \text{(Equation 3)}$$

pre-heating the supply air per year

$$Q = \sum^{USE\ time} V * \rho * c_p * \left(T_{amb} - T_{supply}\right) \qquad \text{(Equation 4)}$$

pre-cooling the supply air per year

With:

V	[m^3/h]	office zone volume flow
ρ	[kg/m^3]	air density
c_p	[kWh/(kgK)]	specific heat capacity of air
T_{supply}	[°C, K]	supply air temperature
T_{amb}	[°C, K]	ambient temperature
hr		heat recovery rate
$\sum^{USE\ time}$		sum over annual operation time of ventilation system

[16] The gross volume of the office zone is 402 m^3. Depending on the different slab types, the net volume varies between 300 m^3 and 330 m^3, which leads to slightly higher and varying air change rates.

The additional annual energy demand based on the net floor area of the office zone has a value of 3.37 kWh/(m^{2}a) for pre-cooling and of 9.25 kWh/(m^{2}a) for pre-heating taking into account a 70% heat recovery rate. These values have been considered for all the results produced using mechanical ventilation strategies (VENT_MECH and VENT_NIGHT).

The auxiliary energy demand (E_{elec}) of these mechanical ventilation systems has been calculated according to the [RGD 173] and using typical specific fan power (SFP) values as defined in the [DIN EN 13779]. The values depend on the category of SFP selected.

$$E_{elec} = \sum^{USE\ time} V * SFP \qquad \text{(Equation 5)}$$

With:

V	[m^3/h]	office zone volume flow
SFP	[Wh/m^3]	specific fan power; category 4, values according to DIN EN 13779
$\sum^{USE\ time}$		sum over annual operation time of ventilation system

The mechanical ventilation strategies (VENT_MECH and VENT_NIGHT) cause an electricity demand for the fans of 5.57 kWh/(m^{2}a).

4.1.6.2 Lighting simulation model

In many new office buildings lighting control systems are currently used in order to save energy used for electricity. A lighting control system can reduce the energy consumed by artificial lighting by 50% and it can also improve thermal comfort in the summer [Thewes].

TRNSYS 17 does not include fully automated coupling between energy and daylight simulation. Commonly lighting simulation depends on an average daylight factor (about 2%) and the global solar radiation on the horizontal exterior. This method is used to estimate illuminance in the space. Activated by default, artificial light is either turned on or off based on either a global solar radiation on the horizontal of 120 W/m^2 or 200 W/m^2 respectively. These values correspond to the illuminance values of 300 lx and 500 lx[17] inside the zone for a mean daylight factor of 2%. The conversion is based on the assumption that 1 W/m^2 global solar radiation is equal to 125 lx outside. As a consequence, light is turned on and turned off respectively based on 15,000 lx (120 W/m^2) and 25,000 lx (200 W/m^2) outside [Transsolar]. The simulation model of the office zone causes approximately 1,500 worklight hours per year. However, no relevant design parameters of the building have been considered, neither the orientation of the facade nor the ratio of window area, type of glazing and shading device. Accordingly, a new lighting simulation model with the following parameter definition has been developed, see table 11.

Table 11: Defining the lighting system

NO.	Parameter	Definition
8	Lighting system	worklight hours 7:00 am to 7:00 pm (5 days a week) => max. 3,120 h/a 10 W/m^2, fluorescent tubes, 40% convective part light control function based on shortwave solar radiation through windows

[17] The recommended light level for work places is 500 lx according to DIN V18599-10 and DIN EN 15251.

The model is based on shortwave solar radiation entering the office zone through the external windows, taking into account the facade related design parameters mentioned above. Artificial lighting is turned on or off respectively, according to the solar radiation inside the zone of 5 W/m^2 and 10 W/m^2 respectively. In comparison to the simulation model commonly used, the improved model leads to a varying amount of annual worklight hours representing the influence of orientation, window area glazing types and shading device, see figure 40.

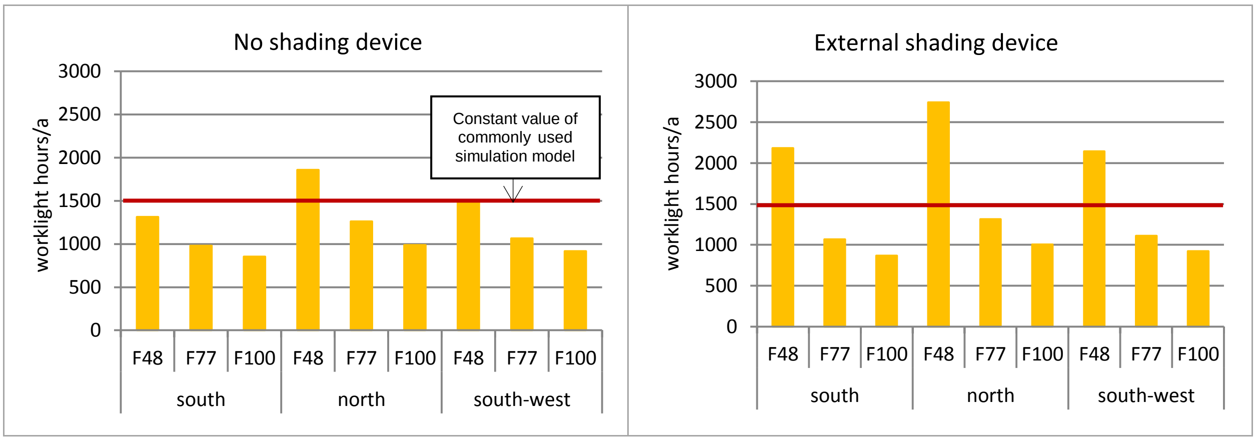


Figure 40: Worklight hours/a calculated for the office zone resulting in a more detailed simulation model compared to the commonly used TRNSYS model [18]

The daylight factor for the office zone has been calculated according to DIN V 18599-04 without considering the external shading device. The factor has a value of 6% for a punctuated facade (F48), 9% with a band window facade (F77) and 12% for a highly glazed facade (F100). A daylight factor of more than 6% is deemed “good” in accordance with DIN V 18599-04 and produces between 500 and 800 worklight hours per year [Szerman] based on an operational time of nine hours a day without taking a shading device into consideration. In this project, the schedule for artificial lighting has been defined as 12 hours a day (7:00 am to 7:00 pm). Due to this fact, realistically the amount of worklight hours for a highly glazed building in this project ranges between 750 and 1,050 hours per year. A study of [Thewes] in regard of the different calculation methods for worklight hours in office buildings, based on window area, shows that in highly glazed buildings (80% window-to-wall ratio) the amount varies between 400 and 1,000 hours per year. The author points out that the major differences highlight the problem of getting an accurate calculation method for transient, external and internal radiation conditions.

The new lighting simulation model provides an appropriate presentation of the worklight hours while taking into account facade-related design parameters for office buildings. Any potential for further optimisation based on dimming effects achieved through installing daylight sensors or light guidance effects have not been considered. This simulation model for lighting, presented above, forms the basis for all the further energetic evaluations in this project.

In addition the model makes it possible to assess more accurately the influence that worklight hours has on the internal gains in the office zone [Degens], see figure 41.

[18] The results presented in figure 40-42 are based on SOLID 1, the natural ventilation strategy (VENT_NAT) and the triple glazing (EW1).

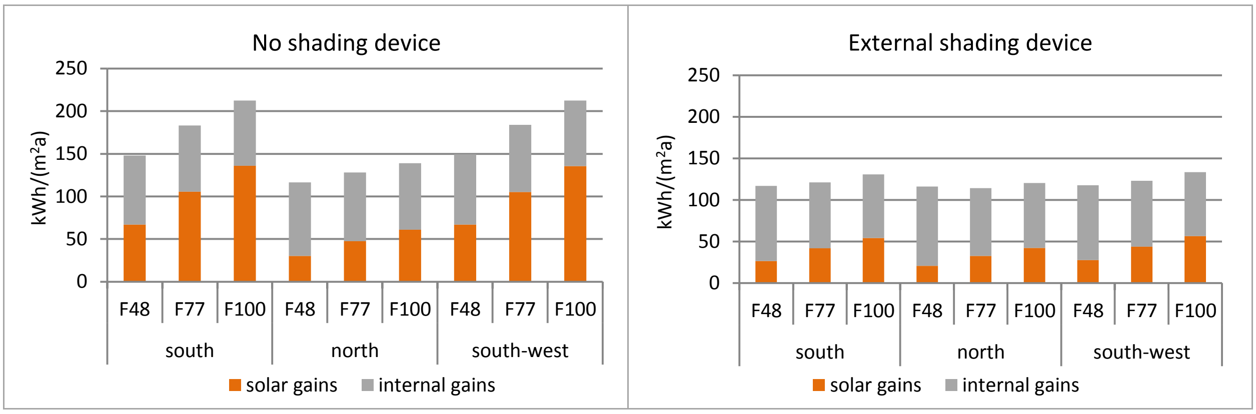


Figure 41: Solar and internal gains of the office zone resulting of a more detailed simulation model

The influence of artificial lighting on the internal gains is lower than expected when compared to the constant values of office equipment representing 48 kWh/(m^{2}a) and heat loads of persons representing 20 kWh/(m^{2}a). The solar gains are strongly influenced by the orientation, window area and particularly the external shading device.

The hours of overheating in the office zone are directly influenced by the sum of the internal and solar gains, see figure 42.

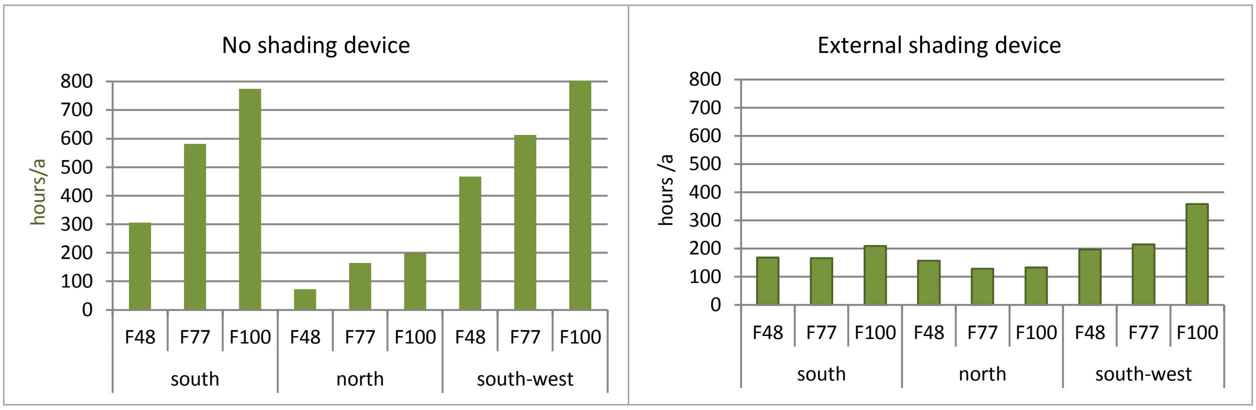


Figure 42: Hours of overheating/a in the office zone produced by a more detailed simulation model

It is crucial that the control systems for artificial lighting and solar shadings are coordinated. It is a challenge to find the optimal adjustment both in practice and in thermal simulations because the internal loads and solar loads are directly affected and the sum of both of them is decisive for improving energy efficiency and thermal comfort. At the time of these current investigations, no fully automated coupling between energy and daylight simulation was included in TRNSYS. However, a new feature for daylight simulation and control of lighting systems has been developed by the software company's research department and should soon be available. It includes the calculation of daylight factor, autonomy, useful daylight, illuminance level and energy use for electric lighting [Transsolar-2]. These developments show the importance of daylight simulation models, especially for thermal simulations of energy-efficient buildings.

4.2 Energy & comfort simulations

Reliable, dynamic, thermal simulation tools are required to assess the energy efficiency of buildings as well as their environmental and thermal comfort performance [Munaretto]. In this project, the energetic evaluation of the office zone has been carried out with the scientifically recognised, transient simulation tool TRNSYS, Version 17.01 (2012). The results represent the net energy demand for heating and cooling respectively overheating hours per year, when the cooling system is switched off.

Several parameter combinations have been analysed, evaluated and excluded iteratively from further investigations when they cause a high energy demand. The objective of this expertise-based selection process is to find an optimised solution for solid structures and in particular for steel composite structures. The general results, further detailed investigations as well as the primary energy demand of selected parameter combinations are presented at the end of this chapter.

4.2.1 Orientation

In a Western European climate, the south-west orientation of facades is the most critical with regard to thermal comfort in summer (overheating risk) and a north orientation results in higher heating demand, especially when there are highly glazed facades, see figure 43.

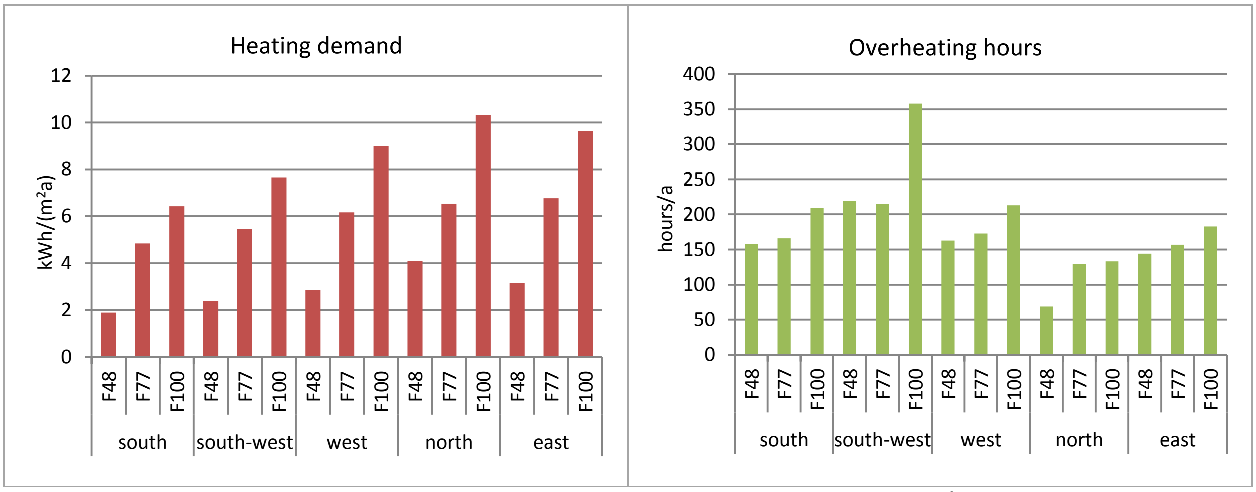


Figure 43: Office zone heating demand and overheating hours with different orientations[19]

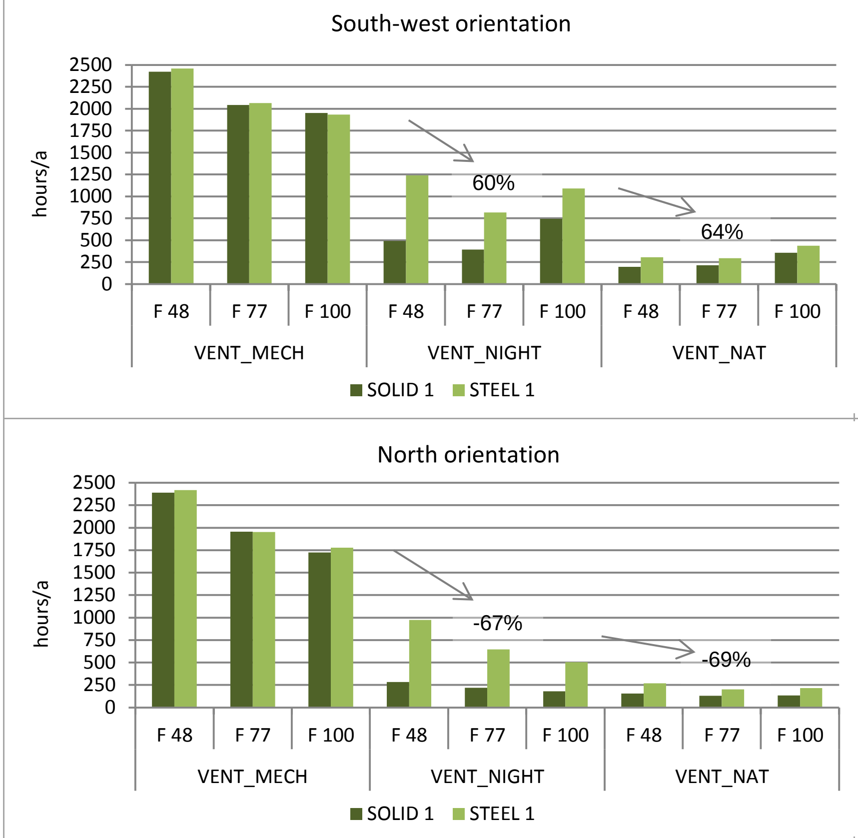
4.2.2 Ventilation strategy

The ventilation strategies defined have a significantly higher impact on the overheating risk than the parameters window area and structure type. The number of overheating hours per year when there is no active cooling is shown in figure 44.

The mechanical ventilation system (VENT_MECH) based on a constant air supply temperature without using passive cooling effects causes the most overheating hours (*Case 2*: active cooling is switched off). The mechanical system with night cooling by enhanced natural ventilation (VENT_NIGHT) improves this situation, but the number of overheating hours remains in an uncomfortable range. An acceptable number of hours can be achieved if

[19] The results represent SOLID 1 without suspended ceiling, with a triple glazing (EW1) and a natural ventilation strategy (VENT_NAT). STEEL 1 shows similar tendencies according to the orientations.

consistent natural day- and nighttime ventilation (VENT_NAT) for efficient heat removal is applied during periods of overheating risk.



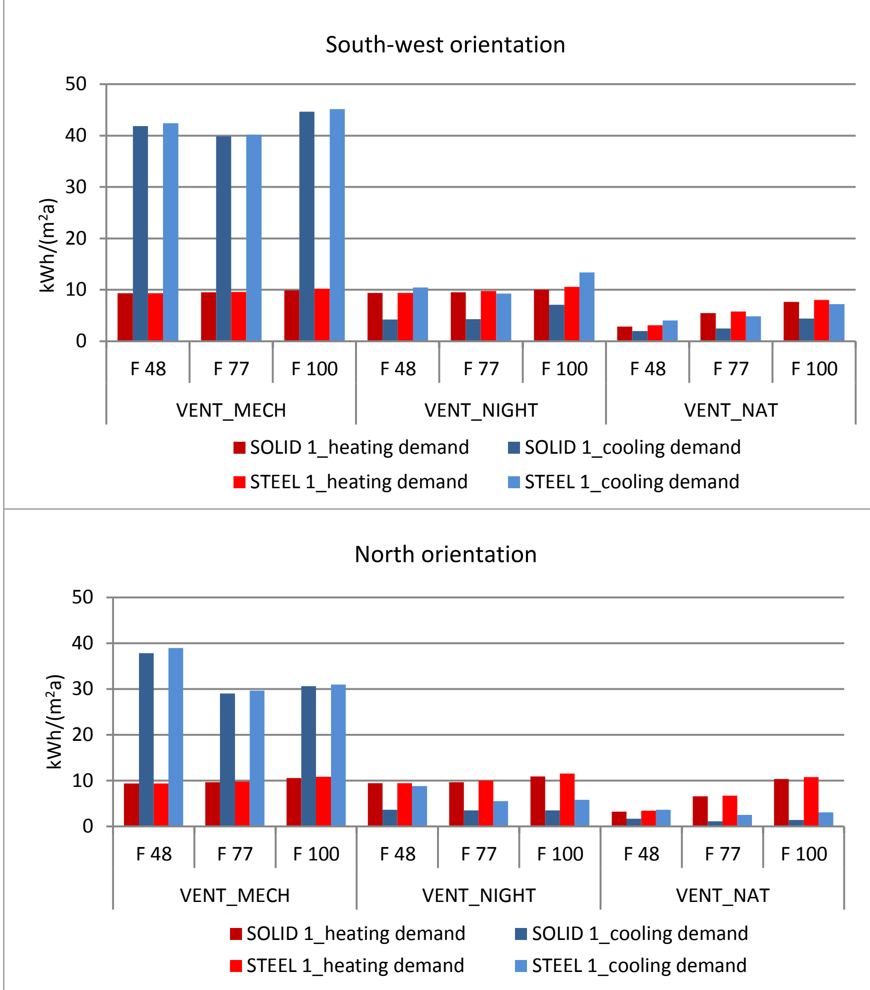
Parameter choice:
punctuated facade (F48)
band window facade (F77)
fully glazed facade (F100)
mechanical ventilation strategy (VENT_MECH)
night ventilation strategy (VENT_NIGHT)
natural ventilation strategy (VENT_NAT)
triple glazing (EW1)
external shading device (SHON)

Figure 44: SOLID1 and STEEL1 overheating hours based on different ventilation strategies

The number of overheating hours when there is a band window facade (F77) and a steel composite structure in a south-west orientation can be reduced by approx. 60% when using night cooling effects (VENT_NIGHT) and by additionally approx. 64% if adequate daytime cooling (VENT_NAT) is provided. The advantage of passive cooling by natural ventilation lies in the effect of a cooler air supply temperature. In practice it has to be taken into account, while designing the air inlets, that outside temperatures can cause local discomfort.

In case of consistent natural day- and nighttime ventilation (VENT_NAT), the office zone almost complies with general thermal comfort requirements. However, the user has to live with temperatures above 26 °C for over 200 hours per year e.g. in south-west orientation, even if the standards define 10% overheating hours per year during USE time as acceptable (approx. 240 hours/a), see [RGD 173]. The natural ventilation strategy causes similar overheating hours in case of the solid and the steel composite structure. A band window facade (F77) is the best choice in both, south-west and north orientation.

The heating demand is very similar for all parameter combinations analysed. The design challenges lie more in cooling issues, see figure 45.



Parameter choice:
punctuated facade (F48)
band window facade (F77)
fully glazed facade (F100)
mechanical ventilation strategy (VENT_MECH)
night ventilation strategy (VENT_NIGHT)
natural ventilation strategy (VENT_NAT)
triple glazing (EW1)
external shading device (SHON)

Figure 45: SOLID1 and STEEL1 energy demand based on different ventilation strategies

The results reveal that the optimisation potential of the heating demand is low regardless of the choice of structure type or ventilation strategy. However, an entirely natural ventilation strategy VENT_NAT) is beneficial and causes a very low heating demand, particularly when the ratio of window area and in consequence the transmission losses are low. The pre-heating of the supply air of the mechanical ventilation systems (VENT_MECH and VENT_NIGHT) is not beneficial despite a heat recovery rate of 70%.
The cooling demand is strongly influenced by passive cooling effects and in this case lower than the heating demand. The enhanced natural ventilation system (VENT_NAT) using these effects is advisable in a Western European climate. It is energy-efficient and improves thermal comfort. Therefore any further simulation results which are presented focus on this system.

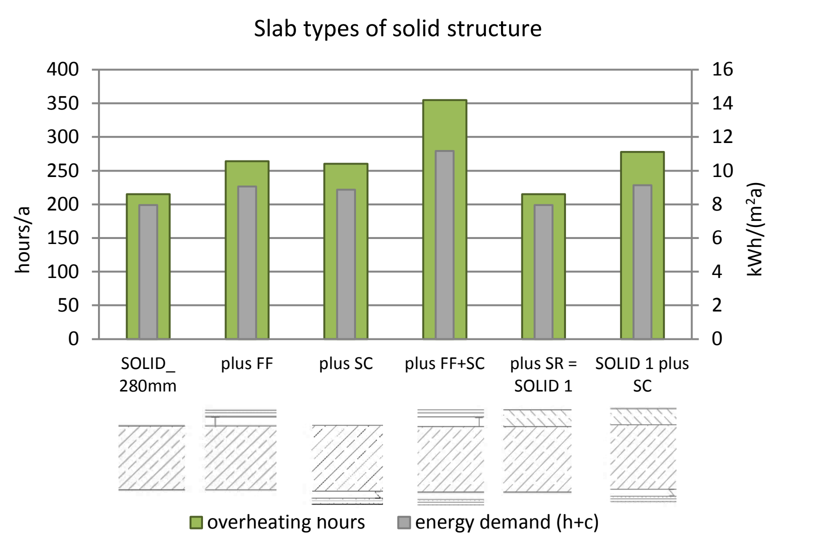
However, purely mechanical ventilation systems (VENT_MECH) without using the effects of passive cooling are often installed in existing office buildings. The field study of [Thewes] reveals that buildings with mechanical ventilation systems and full climate control lead to a rising demand for comfort by the user which finally results in an increasing energy demand.

4.2.3 Structure type

The results indicate that structure type has nearly no influence on heating but exerts an influence on cooling demand, see figure 45. The steel composite structure with profiled sheeting, concrete, floating screed and a suspended ceiling (STEEL 1) leads to more overheating hours than the solid structure consisting of reinforced concrete and screed (SOLID 1). The differences are slight whenever there is no mechanical ventilation in the office zone (VENT_NAT). Whether the structure type (mass) or the slab type e.g. the suspended ceiling (accessibility of the mass) is decisive is clearly indicated in the following figures.

4.2.3.1 Influence of slab type on solid structure

The assumption has been confirmed that energy demand and overheating hours increase significantly if the thermal storage capacity of the slab is reduced, for example, by adding a false floor (FF) instead of a screed (SR) or a suspended ceiling (SC). The impact of different slab types in a solid structure has been compared, see figure 46.



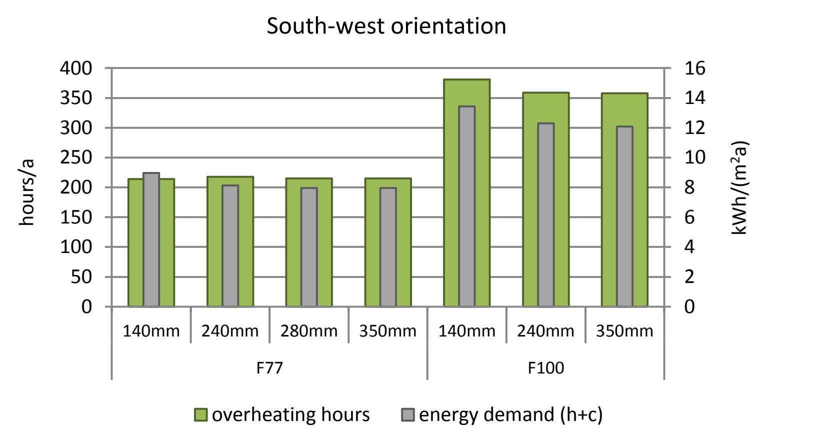
Parameter choice:
south-west orientation
band window facade (F77)
triple glazing (EW1)
external shading device (SHON)
natural ventilation strategy (VENT_NAT)

Base: solid structure
with 280 mm concrete

SC: suspended ceiling
FF: false floor
SR: screed, 70 mm

Figure 46: Overheating hours and energy demand for different slab types of a solid structure

Covering the slab with a false floor (FF) as well as a suspended ceiling (SC) has a negative effect on the overheating risk in the office zone. Whether a false floor or a suspended ceiling is installed plays a minor role. Increasing the mass by a 70-mm-thick screed (SOLID 1) improves neither thermal comfort nor energy demand in comparison to the slab of 280 mm. If in addition a suspended ceiling is installed, a slightly negative effect occurs in comparison to the results from using a base structure plus suspended ceiling (plus SC). Varying the thickness of a concrete slab reveals that an increase of mass above 240 mm only produces small improvements, regardless of whether there is a band or fully glazed facade, see figure 47.



Parameter choice:
SOLID 1
band window facade (F77)
fully glazed facade (F100)
triple glazing (EW1)
external shading device (SHON)
natural ventilation strategy (VENT_NAT)

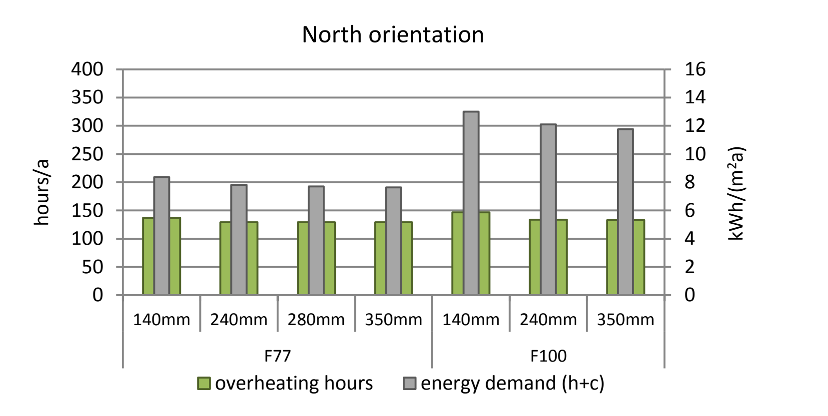


Figure 47: Overheating hours and energy demand for different slab types of the solid structure

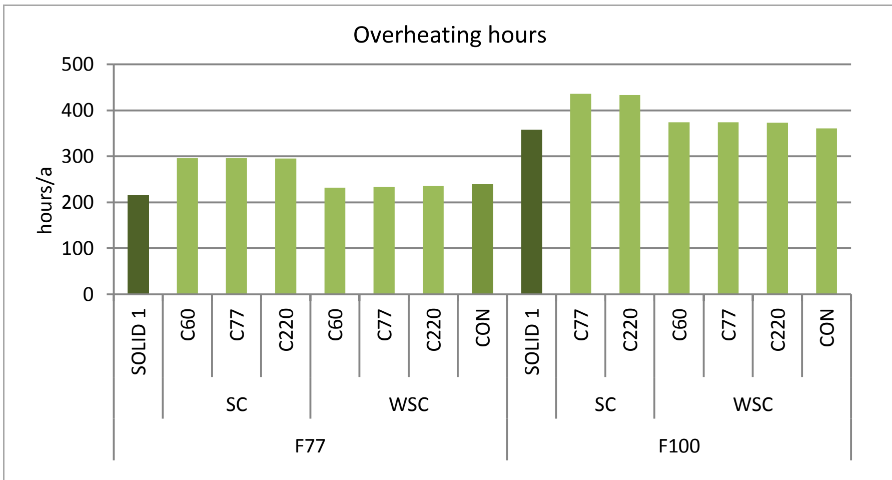
4.2.3.2 Solid structure in comparison to steel composite structures

Next the steel composite slabs were varied with regard to their thickness and the accessibility of the mass, for example, by removing the suspended ceiling and replacing the profiled sheeting with precast concrete elements. The steel composite slabs presented, see table 12, and the solid structure (SOLID 1) have been compared.

Table 12: Steel composite structure slab types

Slab type	Nomen-clature	Definition
STEEL 1	C60	profiled sheeting C60 + 100 mm concrete slab, floating screed
STEEL 1	C77	profiled sheeting C77 + 130 mm concrete slab, floating screed
STEEL 2a	C220	profiled sheeting C220 + 190 mm concrete slab, floating screed
STEEL 2b	CON	precast concrete elements 230 mm, floating screed
	SC	types with suspended ceiling
	WSC	types without suspended ceiling

Omitting the suspended ceiling (cases marked in figure 48 as “WSC”) of the steel composite structures has an enormous effect on thermal comfort in the office zone. Overheating hours can be reduced to similar values, as with the solid structure without a suspended ceiling (SOLID 1).



Parameter choice:
south-west orientation
band window facade (F77)
fully glazed facade (F100)
triple glazing (EW1)
external shading device (SHON)
natural ventilation strategy (VENT_NAT)

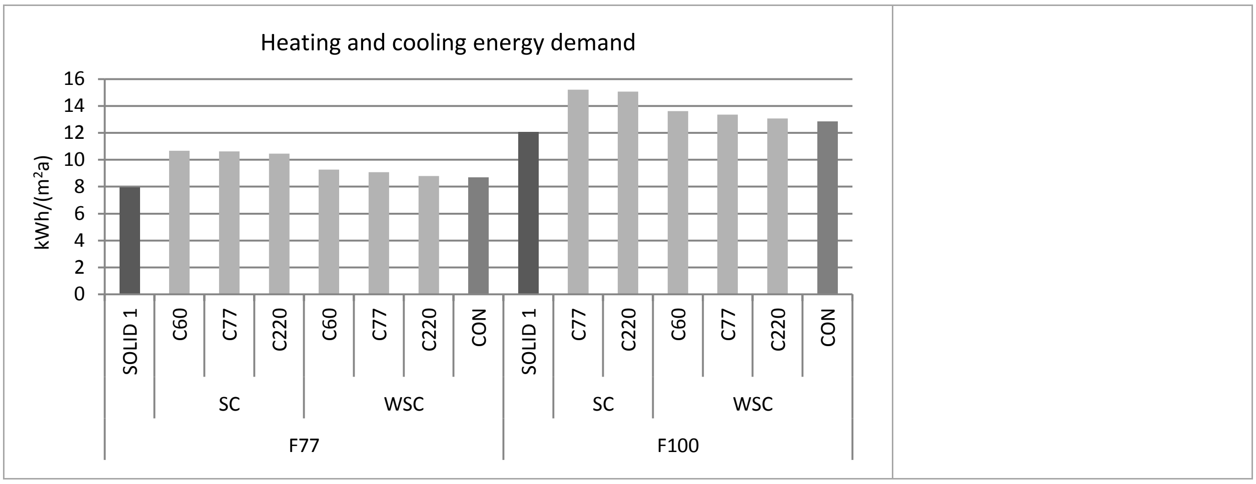


Figure 48: Overheating hours and energy demand for different slab types of the steel composite structure

The massivity and choice of structure type has less influence than would be expected. The slab covering is decisive when there is enhanced natural day- and nighttime ventilation. The accessibility of the thermal mass and night cooling systems have a strong influence on reducing overheating hours [Leenknegt]. Analysis of the entire heating and cooling demand shows similar results and reveals that integrated floor beam systems (C220 and CON) have a positive effect. The difference between these structure types and the solid structure (SOLID 1) is less than 10% which stands at 1.5 kWh/(m^{2}a).

It is obvious that the problem of steel composite structures in office buildings lies in the fact that generally they are covered with a suspended ceiling so that the space can be used for technical installations or to provide sound insulation. To comply with acoustic and thermal comfort requirements, an alternative solution is to have free-hanging sound absorbers or acoustic panels on the walls. This project does not cover simulation of the impact of sound absorbers, but it is part of ongoing research studies [Lombard].

The slabs of the steel composite structures with profiled sheeting have been defined as flat slabs for the thermal simulations. However, according to [Döring] it can be assumed that profiled steel sheet decking has a higher effective thermal capacity than conventional flat slabs. The author points out that the sheet's profile and its heat conductivity provide better opportunities for passive cooling. An interesting alternative to increase the thermal capacity of lightweight systems can be provided by phase-change materials [Döring].

4.2.4 Glazing types and shading devices

The solid structure (SOLID 1), natural ventilation strategy (VENT_NAT) and band window facade (F77) have been identified as beneficial for improving thermal comfort and energy efficiency in the office zone. This configuration has been considered for further analysis.

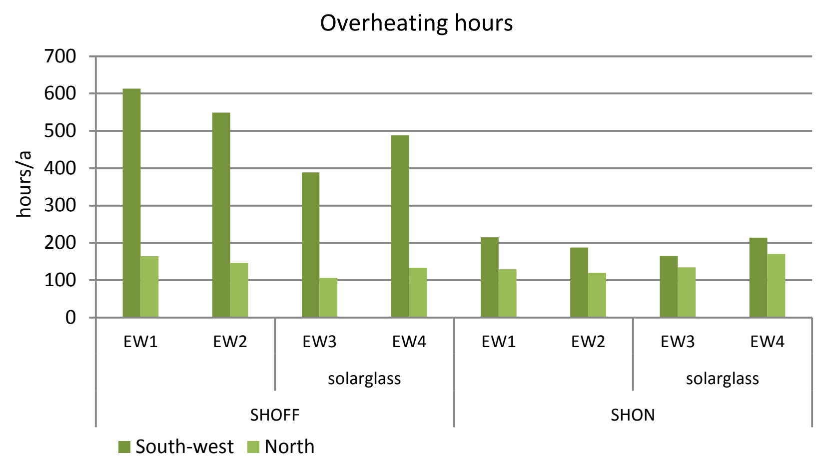
4.2.4.1 Glazing types and external shading device

The influence of different types of thermal insulating and solar control glass and an external shading device has been evaluated, see table 13.

Table 13: Definition of glazing types and shading devices

Nomen-clature	Definition	U_g-value in W/(m²K)	g-value	Tvis	Selectivity
EW1	Triple glazing, insulating glass unit (IGU)	0.59	0.58	0.74	1.27
EW2	Double glazing, insulating glass unit (IGU)	1.24	0.58	0.76	1.30
EW3	Double glazing, solar control glass	1.23	0.44	0.62	1.41
EW4	Triple glazing, solar control glass	0.59	0.45	0.66	1.46
SHON	External shading device, solar radiation controlled, all times, 70% opaque fraction	Close if total radiation on facade >140 W/m²		Open when total radiation on facade <120 W/m²	
SHOFF	No shading device				

An external shading device controlled by solar radiation on the facade is essential and has a high impact on decreasing the overheating risk of the office zone, see figure 49.

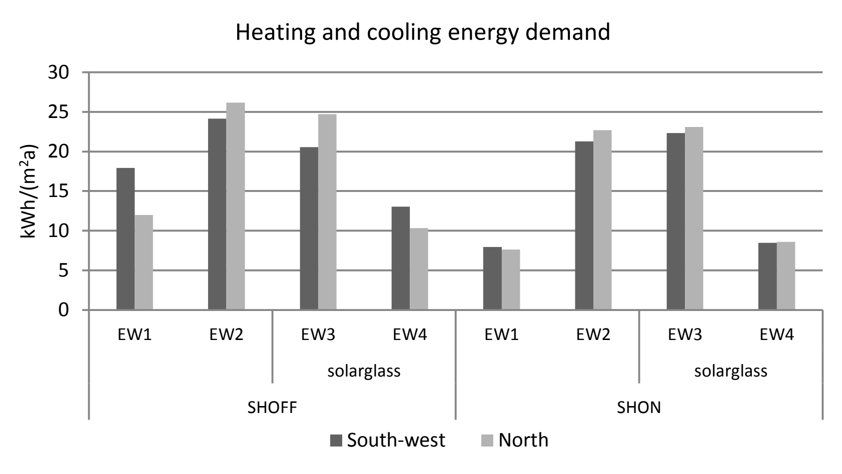


Parameter choice:
solid structure (SOLID 1)
band window facade (F77)
no shading device (SHOFF)
external shading device (SHON)
natural ventilation strategy (VENT_NAT)

Figure 49: Overheating risk of different types of glazing and external shading device

For a south-west orientation, the number of overheating hours could be reduced by about one third while for north orientation the impact is low. When the four types of glazing are compared, this reveals that double glazing instead of triple glazing with an equivalent g-value (EW2 and EW1) reduces the overheating risk. Higher transmission losses are beneficial in this case. Solar control glass with a lower g-value of 0.436 (EW3) reduces solar gains and could offer a slight improvement.

Thermal insulating glass (EW1 and EW4) offers the best choice for the entire energy demand for heating and cooling. The reason for this is that heating demand has a higher impact than cooling demand in case of efficient sun protection, see figure 50.



Parameter choice:
solid structure (SOLID 1)
band window facade (F77)
no shading device (SHOFF)
external shading device (SHON)
natural ventilation strategy (VENT_NAT)

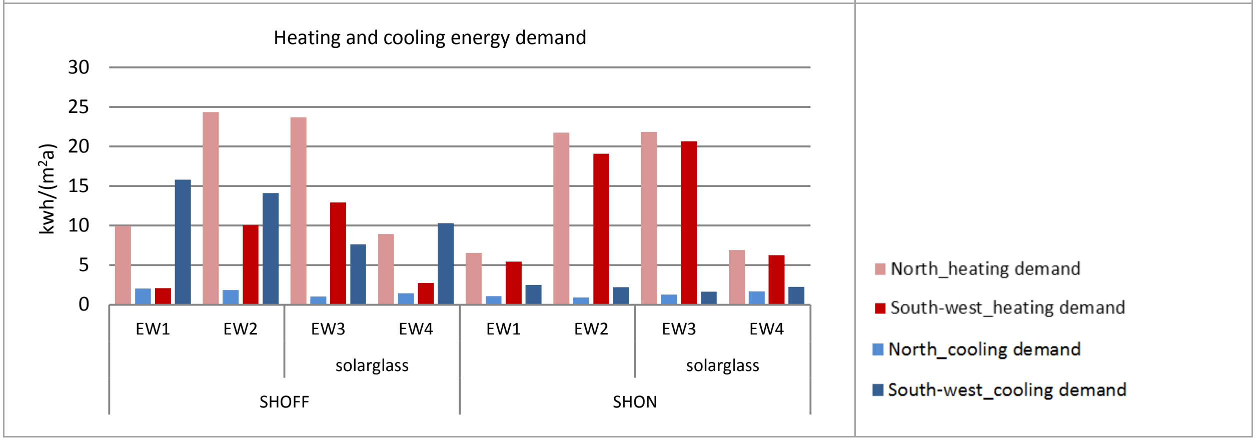


Figure 50: Energy demand for different types of glazing with and without a shading device

The combination of solar control glass and an external shading device has a minor positive effect on overheating hours in a south-west orientation, but a negative influence on heating demand. For a north orientation, this combination should generally be avoided.

Whether solar or internal gains are more important is shown in figure 51.

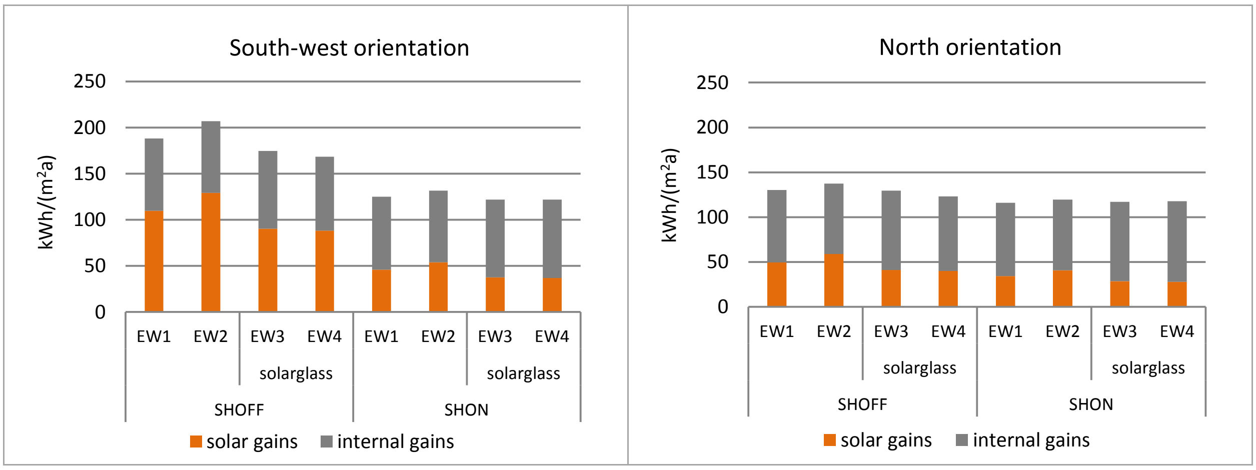


Figure 51: Solar and internal gains depending on different types of glazing

The internal gains vary only slightly, depending on the influence of the artificial lighting, see chapter 4.1.6.2 above. They are essentially determined by the continuous impact of the office equipment and the occupancy rate and cannot be influenced by the building design. The solar gains are strongly influenced by the facade design (window area, shading device and characteristics of the type of glazing). Their amount is almost always lower than that of the internal gains but the planner has much greater influence when improving thermal comfort and energy efficiency.

In a highly insulated building with efficient sun protection the cooling demand is lower than the heating demand. Therefore the best type of glazing is thermal insulation glass despite the advantages of a solar protection glass or a double glazing during periods of overheating risk. The thermal insulation glass should have a low thermal transmittance (U_g-value), a solar energy transmittance (g-value) lower than 0.6 and a high light transmittance (Tvis) of 70% (minimum 1.3 selectivity). It improves the entire energy demand of the office zone in a south-west and north orientation.

Light transmittance (Tvis or τ-value) influences the daylight factor, and consequently the amount of artificial lighting [Thewes]. The author reveals that worklight hours can be reduced by approximately 30% with light transmittance above 68% and solar energy transmittance lower than 0.4 (selectivity of approximately 1.7). However, for the overheating hours, the choice of light transmittance does not exert much influence [Thewes]. The reason for this is that the internal loads are only slightly influenced by artificial lighting and the solar gains are more decisive for improving thermal comfort.

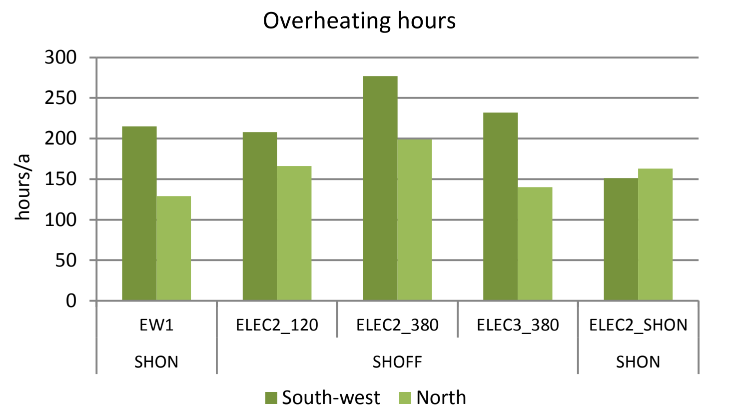
4.2.4.2 Electrochromic glazing systems

An interesting alternative to a conventional, external shading device is electrochromic glazing (ELEC). The two systems presented allow the variation of visible light transmission (Tvis) and solar energy transmittance (SHGC) in five states. They are controlled by different thresholds of total solar radiation on the facade. Both systems have a low U_g-value and in the clear state a g-value of 0.4, which is similar to solar control glass, see table 5 and 14.

Table 14: Definition of electrochromic glazing systems

Nomen-clature	Definition	Thermal transmittance (U_g-value in $W/(m^2K)$)	Solar energy transmittance (g-value)
ELEC2_120	Electrochromic triple glazing, solar radiation control, 120 W/m^2 - 420 W/m^2	0.78	0.41 - 0.05
ELEC2_380	Electrochromic triple glazing, solar radiation control, 380 W/m^2 - 780 W/m^2	0.78	0.41 - 0.05
ELEC3_380	Electrochromic triple glazing, solar radiation control, 380 W/m^2 - 780 W/m^2	0.74	0.37 - 0.03
ELEC2_120+SHON	Electrochromic triple glazing + external shading device, radiation controlled		

The electrochromic glazing systems achieve a performance similar to triple glazing with an external shading device (EW1_SHON), see figure 52.



Parameter choice:
solid structure (SOLID 1)
band window facade (F77)
natural ventilation strategy (VENT_NAT)
external shading device (SHON)
no shading device (SHOFF)

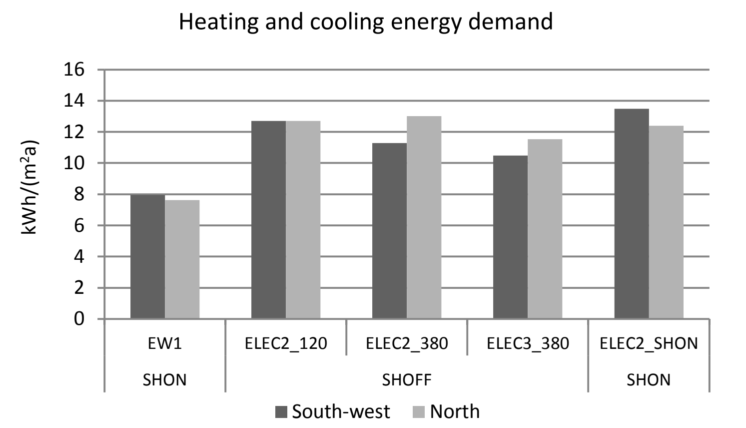
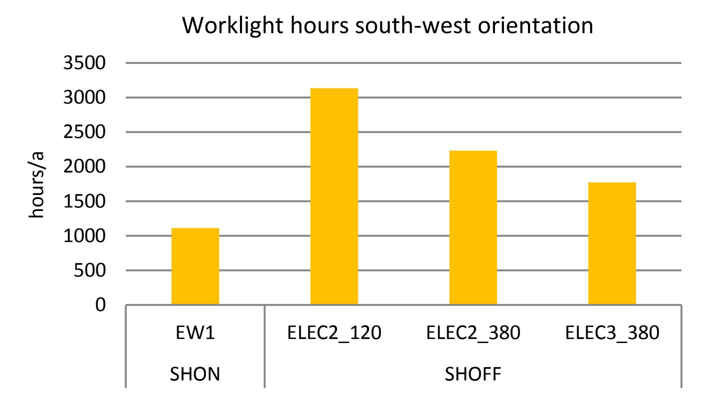


Figure 52: Overheating hours and energy demand for different electrochromic glazing types

The overheating risk of the south-west oriented office zone could be reduced by installing electrochromic glazing which starts the tinting process when there is a value of 120 W/m^2 solar radiation on the facade (ELEC2_120). The energy demand of all electrochromic systems selected is higher because they have a different U_g-value from the triple glazing (EW1). The best choice is a system with a low U-value which starts tinting whenever there is a value of 380W/m^2 solar radiation on the facade (ELEC3_380). A combination of the sensitive system (ELEC2_120) and an external shading device could lead to a further small improvement (ELEC2_SHON) in the overheating risk. In practice, a cost-benefit analysis is required to check whether this does provide a reasonable solution.

The challenge when designing an electrochromic glazing system is to find an appropriate radiation control system and a feasible choice of the relevant optical data for the type of glazing, e.g. solar energy, visible light and solar transmittance. An increase in worklight hours should be avoided as well as an uncomfortable illumination level or glare inside the office zone, see figure 53.



Parameter choice:
solid structure (SOLID 1)
band window facade (F77)
natural ventilation strategy (VENT_NAT)
external shading device (SHON)
no shading device (SHOFF)

Figure 53: Worklight hours based on electrochromic glazing types

The system with better light transmittance and higher thresholds for the tinting process (ELEC3_380) results in less worklight hours per year (similar to the solar control glass EW4_SHON). It is obvious that not only the adjustment of the control system but also the choice of selectivity for the glazing is decisive. In general, electrochromic glazing systems consist of solar control glass which has low solar energy and low visible light transmittance.

Electrochromic glazing systems offer an interesting and feasible alternative because they provide a good level of transparency (visibility), see chapter 2.7.4.1, when compared to a closed external shading device. The analysis has shown that the last stage of the tinting process (fully tinted) is not used very often. They are suitable for high rise buildings where the external shading device would require additional wind protection.

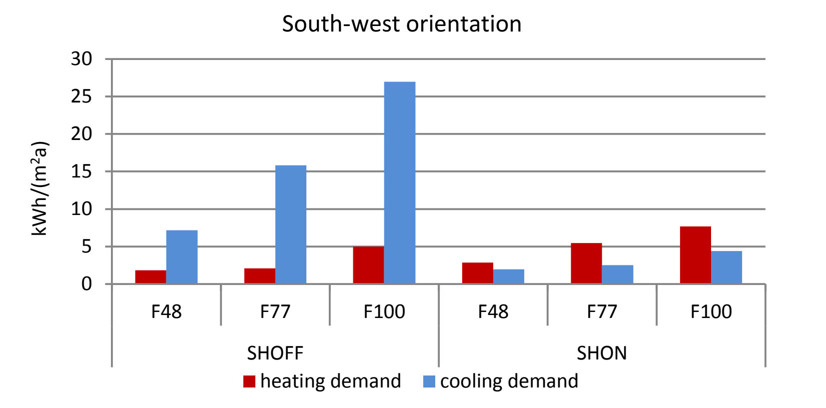
4.2.5 General results

The parameter study produces numerous results and statements as to how the design parameters:

- orientation
- window area
- structure and slab type
- type of glazing
- shading devices
- ventilation strategy and lighting systems

affect thermal comfort, energy efficiency and use of artificial lighting in office buildings. The main results and trends are summarised here and further optimisation potential is discussed in chapter 4.2.6. In each simulation step only one parameter has been varied, so that a clear assignment of cause and effect is possible. The parameter combinations are based on the parameter definition mentioned above, see chapter 4.1 and the general comfort requirements, see chapter 2.9.

The relevant design parameters for highly insulated office buildings are the ventilation strategy in conjunction with accessibility of the mass (slab type) and the external, radiation controlled shading device. In a moderate Western European climate, the design challenges lie more in optimising thermal comfort in summer than in heating issues. Thermal behaviour in the office zone is strongly influenced by the internal and external gains and less by transmission losses. The internal gains are determined by the office equipment and occupancy rate and vary only slightly due to the influence of artificial lighting. The solar gains are mainly determined by the solar protection for the office zone. Installing an external shading device has a direct positive impact on energy demand for cooling. The heating demand slightly increases due to the reduction of solar gains, see figure 54.



Parameter choice:
SOLID 1
natural ventilation strategy (VENT_NAT)
triple glazing (EW1)
external shading device (SHON)
no shading device (SHOFF)

Figure 54: Office zone heating and cooling demand

A higher ratio of window area leads to an increasing energy demand for heating and cooling. However, the latter is significantly less influenced if an external shading device is installed.

Adjustment of the shading and lighting control systems is essential and should fit with the choice of glazing system. The best choice is a shading device which offers the most accurate light control e.g. using light-directing slats to increase the efficiency of daylight use, and the most transparency so that the number of worklight hours can be reduced without impairing the users' visual comfort.

The choice of type of glazing should be made based on the building's orientation, although if there is efficient solar protection, the type of glazing does not greatly affect thermal comfort in summer. A double glazing with a higher thermal transmittance (U_g-value) is beneficial to reduce the overheating risk. The choice for a triple glazing with a lower U_g-value decreases the heating demand significantly. If a building is well-designed and energy-efficient the heating demand is higher than the cooling demand and determines the total energy demand. In consequence, the U_g-value of the type of glazing is the decisive factor in the temperate climate zone. Investigations of electrochromic glazing systems have shown that similar results can be achieved as in case of an external shading device. They can be regarded as an interesting alternative.

A highly glazed facade leads to an increase of energy demand. However, to improve thermal comfort in summer for the configuration presented, a band window facade performs better in some orientations (east, north, south) than a punctuated or fully glazed facade, assuming that optimised shading devices and a radiation controlled lighting system are used. A reduced window area leads to more artificial lighting and in consequence to higher internal gains and a larger area to higher solar gains. Finally, the number of overheating hours is lower than expected when there is a fully glazed facade. In a south-west orientation, it should be avoided because of the high overheating risk, see figure 43.

An adequate ventilation strategy is more important for energy efficiency and thermal comfort than other building-related design parameters such as the ratio of window area or structure type. Installing night cooling (VENT_NIGHT) and particularly an enhanced natural day- and nighttime ventilation system (VENT_NAT) using passive cooling effects is a powerful low-tech option for office buildings to reduce heat loads. In this case, the accessibility of the mass becomes decisive in achieving thermal comfort in summer. The mass of the slab is less important but accessibility is essential when it comes to using thermal storage capacity. The differences between solid and steel composite structures are not as significant as might be expected. If an enhanced natural ventilation strategy is used, both structure types produce very similar results and the integrated floor beam systems (STEEL 2) with profiled sheeting or precast concrete elements are comparable to the solid structure. The problem of steel composite structures in practice is the covering with a suspended ceiling or/and a false floor which is commonly used.

The expertise-based selection method has indicated several optimisation steps for improving energy efficiency and thermal comfort in the office zone. Choosing a solid structure is almost always beneficial. However, one objective of the study is to extend the range of optimisation steps for steel composite structures. Therefore further constructive and technical measures have been investigated not only for the solid but as well as for steel composite structures, see following chapter 4.2.6.

4.2.6 Further detailed investigations

This part of the study should reveal the potential for further optimising the solid and steel composite structures already presented. The influence of different strategies for controlling the shading devices, the cooling and ventilation systems and another type of glazing providing a different ratio of thermal, solar energy and light transmittance, have been investigated. Furthermore, the cooling and heating strategies have been adapted to a Southern and Northern European climate.

4.2.6.1 Visual comfort

To achieve efficient sun protection, the external shading devices in office buildings are often closed, which means that visual contact to the outside is restricted and more artificial lighting is required. The aim is to examine whether modifying the type of shading and control system could improve this situation. The analysis is based on the solid structure without suspended ceiling (SOLID 1[20]). The results showed that an external shading device with an opaque fraction of 50% (e.g. single slats or an overhang) instead of 70% (e.g. venetian blinds or horizontal slats) is beneficial when there is a punctuated facade. The worklight hours in the office zone decrease by one quarter and reach values of approximately 1,500 hours annually. Energy demand for heating and cooling could be improved slightly. The choice of an opaque fraction of 50% is however not advisable for a band window or highly glazed facade.

The control system of the external shading device has been adjusted, see table 15. The shading closes at a higher threshold of solar radiation on the facade and opens again at a higher value when compared to the previous system, see chapter 4.1.4.

[20] including the natural ventilation strategy (VENT_NAT) and triple glazing (EW1)

Table 15: Change of control system of the external shading device

Nomen-clature	Definition	Opaque fraction	Close if	Open when
SHON2	External shading device, radiation-controlled, at all times	70%	total radiation on facade >180W/m^2	total radiation on facade <150W/m^2

When there is a band window facade (F77) the change of the control system reduces the period of time during which the shading is closed by 10% to 15% and in consequence the number of worklight hours by 5% to 8% with a south or south-west orientation. On the other hand, the number of overheating hours increases by 10%, particularly with a south-west orientation. With a north orientation, changing the control system has less influence on the worklight hours by approx. 4% but reduces the period of time during which the shading is closed by 50%. This also results in a negative effect on the overheating hours.
The challenge is to find a compromise between improving visual comfort from gaining more transparency and thermal comfort in summer. With a south orientation, the control system based on higher thresholds of solar radiation (SHON2) is advisable because the impact on the overheating risk is very low.

4.2.6.2 Thermal comfort in summer

Setpoint temperature of cooling system

The aim of this analysis is to evaluate the increase in cooling demand when it is switched on at a setpoint temperature of 24 °C instead of 26 °C. The analysis is focussed on the mechanical ventilation system including night ventilation (VENT_NIGHT) and the natural ventilation strategy (VENT_NAT), see chapter 4.1.6.1, and is based on the solid structure (SOLID 1[21]). To guarantee the effectiveness of both ventilation strategies, their control systems have to be modified due to the lower set point of the cooling system. The new strategies are denoted as VENT_NIGHT_24 °C and VENT_NAT_24 °C, see table 16.

Table 16: Change of the control system for the cooling and ventilation strategy

NO.	Parameter	Definition
8	Cooling	***Case 3*: cooling on** setpoint indoor temperature: **24 °C** at all times, unlimited cooling power, no dehumidification
9	Ventilation	**VENT_NIGHT_24 °C**: mechanical ventilation system controlled, constant air flow during USE (7:00 am - 6:00 pm) supply temperature of 18 °C air change rate 1 h^{-}1, heat recovery rate of 70% controlled **night-time ventilation** (natural cooling by automated facade flaps) air change rate 4 h^{-1} ventilation is switched on if room air temperature is ≥ **23 °C** and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ **20 °C**

[21] without suspended ceiling and tested when there is a band window (F77) or a highly glazed facade (F100)

Table 16: continued		
9	Ventilation	**VENT_NAT_24°C**: natural ventilation by enhanced daytime-nighttime ventilation hygienic base change rate 0.7 h^{-1} during USE (7:00 am - 6:00 pm), controlled **daytime ventilation** (automated windows and/or users) air change rate 2 h^{-1} ventilation is switched on if room air temperature is ≥ **23 °C** and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ **22.5 °C** controlled **night-time ventilation** identical as in case of **VENT_NIGHT_24°C**

Cooling to a set point of 24 °C instead of 26 °C leads to a three- or fourfold increase in cooling demand for the mechanical ventilation system (VENT_NIGHT_24°C) and to a two- to threefold increase for the natural ventilation system with enhanced day- and nighttime ventilation (VENT_NAT_24°C), see figure 55.

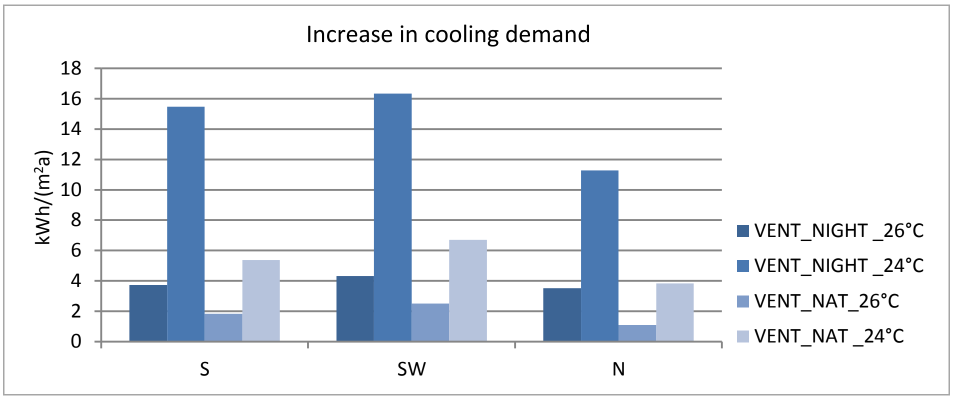


Figure 55 Increase in cooling demand from lowering the setpoint temperature

Lowering the setpoint temperature of active cooling is acceptable in buildings where efficient use of passive cooling effects is feasible and the energy demand for cooling is low.

Control system of the ventilation strategy

The natural ventilation system (VENT_NAT according to table 10) can further be optimised by lowering the temperature thresholds of the control system, see table 16. This modification produces in case of waiving active cooling a significant improvement in thermal comfort in the summer. The number of overheating hours per year decreases by 50% when the office zone has a band window (F77) and by 45% when it has a fully glazed facade (F100), see figure 56.

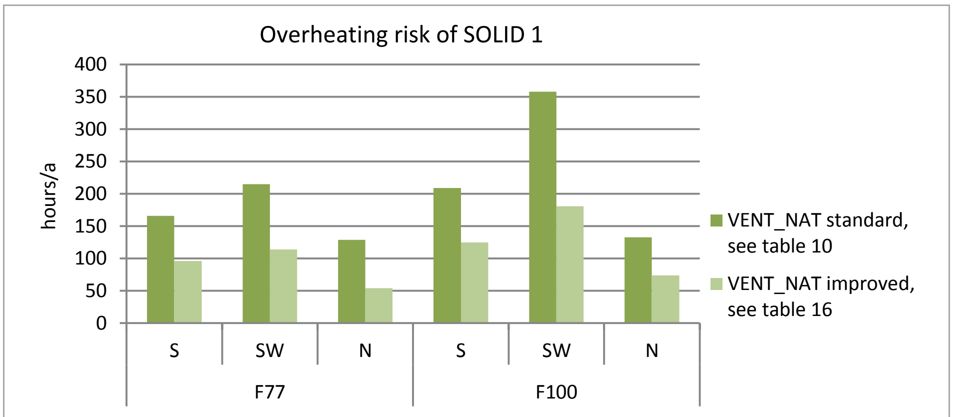


Figure 56: Impact of the improved natural ventilation strategy on the overheating risk in the office zone

The energy demand for heating increases by approx. 13%-15% due to the incoming air being at lower temperatures. However, this negative effect is not as decisive as the improvement in thermal comfort in summer and possible energy savings from using active cooling. It is only with a north orientation that modifying the control system proves not to be beneficial.
Further adjusting the air change rate at nighttime by 6 h^{-1} instead of 4 h^{-1}, produces only small improvements to reduce the overheating risk.
A steel composite structure with precast concrete elements (STEEL 2b_CON) and no suspended ceiling produces very similar results to the solid structure.

4.2.6.3 Glazing type

The expertise-based optimisation, see chapter 5.3.2, has led to the assumption that a best choice of glazing type should have a U_g-value > 0.8 W/(m^2K) and a g-value of 0.3 to 0.45 in case of thermal comfort in summer. The aim is to evaluate whether energy demand and the risk of overheating can be improved by using this type of glazing instead of triple, thermal insulation glass (EW1). The challenge is to find a glazing type, readily available on market, with the desired proportion of thermal and optical values due to physical and technical limitations. The glazing type chosen provides a good combination of low U_g-value and high selectivity (EW6), see table 17.

Table 17: Thermal and optical data for two types of glazing

Nomen-clature	Definition	Thermal transmittance (U_g-value in W/(m^2K))	Solar energy transmittance (g-value)	Visible light transmittance (Tvis)	Selectivity (S)
EW1	Triple glazing, insulation glass unit	0.59	0.58	0.74	1.27
EW6	Double glazing, insulation glass unit	0.75	0.44	0.71	1.62

The analysis is based on the steel composite structure with precast concrete elements (STEEL 2b_CON), a band window facade (F77) and the improved natural ventilation system VENT_NAT_24 °C. With a south and south-west orientation, installing the glazing type (EW6) reduces the overheating hours to a range of approx. 100 hours per year. The reasons are less solar gains and higher transmission losses. The influence with a north orientation is low, see figure 57.

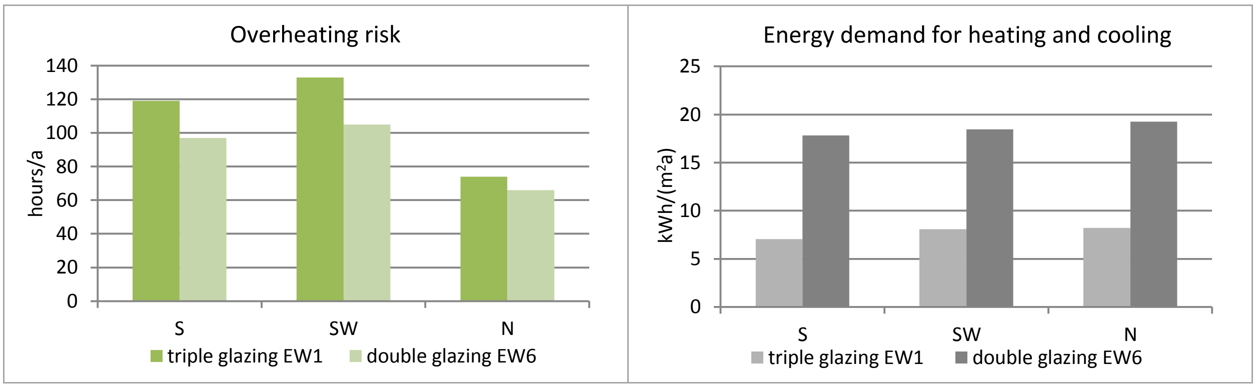


Figure 57: Impact of a new type of glazing on overheating risk and energy demand

On the other hand, the glazing type (EW6) has a negative impact on the energy demand for heating. In consequence, the overall energy demand increases by more than 50%. In highly insulated office buildings with active cooling systems fitting such a glazing type is not advisable. However, thermal comfort in summer can be improved particularly when the building has no active cooling system. In this case the increased energy demand for heating should be met by using renewable resources.

4.2.6.4 Climate in Southern and Northern Europe

The aim of this analysis is to identify whether climate conditions in different parts of Europe are more suitable for lightweight steel composite structures with regard to energy demand and thermal comfort. In addition to the temperate Western European climate of Saarbrücken, Germany, the cool Northern climate of Östersund, Sweden, and the warmer Southern European climate of Madrid, Spain, has been investigated using the weather data of Meteonorm (European database). All these locations have a continental climate characterized by long transition periods without extreme fluctuations of temperature and humidity, while solar radiation varies considerably over the year [Hausladen, 2012].

The Northern European climate is determined by extremely low temperatures from December until the end of February. In January values of approx. -27 °C could be achieved. Daily temperatures above 20 °C are possible from mid-June until mid-August. Temperature peaks occur in August and have values of approx. 23 °C.

The climate conditions in Southern Europe are determined by ambient temperatures above 30 °C from mid-June until mid-September. Temperature peaks occur in July and could reach values up to 36 °C. Average temperatures in January and December are approx. 6 °C (lowest value -5.6 °C). In comparison to Western and Northern Europe, the amount of incident global solar radiation is much higher, see figure 58.

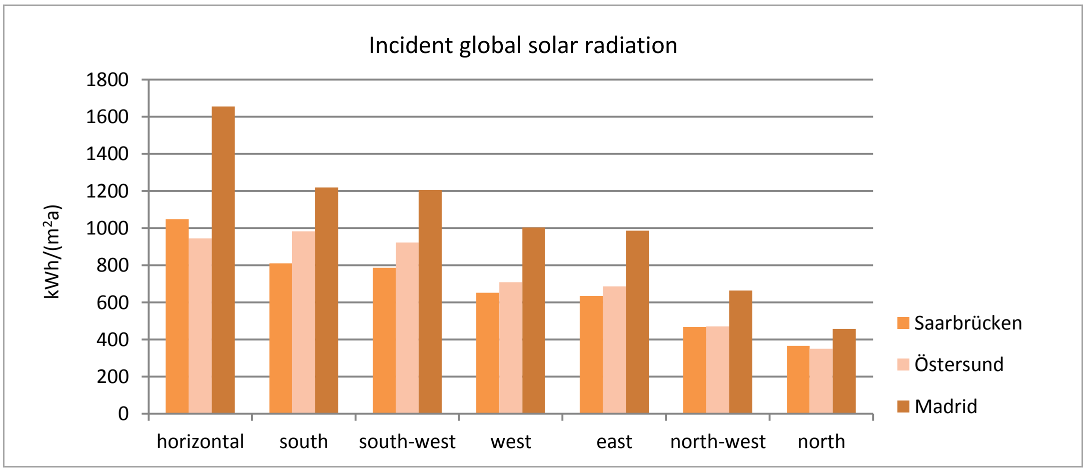


Figure 58: Incident global solar radiation for Saarbrücken, Germany, and Östersund, Sweden, and Madrid, Spain

The analysis is focussed on a steel beam system with profiled sheeting (STEEL 1_C77) without a suspended ceiling[22], a band window facade (F77) and initially triple thermal insulation glass

[22] providing a weight of approx. 320 kg/m² + 100 kg/m² screed without including steel beams and columns

(EW1, see table 17). The control systems of the ventilation strategies (VENT_NIGHT and VENT_NAT, see chapter 4.1.6.1) have been adapted to the specific climate conditions.

Northern Europe, Östersund in Sweden

In a Northern European climate potential for optimisation lies in the mechanical ventilation system's[23] heat recovery rate. Heating demand can be reduced when a heat recovery rate of 75% (VENT_NIGHT_75) or 80% (VENT_NIGHT_80) is provided instead of a rate of 70% (VENT_NIGHT_70), see figure 59.

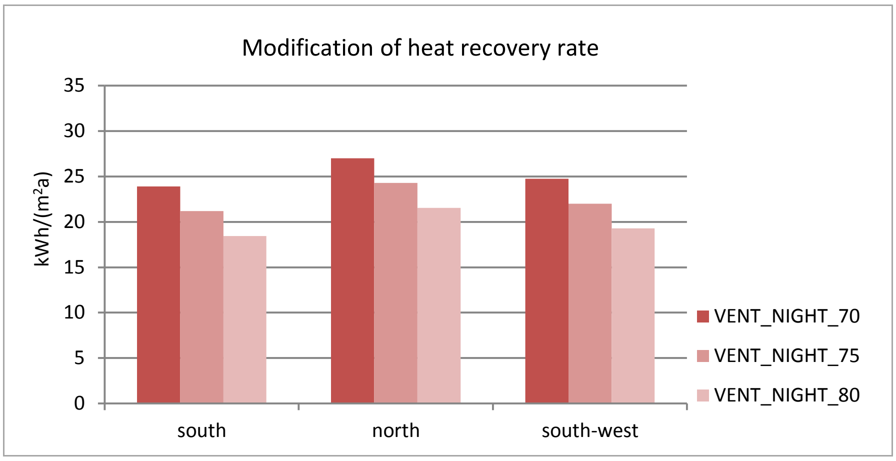


Figure 59: Influence of different heat recovery rates on heating demand in a cool climate

Heating demand decreases by 22% with a heat recovery rate of 80% (including the energy demand for pre-heating the supply air of 10.94 kWh/(m^2a)).

The challenge for the natural ventilation system with enhanced day- and nighttime ventilation (VENT_NAT) is to provide supply air when it is operating without causing comfort problems due to cool ambient temperatures as well as to guarantee a sufficient air change rate. Opening windows in the daytime can cause draughts and the hygienic base change rate of 0.7 h^{-1} constantly brings fresh, cool air into the building. Lowering this base change rate from 0.7 h^{-1} (ACR 0.7) to 0.5 h^{-1} (ACR 0.5) can improve the situation and this decreases heating demand by approx. 28%, see figure 60.

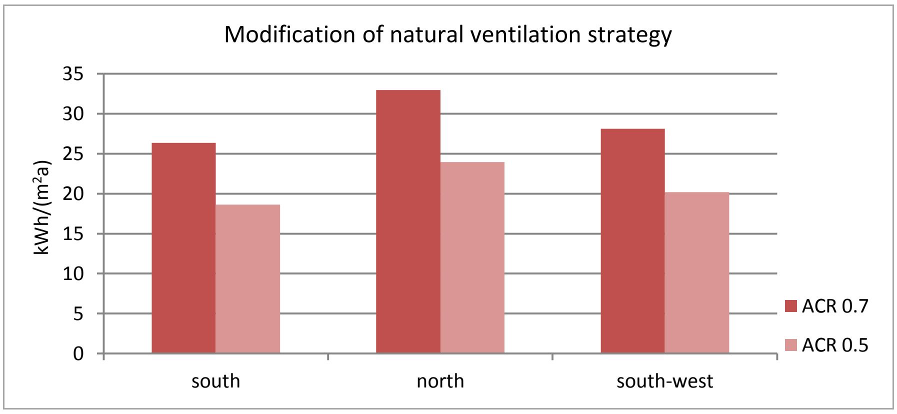


Figure 60: Impact of the improved natural ventilation strategy on heating demand in a cool climate

[23] A value of 16.41 kWh/(m^2a) for pre-heating (heat recovery rate 70%) and 0.46 kWh/(m^2a) for pre-cooling the supply air at a constant temperature of 18 °C has been taken into account with regard to the climate conditions in Öestersund, Sweden.

In a Northern European climate a combination of mechanical and natural ventilation strategy is advisable. The mechanical ventilation system with pre-heating the supply air and improved heat recovery rate is beneficial for guaranteeing thermal comfort in winter. In the summer, however, the risk of overheating increases by the use of a mechanical ventilation strategy. The cooling requirement can be covered by active cooling which only causes up to 4 kWh/(m^{2}a), when using a set point temperature of 26 °C, or by enhanced natural day- and nighttime ventilation using passive cooling effects.

Possible benefits from using a steel composite structure compared to the solid structure have not been identified. The results from using both structure types are very similar.

Southern Europe, Madrid in Spain

In a Southern European climate, further potential for optimisation lies in solar protection for the building so as to reduce the energy demand for cooling. The focus is on different glazing types and the external shading device. First the impact of the glazing type (EW6), a triple, thermal insulation glass (EW1) and a solar control glass (EW4) were investigated, see table 18.

Table 18: Types of glazing investigated in Southern Europe

Nomen-clature	Definition	Thermal transmittance (U_g-value in W/(m^{2}K))	Solar energy transmittance (g-value)	Visible light transmittance (Tvis)	Selectivity (S)
EW1	Triple glazing, insulation glass unit	0.59	0.58	0.74	1.27
EW4	Triple glazing, solar control glass	0.59	0.45	0.66	1.46
EW6	Double glazing, insulation glass unit	0.75	0.44	0.71	1.62

In Southern Europe a triple, solar control glass with a low U_g-value and low g-value (EW4) is beneficial for a south-west orientation (similar for a south orientation) and a triple, thermal insulation glass (EW1) for a north orientation, see figure 61.

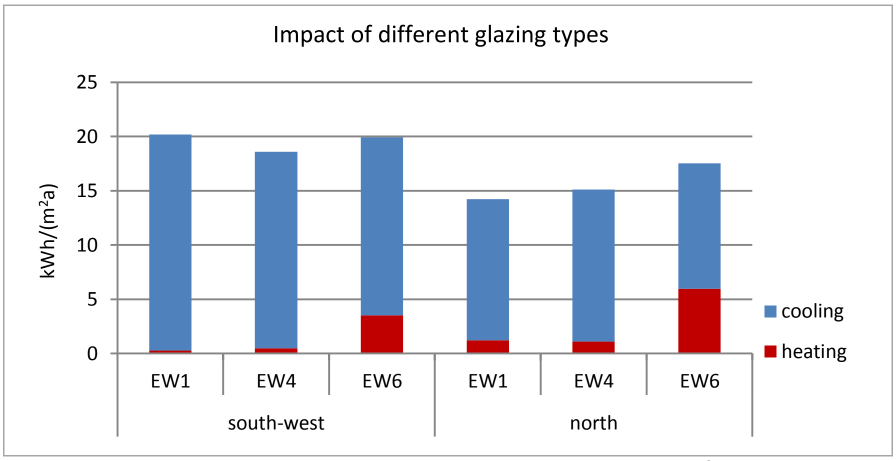


Figure 61: Best choice of glazing type in Southern Europe, Madrid[24]

The modification of the external shading device's control system, as mentioned above (see table 15) is beneficial for visual comfort. The periods of time when the shading devices are

[24] The analysis is based on the natural ventilation strategy VENT_NAT_24 °C, see table 16.

closed can be reduced by approx. 26%. On the other hand the modification leads to a slightly higher cooling demand. Electrochromic glazing might be an interesting alternative in a Southern European climate as it offers a compromise between visual comfort and efficient solar protection.

The control systems of both, the mechanical[25] and the natural ventilation system, have been adapted in order to investigate the effectiveness of passive cooling effects in a Southern European climate, see table 19.

Table 19: Ventilation strategies adapted to the Southern European climate of Madrid

NO.	Parameter	Definition
9	Ventilation	**VENT_NIGHT_adapted**: mechanical ventilation system controlled, constant air flow during USE (7:00 am - 6:00 pm) supply temperature of 18 °C air change rate 1 h^{-1}, heat recovery rate of 70% controlled **night-time ventilation** (natural cooling by automated facade flaps) air change rate 4h^{-1} ventilation is switched on if room air temperature is ≥ **25 °C** and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ **19 °C**
		VENT_NAT_adapted: natural ventilation by enhanced daytime-nighttime ventilation hygienic base change rate 0,7 h^{-1} during USE (7:00 am - 6:00 pm), controlled **daytime ventilation** (automated windows and/or users) air change rate 2 h^{-1} ventilation is switched on if room air temperature is ≥ **25 °C** and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ **22.5 °C** controlled **night-time ventilation** identical as with VENT_NIGHT

Lowering the setpoint temperature when night ventilation is switched off, leads to energy savings for cooling of approx. 6% for the mechanical system with night ventilation (VENT_NIGHT_adapted). Energy savings for cooling of 11% can be achieved by changing the control system for the day- and nighttime natural ventilation strategy (VENT_NAT_adapted). Heating demand plays a minor role and is only required during January and December. Lowering the set point temperature (< 19 °C) any further during nighttime could lead to uncomfortable room air temperatures in the morning.

In a Southern European climate, active cooling is essential, because despite efficient solar protection, the amount of overheating hours per year falls in an unacceptable range (> 600 hours/a). Furthermore, using passive cooling effects during the night is efficient, but natural ventilation during daytime is limited due to the high ambient temperatures. To comply with comfort requirements, using a mechanical ventilation system with pre-cooling for the supply air is advisable. The steel composite structure's energy demand is slightly higher in comparison to the solid structure. In a Southern European climate, a steel composite structure

[25] A value of 5.31 kWh/(m^2a) for pre-heating (heat recovery rate 70%) and 11.62 kWh/(m^2a) for pre-cooling the supply air at a constant temperature of 18 °C has been taken into account with regard to the climate conditions of Madrid, Spain.

is merely advisable when presenting a heavier construction with a weight above 470 kg/m^2, for instance the integrated floor beam systems (STEEL 2a and 2b, see chapter 4.1.5).

Comparison of the different locations investigated

A low-tech concept without an active cooling and mechanical ventilation system can best be implemented in the temperate Western European climate. This concept's limitations become apparent when the number of overheating hours per year is considered; the hours fall in an acceptable range but one that is not comfortable, see chapter 4.2.2. The detailed investigation has shown that even when the natural ventilation strategy is improved this results in a comfortable range of less than 100 overheating hours per year.

Natural air exchange during operational time is not advisable for a Northern or Southern European climate. In Northern Europe, the problem is to find a best solution for the incoming air without causing local discomfort due to cool ambient temperatures. A mechanical ventilation system where the supply air is pre-heated is more advisable to ensure thermal comfort in winter. In Southern Europe, the limits of a low-tech concept are determined by high ambient temperatures so that natural daytime ventilation is possible solely in the morning hours and active cooling is mandatory to fulfil comfort requirements.

The energy demand for heating and cooling based on the climate-adapted ventilation strategies is much lower in a Western European climate where passive cooling effects are very efficient when compared to a Northern or Southern European climate, see figure 62.

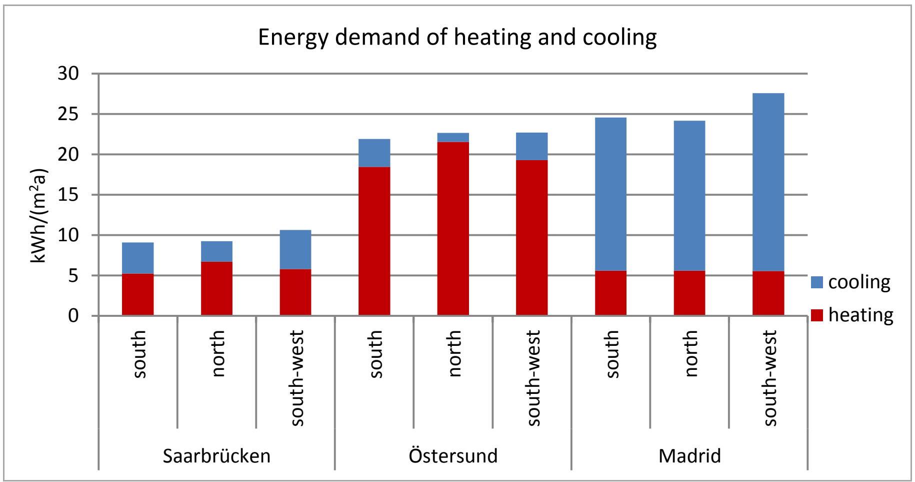


Figure 62: Energy demand in Saarbrücken, Germany, and Östersund, Sweden, and Madrid, Spain

In Northern Europe, a structure with less weight produces very similar results to those when a heavy, solid structure is used. In Southern Europe, more massivity is beneficial and an integrated floor beam system is to be recommended. In general, the differences between the structure types are lower than 2 kWh/(m^{2}a). If the energy concept and the design parameter choice respect the local climatic conditions, the choice of structure type is less decisive.

4.3 Primary energy demand

The influence of the design parameters on the office zone`s primary energy demand has been studied. The analysis is based on already optimised parameter combinations and the temperate Western European climate. The focus is placed on the following important aspects:

1) the impact of heating, cooling and lighting demand for all orientations and window areas
2) the impact of the appropriate parameter shading device based on a south-west orientation (most critical with regard to overheating risk)
3) comparison of SOLID 1, STEEL 1 (WSC) and STEEL 2 using the example of a band window facade (F77)
4) the natural ventilation strategy (VENT_NAT).

4.3.1 Methodology

The primary energy demand for heating and cooling ($E_{prim}1$) and the demand including lighting ($E_{prim}2$) have been analysed:

$$\mathrm{E_{prim}1 = E_{prim,heat} + E_{prim,cool}}$$ (Equation 6)

$$\mathrm{E_{prim}2 = E_{prim,heat} + E_{prim,cool} + E_{prim,light}}$$ (Equation 7)

Primary energy demand for heating and cooling has been calculated by converting net and end energy demand.

4.3.1.1 Heating

The end energy calculation is based on a typical energy supply using natural gas and an appropriate expenditure factor (e_p) based on previous studies carried out by the University of Luxembourg [Maas, RGD 221]. This factor takes into account approx. 10% distribution and 10% energy production losses. The primary energy calculation is based on the factor ($f_{p,x}$) according to [RGD 173]:

$$E_{end,heat} = Q_{heat} * e_p \; ; \; with\, e_p = 1.2\ (fixed)$$ (Equation 8)

$$E_{prim,heat} = E_{end,heat} * f_{p,x} \; ; \text{ with } f_{p,x} = 1.12$$ (Equation 9)

4.3.1.2 Cooling

A compression refrigeration machine typically covers the cooling demand in office buildings. The end energy has been calculated with an energy efficiency ratio (EER) for the machine appropriate for current standard office buildings. The value is based on studies carried out by the University of Luxembourg [Maas, RGD 221]. The primary energy calculation is based on the factor ($f_{p,x}$) for electricity according to [RGD 173]:

$$E_{end,cool} = \frac{Q_{cool}}{EER} \; ; \text{ with } EER = 3.5\ (fixed)$$ (Equation 10)

$$E_{prim,cool} = E_{end,cool} * f_{p,x} \; ; \text{ with } f_{p,x} = 2.66$$ (Equation 11)

4.3.1.3 Lighting

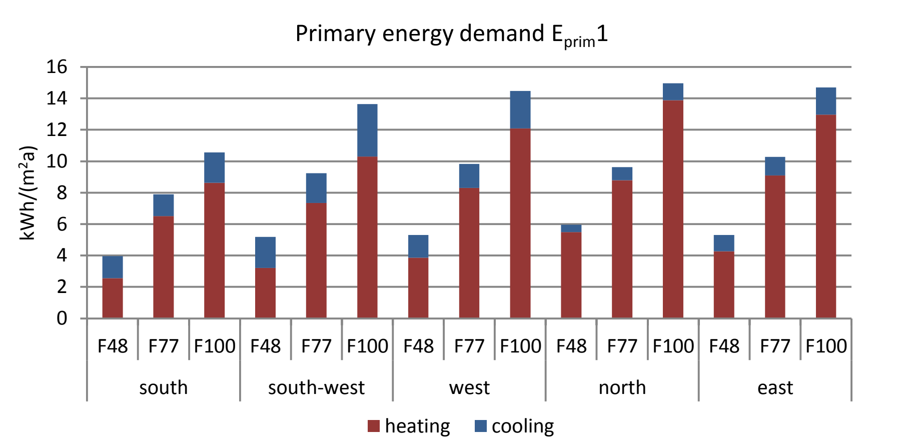
The electricity demand of net energy is equal to end energy. The primary energy demand for lighting according to [RGD 173] is given by:

$$E_{prim,light} = E_{light} * f_{p,x} \; ; \; with\, f_{p,x} = 2.66$$ (Equation 12)

4.3.2 Results

4.3.2.1 Influence of orientation and window area

The results of the primary energy demand for heating and cooling ($E_{prim}1$) show that the ratio of window area is more decisive than orientation (similar results as for net energy demand) in the temperate climate zone of Western Europe. Energy demand rises when the window area increases, see figure 63.

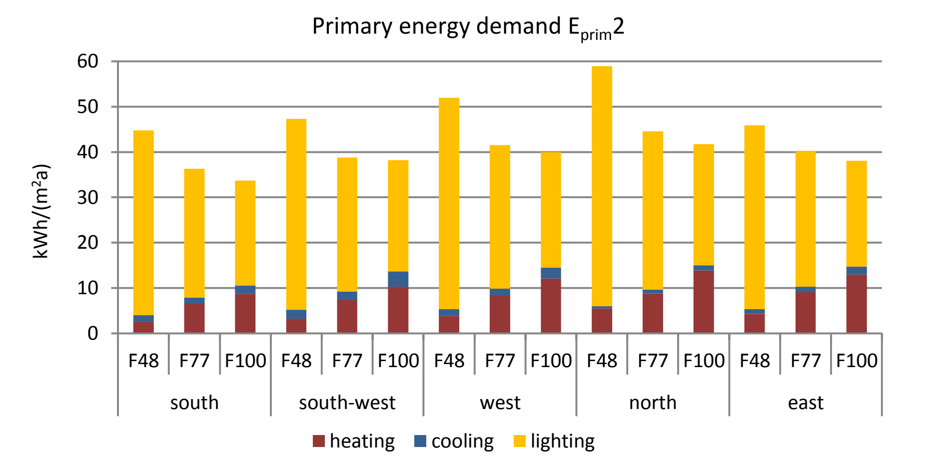


Parameter choice:
SOLID 1
natural ventilation strategy (VENT_NAT)
triple glazing (EW1)
external shading device (SHON) with F77 and F100: F_c 0.3, F48: F_c 0.5

Figure 63: Primary energy demand for office zone heating and cooling with different orientations

The cooling demand has less impact on the primary energy demand than the heating demand. This is a consequence of the optimisation measures which have already been undertaken with efficient sun protection and passive cooling through enhanced day- and nighttime ventilation.

Given that primary energy demand for heating and cooling is very low, the influence of demand for artificial lighting ($E_{prim}2$) has an enormous impact, see figure 64.



Parameter choice:
SOLID 1
natural ventilation strategy (VENT_NAT)
triple glazing (EW1)
external shading device (SHON) with F77 and F100: F_c 0.3, F48: F_c 0.5

Figure 64: Office zone primary energy demand for heating, cooling and lighting with different orientations

The primary energy demand for artificial lighting decreases from approx. 50 kWh/(m^{2}a) to approx. 20 kWh/(m^{2}a) which stands for approx. 1,000 worklight hours per year with highly glazed facades. The rising demand for heating and cooling plays a minor role. The band window (F77) and the highly glazed facade (F100) are an advantage. The analysis presented comes to a similar conclusion as [Knaack] that high facade quality and a higher ratio of window area allow a more efficient building operation, see chapter 2.7.2.

The choice for a band or highly glazed facade is less dependent on the office zone`s orientation. If there is a punctuated facade, however, the orientation is more decisive with regard to the primary energy demand. Regardless of the window area the office zone south orientated causes the lowest demand and if it is north orientated the highest demand.

4.3.2.2 Influence of shading device

The influence of an external shading device is clearly indicated and shown by the example of a south west orientation of the office zone, see figure 65.

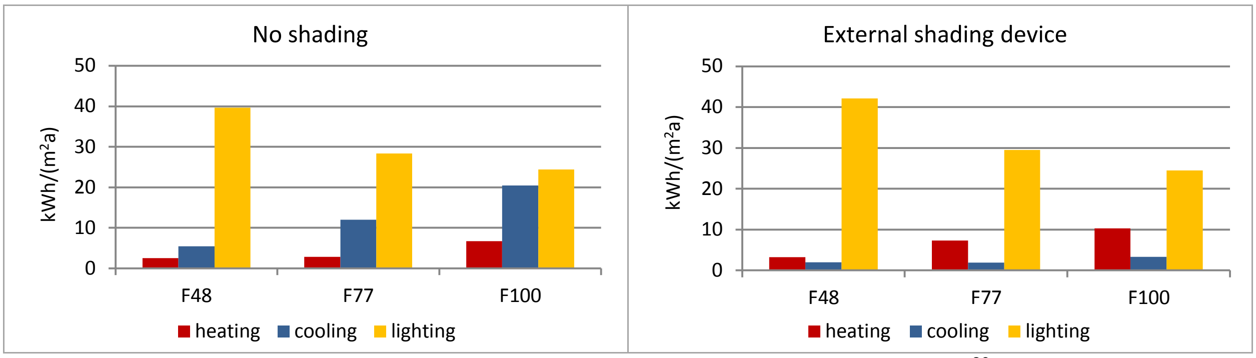
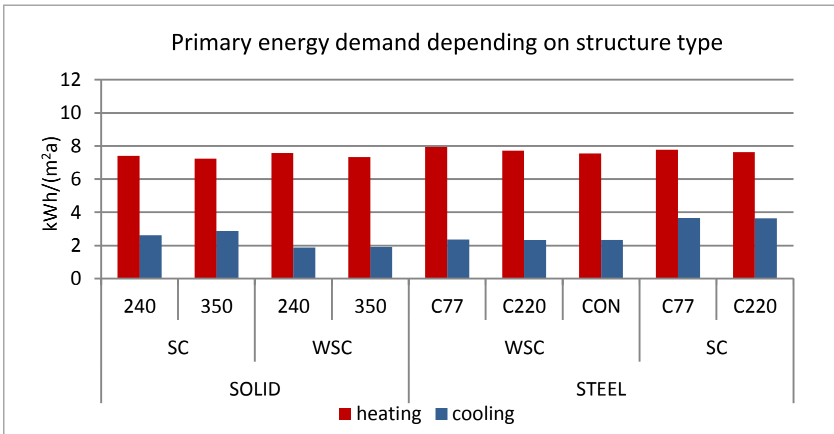


Figure 65: Office zone primary energy demand with and without an external shading device[26]

The positive effect of the shading device is most evident when there is a highly glazed facade to reduce the cooling demand. If there is no shading device, the cooling demand is much higher than the heating demand. The shading device has less influence on the primary energy demand for artificial lighting and a highly glazed facade causes the lowest demand due to efficient use of daylight.

4.3.2.3 Influence of structure type

The choice of structure and slab types does not have much impact on primary energy demand for heating but it does have a small impact on cooling demand, see figure 66.



SOLID with:
240mm concrete slab
350mm concrete slab

STEEL with:
C77 profiled sheeting + 130 mm concrete slab, floating screed
C220 profiled sheeting + 190 mm concrete slab, floating screed
CON precast concrete elements 230 mm, floating screed

SC: suspended ceiling
WSC: without suspended ceiling

Figure 66: Solid and steel composite structures primary energy demand[27]

[26] The results are based on a south-west orientation, SOLID 1, triple glazing (EW1) and the natural ventilation strategy (VENT_NAT).

[27] The results are based on a south-west orientation, a band window facade (F77), an external shading device (SHON), triple glazing (EW1) and the natural ventilation strategy (VENT_NAT).

The positive effect of the accessibility of the mass (WSC) can be seen for the solid and steel composite structure. The massivity of the slab has less influence and the differences between both structure types are slight.

4.3.2.4 Summary

The results have shown that even in highly glazed office buildings with solar controlled shading and lighting systems very low primary energy demand for heating, cooling and artificial lighting can be achieved. The decisive parameter in an energy-efficient building with natural ventilation is the energy demand of the artificial lighting. When compared to the study of [Knaack], see chapter 2.7.2, who investigated a typical air-conditioned office building in Central Europe, the electricity demand for artificial lighting is similarly[28] and the results corroborate the importance of this parameter for the design of energy-efficient office buildings. The author underlines the importance of efficient external shading device and the benefits of a thermal insulation glass. The parameter study of this project comes to the same conclusions, see chapter 4.2.5, although the office zone`s primary energy demand for heating, cooling and ventilation is much lower compared to the study of [Knaack]. A reason could be the high insulation standard of the office zone and the installation of a natural ventilation strategy using passive cooling effects.

A study carried out by the German Federal Ministry of Economics and Technology (BMWi), research field for energy-optimised building (EnOB) indicates that optimised or even passive cooling concepts can significantly reduce electrical energy consumption and primary energy demand. The authors state that the energy saving potential in today's office buildings is particularly in the electricity consumption of ventilation, cooling and lighting equipment. The significance of electricity consumption in relation to the total energy balance of a building has increased because of the improvement in insulation measures in recent years [EnOB].

The low primary energy demand in this project meets requirements of the BMWi`s funding for energy-optimised construction (EnOB). The aim is to achieve a primary energy demand for heating, cooling, ventilation, lighting and auxiliary power up to 100 kWh/(m^2a) based on the net floor area. The office zone models examined in this study lead to an average value of approx. 75 kWh/(m^2a) of all 410 simulation results without taking into account office equipment. Additional transmission, ventilation and infiltration losses through the building envelope of roof or ground plate of a real building as well as further savings through using efficient lighting systems have not yet been considered.

4.4 Analysis and discussion

The examination was focussed on the facade design and thermal storage capacity of slab systems, which have been analysed in connection with the possibilities of low-tech concepts, waiving mechanical ventilation and active cooling systems. Energy-relevant parameters and potential optimisation steps for highly glazed buildings and steel composite structures have been identified. The study has shown that even in the temperate climate zone it is feasible to design an energy-efficient building that meets the comfort requirements set on office

[28] The study of Knaack is based on a specific electricity consumption for lighting of approx. 12 W/m^2 and a daylight coupled simulation without taking into account dimming effects of artificial lighting (using TRNSYS).

workplaces without generally excluding certain structure types or ratios of window area. Design flexibility will be preserved if the energy-relevant key parameters are implemented in an optimal manner. In this case the building is resistant against the sum of solar loads and high internal loads, which frequently occur in office buildings.

4.4.1 Synthesis of results

The thermal storage capacity of the slab systems is a key parameter in case of highly glazed and flexibly designed office buildings with light partition walls. The examinations have shown that the covering of the slabs is a decisive factor to meet the requirements of a low-tech concept with passive cooling. On the other hand, the increase of the storage mass due to the thickness of the slab is of subordinate importance. The differences between solid and steel composite structure are lower than 10% when omitting a suspended ceiling and /or a false floor. The selection of a steel beam structure with profiled sheeting (C77) corresponds to a medium weight construction[29] and is already energy-efficient in case of an optimum selection of the other energy-relevant design parameters. When opting for a heavy construction, which corresponds to integrated floor beam systems or a solid structure with a concrete slab of 240 mm (approx. 580 kg/m^2), only further slight improvements can be achieved.

The facade design determines solar loads and the key parameter is an external, solar-controlled shading device. Provided that it works in an optimum manner, orientation, ratio of window area and the choice of the glazing become less relevant. The number of hours which require artificial light (worklight hours) also depends directly on the facade design. The demand for electricity needed for lighting, has a significant influence on the primary energy demand and is approx. two times higher than the demand for heating and cooling already optimised. For this reason the advantages of a highly glazed facade become evident in case of an energy-efficient office building, see [Knaack], chapter 2.7.2. A decisive factor for the total energy balance is the adjustment of the solar radiation based control systems of the shading device and the lighting system in order to avoid times with closed shading devices and the lights switched on.

With respect to the use of daylight and the reduction of worklight hours, the benefits of a fully glazed facade are small compared to a band window facade, see [de Boer], chapter 2.7.2. Moreover, it can be assumed that the hours of artificial lighting can be further reduced by using light-directing shading elements and dimmable daylight-controlled systems. As a consequence, band window facades with a ratio of 70% - 80% (window area calculated from the interior) are being recommended for energetic and for comfort reasons.

Furthermore, the analysis has clearly demonstrated the limits of the low-tech concept. In the absence of active cooling the number of overheating hours stands at approx. 150 - 200 over-heating hours per year even in case of highly optimised models. In terms of legislation a maximum value of 10% during operating hours of max. 240 h/a is acceptable but however, not in a comfortable range. Compared to that the energy demand for cooling is very low on the assumption of an active cooling system and lower than the energy demand for heating. The net as well as the primary energy demand can thus be considered optimised. A further reduction of

[29] In this case the calculation of the weight only refers to the slab systems without taking into account columns, beams and parapets. A medium weight construction means 350 kg/m^2 and a heavy one 500 kg/m^2 according to [ABP].

the energy demand for heating, only offers further saving potential by lowering the room air temperature and consequently accepting a loss of thermal comfort. From a maximum room air temperature of 26 °C the climate control of the office zone is already equal to the upper limit value of the legal requirements and lowering the temperature to 24 °C leads to approx. threefold increase in cooling energy demand.

As a conclusion, it can be said that in the temperate Western European climate zone highly glazed buildings are feasible in terms of thermal comfort although occupancy rate and office equipment are not yet known at the moment of planning. In order to design a building with a low primary energy demand, the selection and coordination (sound planning in the concept phase) of the following factors is indispensable:

- orientation
- external shading device
- type of glazing and light control
- appropriate fine tuning of the ventilation strategy.

The installation of an internal sun shading system or the possibility to close separately different parts of an external shading device for glare protection is an additional feature of highly glazed buildings in order to guarantee the visual comfort at the workplace [VBG].

4.4.2 Evaluation of the results and assumptions

The results reveal a broad range of possible combinations of parameters whose structure is plausible and explainable from a physical point of view. The assumptions made are regarded as realistic and typical for new office buildings. The conclusions and recommendations are representative for buildings of a similar structure and in consideration of the parameter definitions made.

When there is purely mechanical ventilation (VENT_MECH, see table 10) and active cooling the results of the office zone follow similar trends in comparison with existing office buildings in Luxembourg of the field study of [Thewes]. The primary energy demand for cooling is approx. two or three times higher than the energy required for heating. Including the demand of artificial lighting, the office zone`s energy consumption accounts for approx. 80% of the total primary energy demand. The proportion indicated in the field study is comparable and stands at approx. 70%. Full climate control leads to a two- or threefold increase in primary energy demand when compared to buildings without or with partial air-conditioning [Thewes]. In the temperate climate zone, the integration of natural night-time ventilation already leads to a significant improvement of thermal comfort. During the transition periods the additional use of natural daytime ventilation is beneficial because with the exception of a few very hot and very cold days in the course of a year natural ventilation is possible also during the daytime.

The energy characteristic values calculated for heating and cooling of the office zone can be considered as optimum. In total, the calculation of a real building causes higher energy characteristic values because transmission and ventilation losses of the entire building envelope enter into the calculation of the energy balance. The assumptions in terms of occupancy rate and operation time with regard to office equipment and artificial lighting, however, correspond to a worst case scenario. This approach has been chosen in order to analyse the limits of a low-tech concept without mechanical ventilation system (natural ventilation by means of window elements) and without active cooling (using passive cooling effects during day- and nighttime). In case of a real building the risk of overheating can be reduced with lower occupancy rates, a more efficient lighting system and energy-saving office equipment.

Already in the early design phase it is necessary to determine comfort requirements and future use concerning e.g. occupancy rate, office equipment and server rooms, see also requirements planning in architecture according to [DIN 18205]. These specifications determine possibilities and limitations of high and low-tech concepts and the influence possibilities of the user. The challenge is that the energy and technology concepts should be as robust as possible and designed also for high internal loads and potential changes in use. Since the planner has only little influence on the future office equipment and future use he has to make sure that the building is highly flexible and robust. The questions that have to be answered prior to the start of the planning phase are:

- If a low-tech concept is planned, can a number of overheating hours of approx. 150 - 200 hours per year or approx. 3 - 4 weeks (less productive employees) be accepted?
- How is the possibility of influence by the user defined? What type of control systems will be accepted to avoid unfavourable constellations for example overlapping times of artificial lighting and closed shading device or natural ventilation while the ambient temperature is too high or which “if-when” control mechanisms such as window open, heating switched off will be accepted?

These informations are essential for the design of the energy and technical concept. The decision conflict is between a low-tech concept and full climate control which offers a lot of opportunities of comfort optimisation but with the negative consequences in terms of electricity or primary energy demand and the lower possibility of influence by the user.

The study has shown that even in consideration of the above mentioned aspects a well-considered building concept leads to an energy-efficient office building which meets the future requirements of a primary energy demand of less than 100 kWh/(m^{2}a) (EnOB).

4.5 Conclusion

The expertise-based parameter study has proven to be a suitable method to identify energy-relevant key parameters and to analyse them in detail for fine-tuning and optimisation reasons. Recommendations and optimisation steps for the concept phase have been pointed out. The selection of key parameters with typical and already optimised values of new office buildings has put forth a broad spectrum of technically feasible and highly efficient parameter combinations. However, this approach, e.g. changing one parameter at a time or the principle of trial and error does not allow a mathematical evidence of the sensitive influence or interactions of key parameters on the results. It has been decided to work with the help of an automatic optimisation tool, which allows the use of design of experiments (DoE) and multivariate statistical methods for a systematic sensitivity analysis, see chapter 5.

Further fine-tuning of single parameters is not intended in this project because it has no relevant influence on the general assertions and conclusions. Optimisation steps and potential for saving will diminish. The approach has already led to a range of “best cases” simulated based on typical and optimised values of office buildings.

Since lighting, however, plays a crucial role a detailed daylight simulation should be carried out in an advanced study to allow the quantification of the potential for savings. The new feature for daylight simulation of the dynamic simulation software TRNSYS or other comparable software packages for example Design Builder (Energy Plus) might be used for that. The objective is a realistic control of lighting taking into account the technologies for lighting efficiency (light guidance effects, light sensors and dimmable daylight controlled systems).

The question of whether and in what respect steel composite structures are able to compete with solid structures will be answered after the examination of further aspects of sustainable building design like the flexibility of the supporting structure with reference to office organisation concepts, prefabrication or reuse possibilities and the environmental impacts. The analysis of environmental impacts is described in chapter 7. The thermal storage capacity will be analysed by means of additional measurements of a concrete slab, see chapter 6. Finally, all the results and planning recommendations will be recapitulated in chapter 8.

5 Surrogate-based Sensitivity Analysis And Optimisation

The number of design parameters that influence energy-efficiency and thermal comfort of office buildings is very high. Extensive parameter studies are necessary and in general these studies are carried out using building thermal simulation (BTS) tools, where all results are determined by the definition and choice of parameter combinations.

During the expertise-based parameter study in this project, the design parameters were defined using typical values for office buildings and their choice is based on architectural experience. To identify and concentrate on the most important parameters, as well as limiting the number of simulations required, several of them have been defined as fixed, discrete or categorical. Only a range of design parameters concerned with facade design, structure type and ventilation strategy have been varied.

The project's objective is to develop general design recommendations of further optimisation steps for office buildings, focused on highly glazed buildings and steel composite structures. A systematic sensitivity analysis based on statistical methods is required to corroborate the robustness of the results and the generalizability of the conclusions drawn from the previous parameter study. The aim is to identify and quantify the sensitivity of design parameters (independent variables) according to their impact on and significance for energy demand, overheating hours per year and primary energy demand (target variables).

5.1 Methodology

To evaluate several independent variables and their influence on one or more target variables, multivariate statistical methods are suitable [Stahel]. They can be applied to determine correlations between variables [Backhaus]. The focus is on the dependency of a target variable (result) of one or more independent variables (influencing factors). The specifications of these factors are called factor levels (categories or groups). If the target variable is scaled metrically and the independent variables, however, have a nominal scaling, an analysis of variance (Anova) can be applied. This method is particularly important for the analysis of experiments or simulation results [Backhaus]. Quote: «*The aim of an Anova is to determine which independent variables have a significant influence on the result. It makes it possible to separate those components from the total variability which can be attributed to causes that have been identified. The size of the unexplained variability can therefore be significantly reduced. This is also called residual variance, variability of the sample or experimental error. It arises after the variability from identified causes is subtracted from the total variability. The experimental error cannot be further analysed* » [Lozan].

5.1.1 Approach and tool

The scope of data generated from the calculation procedures of multivariate statistical methods makes it necessary to use computer-assisted methods [Backhaus]. Also in this project, it was found that the support of a tool is required due to the complexity of influencing factors representing two to three factor levels, the number of possible parameter combinations and their interactions.

It has been decided to use the optimisation and data analytics platform “Minamo” (Version 2.1.0, 2014) of the applied research centre “Cenaero” to corroborate the results of the expertise-based parameter study and to quantify key parameter. The software includes multivariate statistical methods for sensitivity analysis as well as an optimisation process for the design of experiments (DoE), surrogate modelling and optimisation methods that allow improving one or more outputs. The advantage of DoE lies in the fact that several parameters can be varied at the same time to determine the parameter influence on the results with as few simulations as possible [Wille].

Minamo is based on an evolutionary algorithm (EA) optimiser accelerated by using approximate models, referred to as surrogate model (SM). In this project, aiming guidelines definition, the focus is on the surrogate modelling capabilities of Minamo. The SM produces a multi-dimensional model giving an input-output relationship and it can be used “as is” for the design exploration and sensitivity analysis. It deals with real, integer, discrete or categorical parameters, which is particularly relevant in building physics.
A surrogate model first based on an initial set of simulation results using design of experiments techniques (DoE) has to be built. The aim is to construct an analytical relationship between the influencing factors (inputs) and the simulation results (outputs or responses). This surrogate model assessment is performed through a leave-one-out cross validation (LOO), where at each design iteration the correlation coefficient R is calculated [Minamo]. This is a reliability assessment to estimate the accuracy of the surrogate model compared to real data. Before the model could be used for statistical analysis purposes, for example, an analysis of variance, it has to be improved by a number of design loops. The aim is to add new simulation results to the database using the adaptive DoE method, see figure 67.

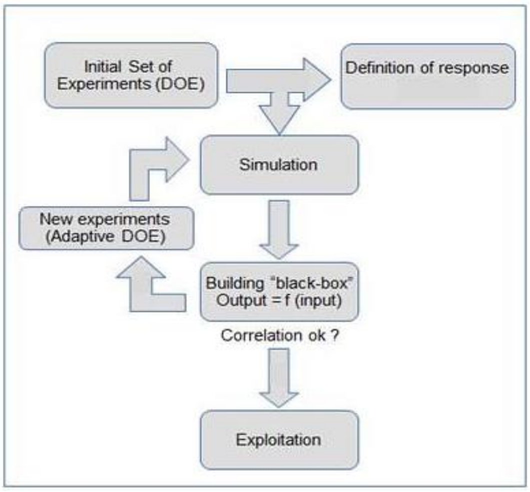


Figure 67: The Minamo design and optimisation approach

To build a surrogate model, in the beginning the number of experiments should correspond to three times and at the end of the process to five to ten times the amount of the input parameter. The quality of a model is sufficient with a correlation coefficient larger than 0.9. This value provides a strong positive linear correlation of the real (actual) and the predicted values for each response, see exemplarily figure 69.
In Minamo the analysis of variance is used as a variance-based, global sensitivity analysis. The aim is to study the impact variations in input parameters on the variation of an output and to quantify the notion that some variables and interactions are more important than others [Minamo]. The method determines the variance in percentages which can be directly

interpreted as measures of sensitivity by giving global indices (first-order or main effects), see exemplarily figure 71.

5.1.2 Parameter set and surrogate model build up

5.1.2.1 Approach

The precise definition of the initial parameter set is essential because the addition of input parameters during the adaptive SM build up does not allow the software to explore all parameter combinations.

In a first step, tests have been made based on an initial database (T_0) representing approx. 20 design parameters and 130 already existing simulation results of the expertise-based parameter study, see figure 68. The tests have shown that the general problem using statistical methods is the parameter definition with mainly discrete or categorical and less continuous parameters (mixed model) from expertise-based decision-making and inherent to building physics.

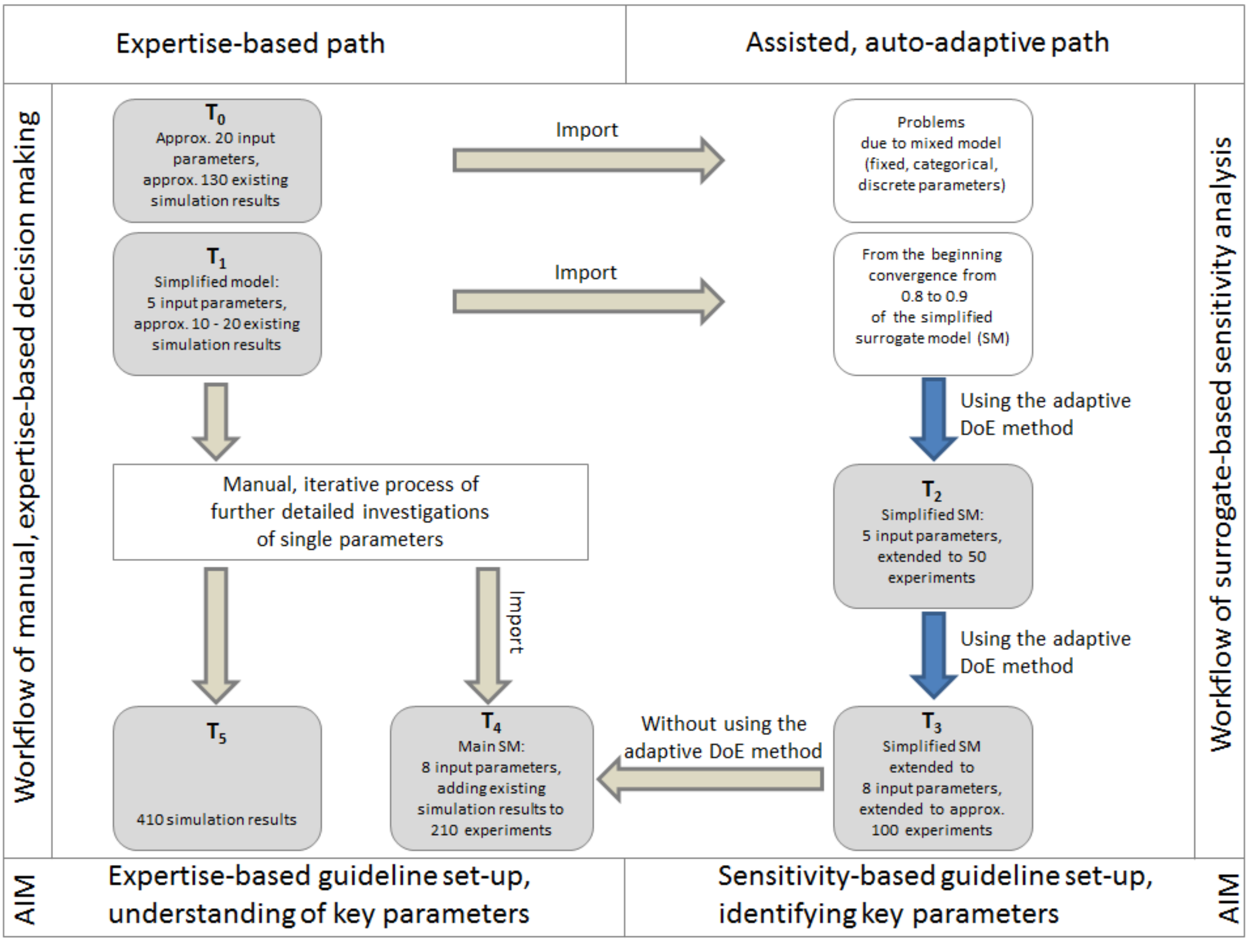


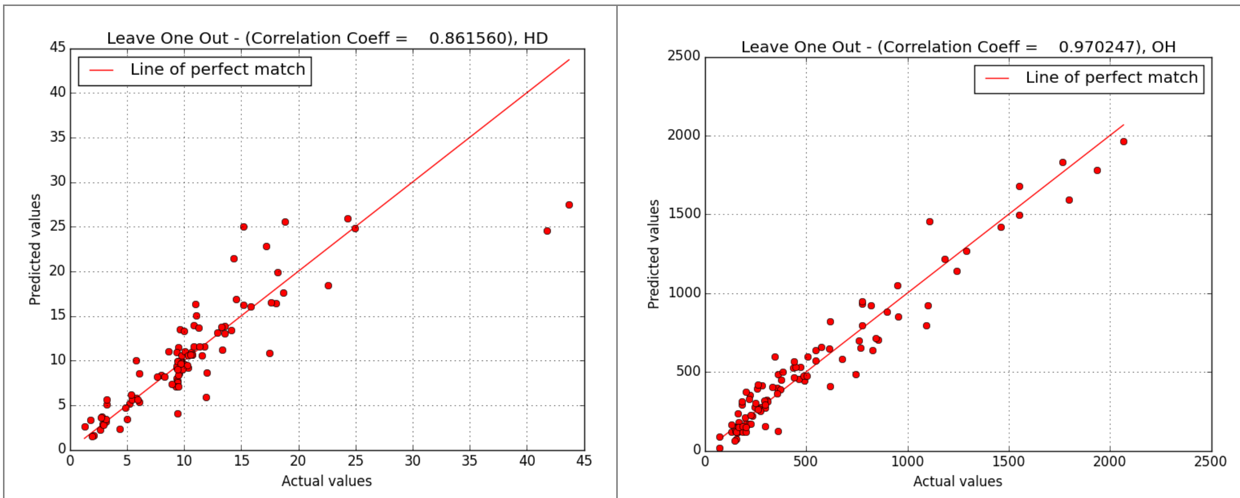
Figure 68: Sensitvity analysis methodology

Therefore a more simplified model (T_1) has been developed. The parameter choice is based on architectural experience and several input parameters have been combined, e.g. different values of the air change rate and the air temperature are representing one ventilation strategy. The simplified model represents a parameter set of five relevant input parameters (orientation, window area, shading device, structure type and ventilation strategy) and three outputs (heating demand, overheating hours and primary energy demand). It has been applied with an initial set of 10 to 20 experiments (already existing simulation results) and has been extended to approx. 50 experiments by using the adaptive DoE method (T_2).

This first convergence model has produced plausible results (correlation coefficients between 0.8 to 0.9)and in the next step the parameter set has been extended to eight energy-relevant design parameters that had already been identified from the expertise-based parameter study (see table 20). They are focussed on the facade design, the structure type and the ventilation strategy and have shown a decisive impact on heating demand and overheating risk of the office zone. Using this parameter set and the adaptive DoE method the model has been extended to approx. 100 experiments (T_3).

5.1.2.2 Leave-one-out validation

The results of the leave-one-out validation (LOO) indicate the accuracy of the surrogate model compared to the real data from the simulation results. The LOO of the surrogate model (T_3) has led to sufficient correlation coefficients of almost 0.9 for the output heating demand and more than 0.9 for the output overheating hours, see figure 69. The graphs from this analysis show that the real actual values match well the perfect line of the model's predicted values.

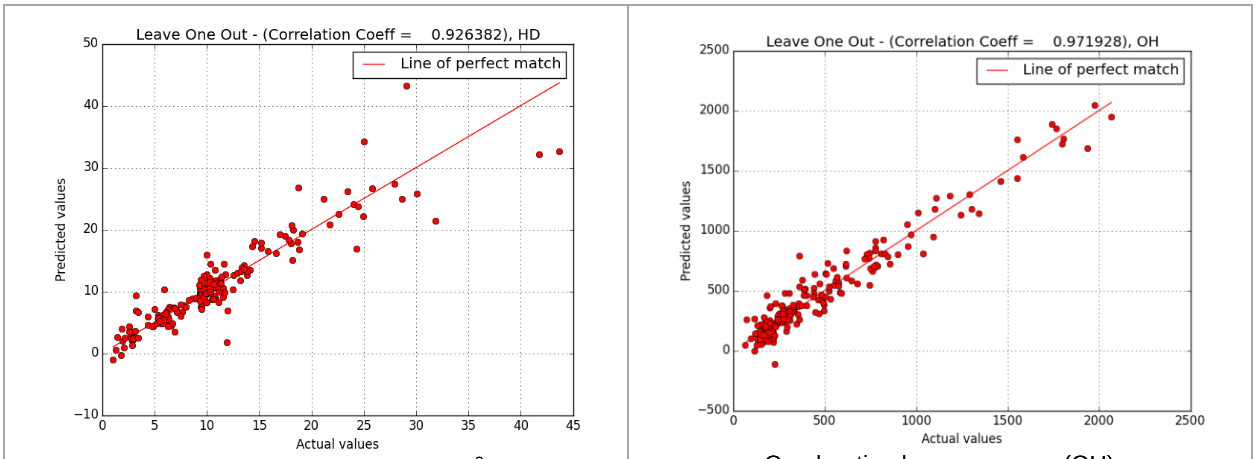


Heating demand (HD) in kWh/(m^{2}a) | Overheating hours per year (OH)

Figure 69: The initial model`s correlation coefficients of approx. 100 experiments

In a next step, this model (T_3) has been extended using already existing simulation results from the expertise-based parameter study to a set of 210 experiments (T_4). This approach that adds experiments without using the adaptive DoE method is possible if the parameter set is not modified. The aim was to cross-check the correlation coefficients of the initial convergence model, which is based on the assisted, auto-adaptive path, with the coefficients of the new extended model, which is based mainly on the simulation results of the expertise-based parameter study.

The correlation coefficients of the extended model (T_4) have been improved, see figure 70.



Heating demand (HD) in kWh/(m^2a) | Overheating hours per year (OH)

Figure 70: The extended model's correlation coefficients of 210 experiments

The model's correlation coefficient has a value of 0.93 for heating demand and 0.97 for overheating hours. The model is well correlated and can be applied to further analysis of variance (Anova) and to the correlation test with self-organizing maps (SOM).
Three spikes in the scatter plot for heating demand represent the office zone north-orientated, highly glazed with a ratio of 100% and a double glazing with a high thermal transmittance of U_g=1.24 W/(m^2K).

5.1.2.3 Conclusion

To achieve a robustness of the results the assisted, auto-adaptive path needs a number of simulation results significantly lower than the expertise-based path for a similar convergence. It can be stated that the number of simulations is less significant for a similar convergence of the surrogate model.

5.1.2.4 Introduction of input and output parameters

Input parameters

The given site and in consequence the orientation of a building exerts great influence on energy demand and the building's climate conditions. The first step in the design process is to define the building concept including the space allocation plan, the structure type and the facade design including the window area. The choice of thermal transmittance for the envelope, type of glazing and shading devices, technical installations, for example the ventilation strategy and the design of the interior (e.g. slab type) will be defined later on in the process. However, they all have an influence on a building's energy demand and thermal comfort. The definition of input parameters and their factor levels is presented in table 20.

Table 20: Parameter set definition

Input parameter	Nomen-clature	Type	Factor levels	Numerical value	Unit
Orientation	OR	Discrete	South	0	azimuth angle in °
			South-West	45	
			North	180	
Window area	WA	Discrete	48%, 77%, 100%	48, 77, 100	ratio in %

Table 20: continued

Input parameter	Nomen-clature	Type	Factor levels	Numerical value	Unit
Shading device	SD	Discrete	SHOFF (no shading device)	0	opaque fraction in %
			SHON (external shading device)	70	
Type of glazing (U_g-value)	GU	Discrete	EW1/EW4 (triple glazing)	0.59	U_g-value in $W/(m^2K)$
			Elec2 (electrochromic glazing)	0.78	
			EW2 (double glazing)	1.24	
Type of glazing (g-value)	GG	Discrete	Elec2 (electrochromic glazing)	0.33	g-value as a factor
			EW4 (triple, solar protection glass)	0.451	
			EW1 (triple, insulation glass unit)	0.584	
Structure type	ST	Categorical	SOLID 1	3	
			STEEL1	1	
Slab type	SL	Categorical	WSC (without suspended ceiling)	0	
			SC (suspended ceiling)	1	
Ventilation strategy	VS	Categorical	VENT_NAT (natural ventilation strategy)	0	
			VENT_NIGHT (night cooling strategy)	1	

Outputs

One of the project's objectives is to find a good solution for a low-tech concept for the office zone with adequate, natural ventilation strategies using as far as possible passive cooling effects and no active cooling system. Therefore the number of overheating hours per year, when the cooling system is switched off, represents an important output. In addition, the net energy demand for heating and the entire primary energy demand for heating and cooling have been included in the analysis, see table 21.

Table 21: Outputs based on simulation results

Output parameter	Nomen-clature	Type	Unit
Heating demand (net energy)	HD	Continuous	$kWh/(m^2a)$
Overheating risk	OH	Continuous	hours/a
Primary energy demand (heating + cooling)	PE	Continuous	$kWh/(m^2a)$

Primary energy demand has been calculated by allocating weighting factors according to converting net and end energy demand as described in chapter 4.3 (see equation 8 to 12). The heating calculation is based on a typical energy supply using natural gas. A compression refrigeration machine has been selected to meet cooling energy demand.

5.2 Sensitivity analysis

5.2.1 Analysis of variance

The following results are based on the surrogate model (T_4) of 210 experiments.

5.2.1.1 Background

The analysis of variance is a sensitivity analysis to study the influence of several input parameters on one output. The results in the following charts show the impact and the quantity of the identified input parameters. If their influence is very low, they are not visualized separately but combined and defined as “other < 3.0%”. Second-order effects which do not give more exploration about other parameters influencing the output are presented as “other orders”. They are the residual variance and represent unidentified causes that could not be further analysed. One reason for these effects can be existing interactions between the input parameters. These effects should be less than 15% - 20% to ensure Anova reliability [Cenaero].

5.2.1.2 Results

The results of the Anova for heating demand and overheating hours are visualized separately. The charts generated clearly indicate the parameters identified and their impact factor, see figure 71.

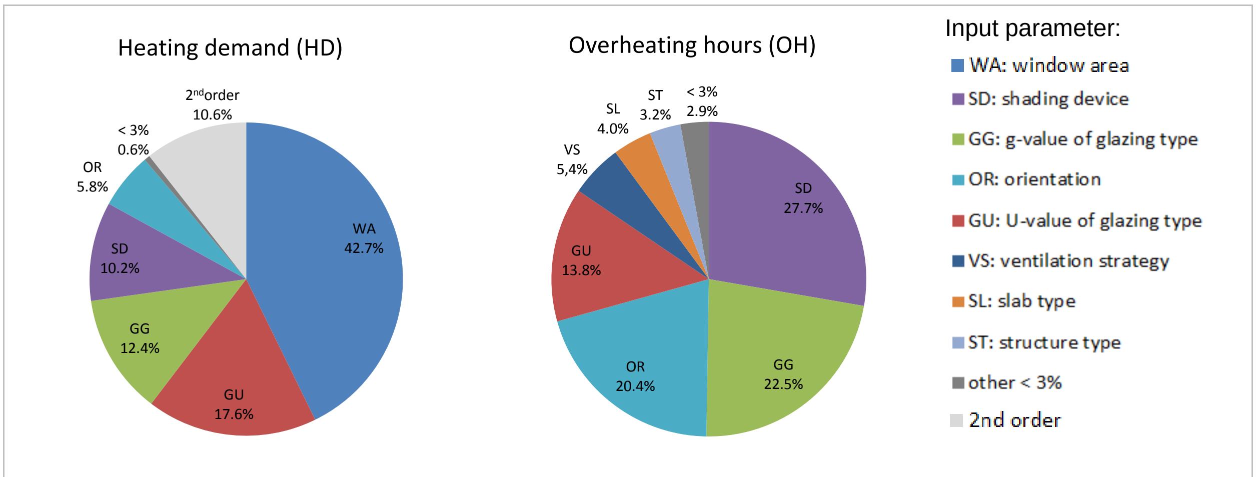


Figure 71: Analysis of variance of heating demand and overheating hours per year

The results cannot be directly compared to the results of the expertise-based parameter study due to the reduced parameter set. The ventilation strategy for example, which has been identified as a key parameter, see figure 44, shows less impact. The reason is that the pure mechanical ventilation strategy (VENT_MECH) has been removed from the parameter set. The results from the expertise-based parameter study have shown that it leads to an unacceptable amount of overheating hours.

Heating demand

Heating demand is significantly affected by the window area and type of glazing, considering the total impact of its thermal (U_g-value) and solar energy transmittance (g-value). The shading device and orientation have a minor impact. The influence of the structure and slab type and the ventilation strategy is less than 3% or could not be identified. The results clearly indicate that a balance between preventing transmission losses and benefits from solar gains is decisive for heating demand.

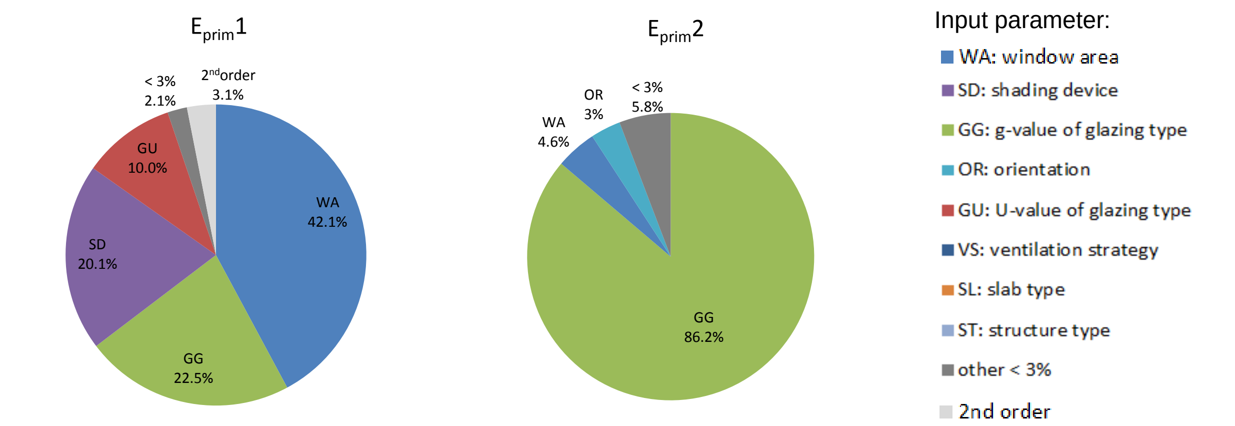
Overheating risk

Overheating risk very much depends on key parameters that have an impact on reducing solar gains. The shading device, the g-value of the type of glazing and orientation are decisive. In addition, the U_g-value has an impact because, in case of identical g-value, the overheating risk decreases when there are high transmission losses. Other input parameters such as the ventilation strategy, structure and slab type and window area are identified but with less impact. They will be further analysed in the next stage of the sensitivity analysis.

Primary energy demand

The primary energy demand for heating and cooling ($E_{prim}1$) and the demand including electricity for lighting ($E_{prim}2$) have been calculated according to the explanations in chapter 4.3. For the analysis of variance for each output ($E_{prim}1$ and $E_{prim}2$) a separate model has been generated. The leave-one-out validation (LOO) of both models leads to a high correlation coefficient of 0.97.

Analysis of variance of the first model ($E_{prim}1$) without lighting shows that the key parameters window area, g-value of the glazing type and shading device identified in the separate analysis of heating demand and overheating hours, mainly influence primary energy demand but with a different impact factor, see figure 1. of 72. The window area has a significant impact. The influence of g-value of glazing type and the shading device is also decisive. Parameters from the previous analysis of heating demand and overheating risk which have already been identified play a minor role. When primary energy demand for artificial lighting is included ($E_{prim}2$), the analysis of variance shows very interesting results, see figure 2. of 72.



1. Primary energy demand excl. demand for lighting ($E_{prim}1$)
2. Primary energy demand incl. demand for lighting ($E_{prim}2$)

Figure 72: Analysis of variance of primary energy demand including and excluding demand for artificial lighting

Solar energy transmittance (g-value) and the corresponding light transmittance for the type of glazing have an enormous impact. The influence of orientation and window area is less than 10%. The fact that only the g-value of the glazing type really has any influence on primary energy demand leads to the assumption that artificial lighting is a decisive parameter for energy efficiency in an office building. This statement can be confirmed by the results of the expertise-based parameter study, see chapter 4.3.2. The primary energy demand for heating and cooling is much lower when compared to the electricity demand for lighting.

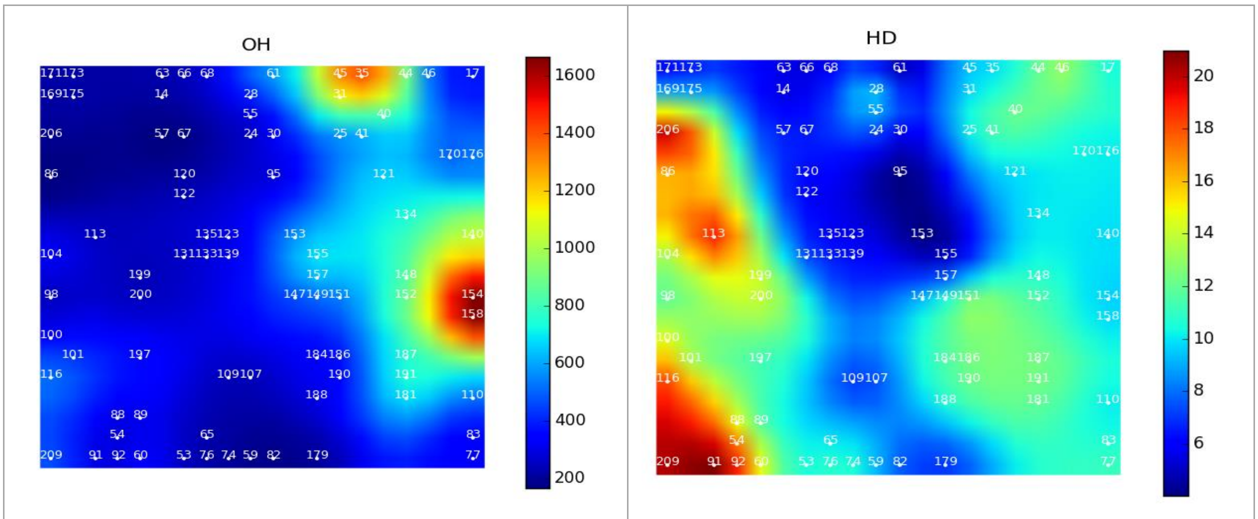
5.2.2 Self-organising maps

5.2.2.1 Background

Self-organising map`s (SOM`s) are a type of artificial neural network that projects high-dimensional data onto a low dimensional 2D space using nodes. It is an abstraction (modelling) of information processing that maps similar data items to nearby locations on the map. The maps are based on raw data and do not use any clustering algorithms [Minamo]. One pixel at the 2D space represents one experiment. However, due to the limits of readability not every experiment is pictured. The ID numbers of the experiments selected are presented on the map, see exemplarily figure 72. The aim is to visualise the qualitative correlation between one input parameter and one output and to reveal major trends. The diagrams give an idea that not only one but several input parameters could have an influence on the output. Existing correlations between input parameters and the influence these interactions have on the result cannot be analysed.

5.2.2.2 Results of heating demand and overheating hours

The following maps show in a graphic manner by the example of the outputs overheating hours and heating demand the possibility for a user to identify favourable/beneficial parameter combinations. The parts in blue and dark blue include the numbers of the experiments with less overheating hours respectively a low heating demand, see figure 73.



Overheating hours per year	Heating demand in kWh/(m^2a)

Figure 73: Example of self-organising maps of the model

5.2.2.3 Results of primary energy demand

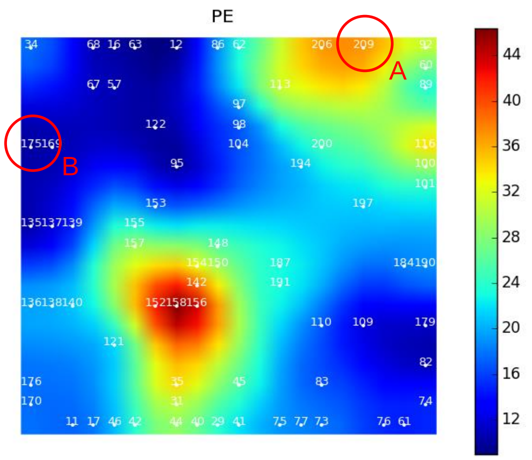
The following maps show in a graphic manner by the example of the output primary energy demand for heating and cooling ($E_{prim}1$) the influence of the chosen input parameters: window area, U_g- and g-value of glazing type, shading device and structure type. The maps of the input parameters: orientation, slab type and ventilation strategy are not presented here. Two experiments are described in detail: a steel composite structure with a high primary energy demand, referred to as “point A” (ID 209) and a steel composite structure with a low demand, referred to as “point B” (ID 175), see table 22.

Table 22: Definition of examples presented in the self-organising maps

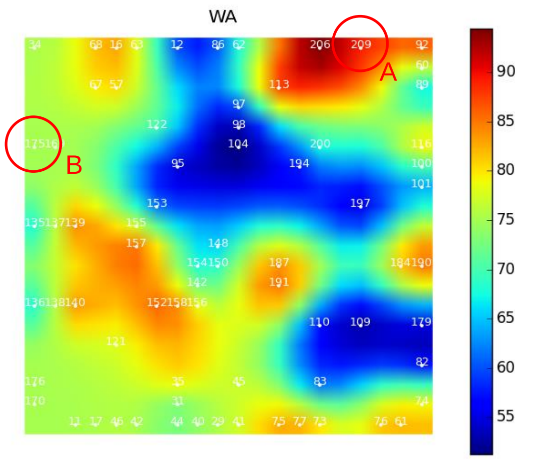
Output	Nomen-clature	Point A (ID 209) Result in kWh/(m2a)		Point B (ID 175) Result in kWh/(m2a)		Map
Primary energy demand	Eprim1	43.31		15.00		72-1
Input parameter	Nomen-clature	Factor level	Value	Factor level	Value	Map
Window area	WA	100%	100	77%	77	72-2
Type of glazing (U_g-value)	GU	(EW2) double glazing	1.24	(EW1) triple glazing, insulation glass unit	0.59	72-3
Type of glazing (g-value)	GG		0.58		0.58	72-4
Shading device	SD	SHOFF (no shading device)	0	SHON (external shading device, opaque fraction 70%)	70	72-5
Structure type	ST	STEEL1	1	STEEL1	1	72-6
Slab type	SL	WCS (without suspended ceiling)	0	WCS (without suspended ceiling)	0	Not presented here
Ventilation strategy	VS	VENT_NIGHT (natural ventilation)	0	VENT_NIGHT (natural ventilation)	0	
Orientation	OR	South-West	45	South-West	45	

The first map of figure 74 represents the range of primary energy demand for 210 experiments presented here. The part of the map marked in orange and red represents experiments which have a high primary energy demand when compared to the rest of the experiments (blue parts). In the second map the colour represents the ratio of window area of all experiments. The blue colour symbolises the punctuated facade (48% ratio), the yellow/orange colour the band window facade (77% ratio) and the red parts the fully glazed facade.

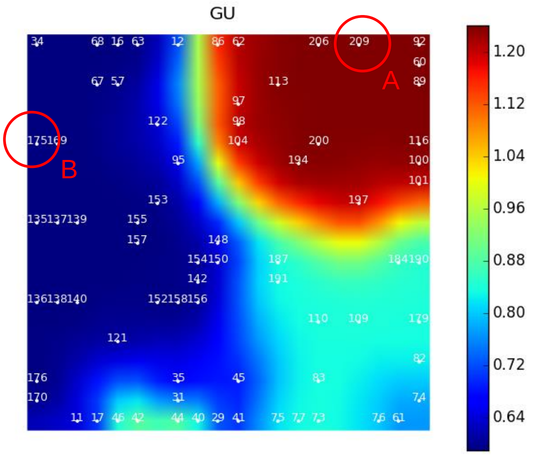
The maps 1 and 2 of figure 74 reveal that one reason for higher primary energy demand is a higher window area, for example in case of experiment 209, point A, with a value of approx. 43 kWh/(m^2a). The graphical intersections of the colours on the maps show the correlation between each input parameter and the output.
With experiment 209, point A, other parameters which have an influence on increasing primary energy demand can be seen in the following maps 3 to 6. The glazing type has a high U_g-value of 1.24 W/(m^2K) (red parts in map 3) and a g-value of 0.58 (red parts in map 4). No shading device is installed (blue parts in map 5) and the steel structure type (blue parts in map 6) is selected. The parameter combination in experiment 209 increases heating and cooling demand and leads to a primary energy demand of approx. 43 kWh/(m^2a). With experiment 175, point B, the choice for a band window facade (77% ratio, green parts in map 2), a thermal insulation glass with a low U_g-value of 0.59 W/(m^2K) (blue parts in map 3) and an external shading device (70=on, red parts in map 5) reduces the primary energy demand to an amount of approx. 15 kWh/(m^2a).



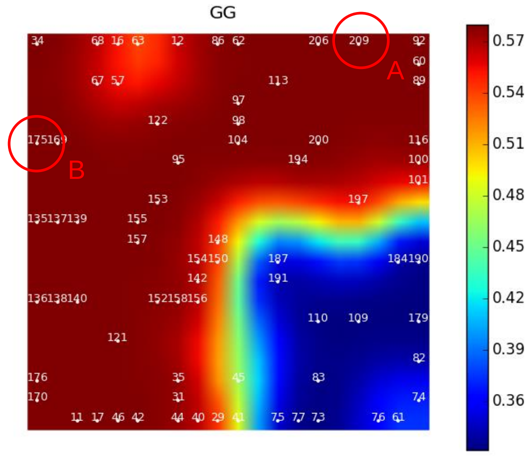
1. Primary energy demand in kWh/(m^{2}a)



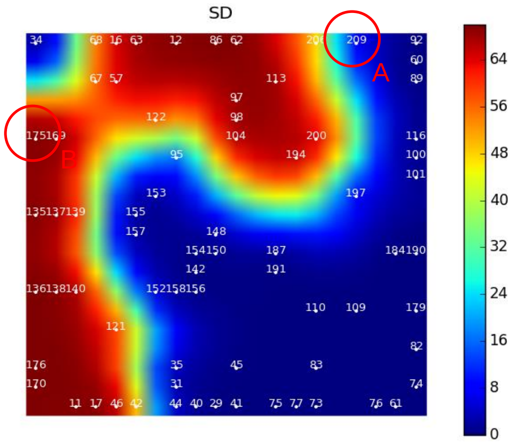
2. Window area, scale from 48% to 100%



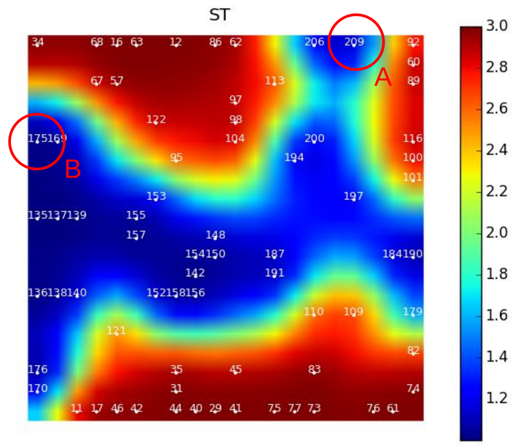
3. U_g-value of glazing type, scale from 0.59 to 1.24



4. g-value of glazing type, scale from 0.33 to 0.58



5. Shading device: 0 = off, 70 = on



6. Structure type: 1=STEEL1, 3=SOLID1

Figure 74: Self-organising maps of the model

In case of a correlation between an input parameter and the output, the maps directly show the positive or negative effect of the parameter choice visualised by the graphical intersections. When the window area is compared with primary energy demand, the orange/red parts represent a high ratio of window area and correlated to that could be one reason for high

primary energy demand. With regard to glazing type, several experiments with a low U_g-value (blue parts in map 3) and a low g-value (blue parts in map 4) have a positive effect on primary energy demand (blue parts in map 1).
As far as the shading device is concerned, also a clear trend can be identified. Primary energy demand is lower (blue parts in map 1) for an external shading device with 70% opaque fraction (red parts in map 5) despite a higher g-value (red parts in map 4) of the glazing type. If there is no external shading device a low g-value could also cause less primary energy demand.
The red parts of map 6 show the experiments with a solid and the blue parts the ones with a steel composite structure. There is no strong correlation visible on the map because the red and blue parts of map 6 show no clear graphical intersections compared to map 1. Neither the steel nor the solid structure seems to strongly influence primary energy demand.

All input parameter presented have an influence on the primary energy demand but with different impact. The maps for the other input parameters which are not presented here: orientation, slab type and ventilation strategy likewise show low or no correlations to the output.

5.2.3 Conclusions from the sensitivity analysis

The self-organising maps have directly visualised the positive or negative effect of different parameter combinations on the outputs: heating demand, overheating hours and primary energy demand. The analysis of variance has shown explicable and coherent results from the point of view of building physics. The results have clearly shown the relevant input parameters and the extent of their impact on the outputs. The parameters identified as key parameters are:

- the window area
- the choice of the type of glazing (U_g-value and g-value) and
- the shading device.

Orientation, structure and slab type and ventilation strategy have less impact.

The results from the expertise-based parameter study have led to similar conclusions. Energy-relevant parameters with a high impact on the heating demand are window area and U_g-value of the glazing type and in the case of overheating risk the shading device and g-value of the glazing type.

To back up the conclusions from the previous analysis and the results from the expertise-based parameter study and to get more specific information concerning the identified key parameters, it has been decided to apply an expertise-based optimisation by using Minamo.

5.3 Expertise-based optimisation

The aim of the expertise-based optimisation is to find a best choice of parameter combinations in order to improve the outputs heating demand, overheating hours and primary energy demand. In this project, it has been decided to apply two methods in parallel instead of the genetic algorithm capacity of Minamo:

- a manual optimisation method of single outputs based on expertise and the main surrogate model (SM of 210 experiments) in order to specify the recommendations based on the identified key parameters, e.g. to define optimised characteristic values of the glazing types and

- a method based on constraints in order to fix or omit single input parameters of the parameter set to find the best solution for the remaining parameters.

The aim is to cross-check if the planning recommendations should be adapted, e.g. for different facade orientations, window-to-wall ratios or structure types. New sub-surrogate-models (SSM) have been generated and additionally an analysis of variance (Anova) and the manual optimisation method have been applied. The following chart represents the entire approach and the expertise-based optimisation by applying both methods, see figure 75.

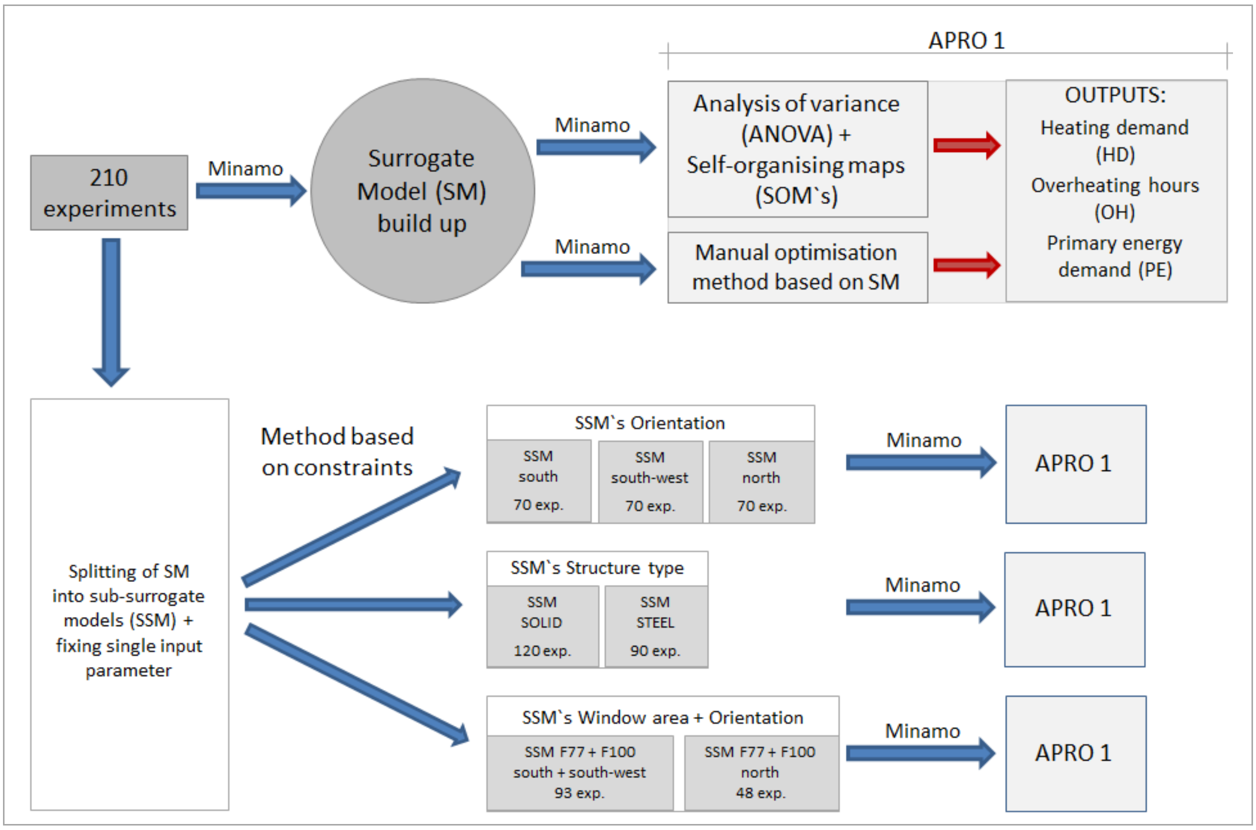


Figure 75: Sensitivity analysis and expertise-based optimisation

The results using the manual optimisation method for the surrogate model (SM) and the sub-surrogate models (SSM) are described in chapter 5.3.2.

5.3.1 Method of constraints

The method of constraints is used for the specification of an optimisation problem. The aim is to fix or omit single input parameters of the parameter set to find the best solution for the remaining parameters. In this project the database, including all 210 experiments, has been divided to generate sub-surrogate models (SSM) for the application of a separate analysis of variance and a manual optimisation method based on expertise. Each SSM represents only the experiments with the fixed input parameter, for example as far as orientation is concerned, each SSM only includes the experiments for a south, south-west and north orientation. In the process, the following input parameters have been selected:

- orientation
- structure type
- window area + orientation.

Further analysis of input parameters is not intended due to the conclusions from the expertise-based parameter study. As regards the ventilation strategy, for example, it is obvious that one choice is more advisable than the other. To improve energy efficiency as well as thermal comfort, the natural ventilation strategy (VENT_NAT) is the best choice, see chapter 4.2.2.

5.3.1.1 Accuracy of the sub-models

Before the analysis of variance can be applied, the accuracy of the sub-models has to be proved using leave-one-out validation (LOO). The results from this validation produce correlation coefficients of ≥ 0.9 of the sub-models, except when there is a north orientation and the output overheating hours when the sub-model has a value of only 0.74. One reason could be the lower overheating risk in a north orientation.

The following charts present the results of the analysis of variance. They do not include the results of parameters which have an influence lower than 3% (other < 3%) and second-order effects, because these results do not provide any further information.

5.3.1.2 Analysis of variance

5.3.1.2.1 Input parameter orientation

The orientation of a building has an influence on energy efficiency and the thermal comfort within its space. The aim of this analysis is to identify whether different recommendations should be given for the facade and structure design depending on the orientation of the building.

Heating demand

The results clearly indicate that the window area and the U_g-value of the glazing type are the key parameters for a south and south-west orientation, see figure 76. For a north orientation, the solar radiation-related parameters, g-value of the glazing type and the shading device, have an additional influence. These parameters are less decisive for a south and south-west orientation, due to there being a high proportion of solar gains which are beneficial to reduce the office zone's heating demand.

Overheating risk

With a south and south-west orientation, the impact of the key parameter g-value of the glazing type and the shading device is significantly higher than for a north orientation. The impact of the facade-related parameters is lower for north orientations. One reason is that the internal gains which remain almost constant are more decisive than the solar gains, see chapter 4.1, figure 40. In consequence the ventilation strategy, the slab and structure type have an impact when compared to a south or south-west orientation.

Primary energy demand ($E_{prim}1$)

The results reveal that for all orientations, the window area is the most decisive parameter. For a south and south west-orientation it is the higher overheating risk (g-value and shading device) and for a north orientation it is the prevention of transmission losses (U_g-value) that determine the primary energy demand.

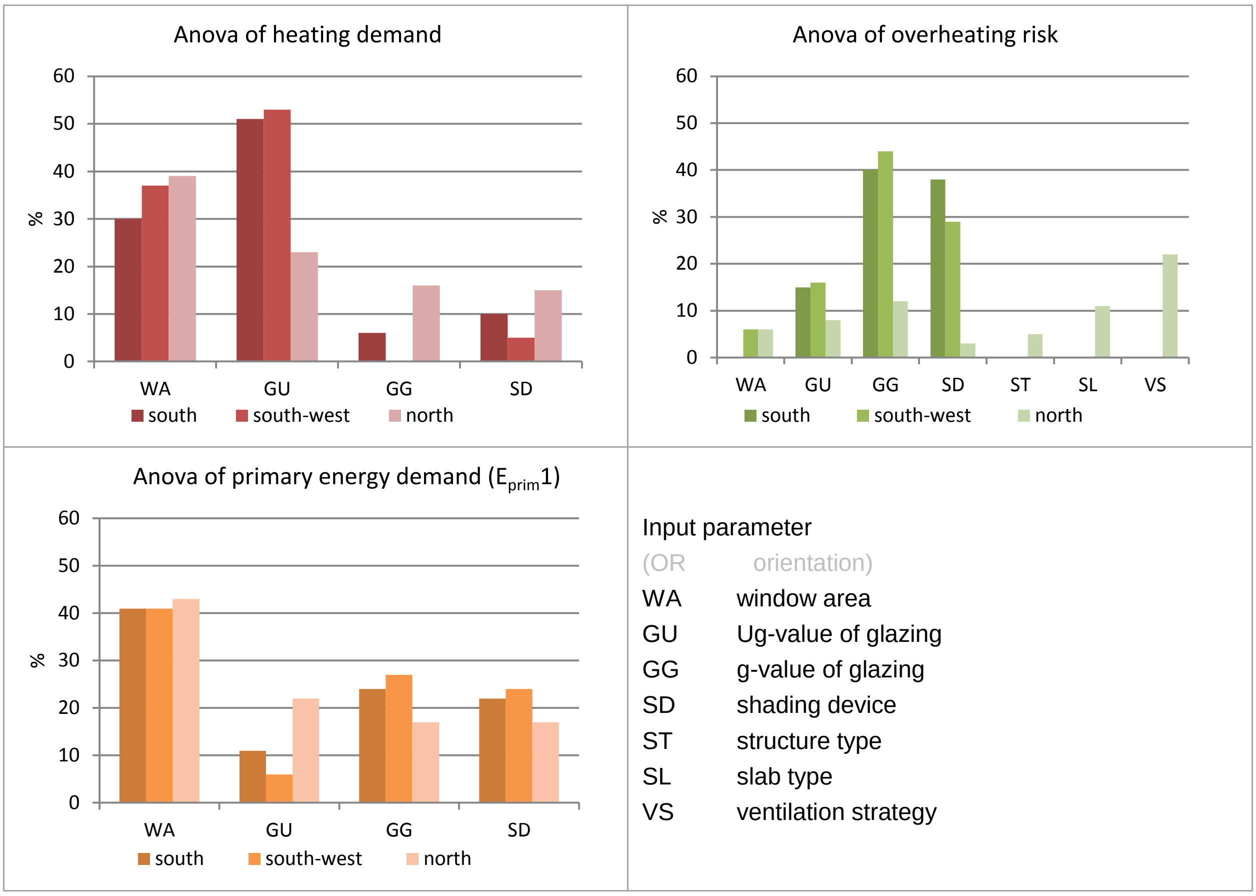


Figure 76: Method of constraints for input parameter orientation, analysis of variance

5.3.1.2.2 *Input parameter structure type*

The aim of this analysis is to identify whether different design recommendations should be given, based on the choice of a solid or a steel composite structure.

Heating demand

The window area has a significantly higher impact in case of a solid structure, while the choice of glazing type (U_g- value and g-value) is decisive for the steel structure. The results indicate that the steel structure is more sensitive with regard to solar gains and the prevention of transmission losses because there is less thermal storage capacity, see figure 77.

Overheating risk

The key parameters for both structure types are the shading device, the g-value of the glazing type and the orientation. All other input parameters have less impact. However, when there is a steel composite structure the slab type (accessibility of the slab) also has an additional influence on the overheating risk.

Primary energy demand ($E_{prim}1$)

The window area has a significantly greater influence on the solid structure, while the shading device and choice of glazing type have more impact in case of a steel composite structure.

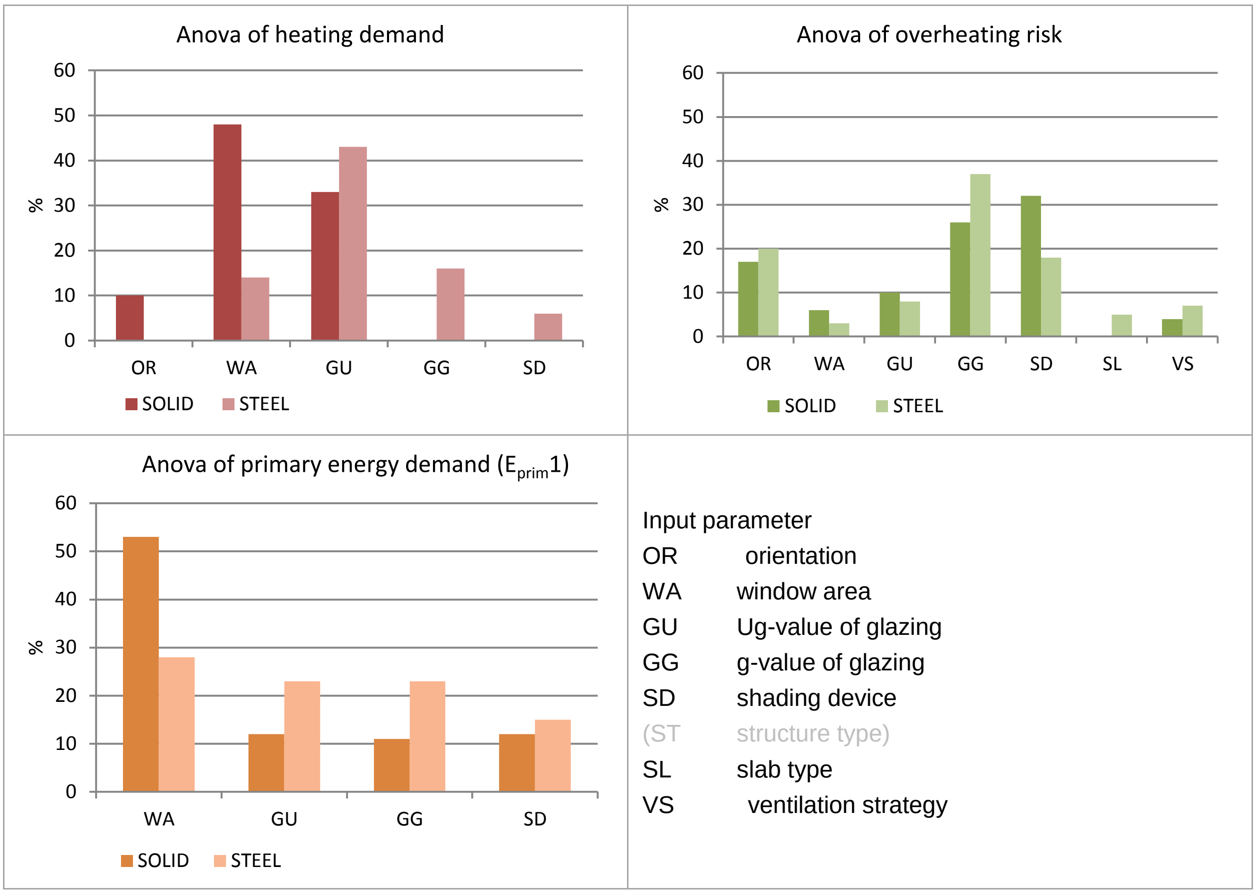


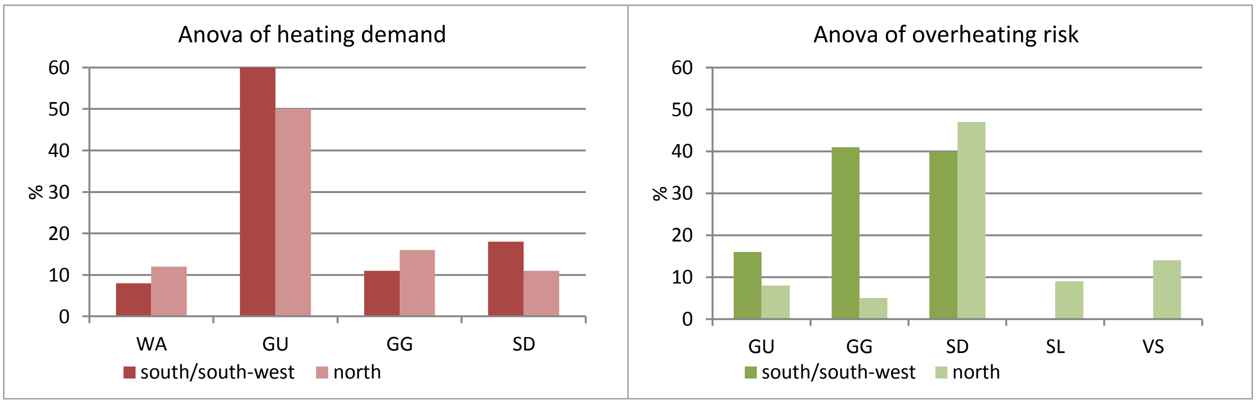
Figure 77: Method of constraints for input parameter structure type, analysis of variance

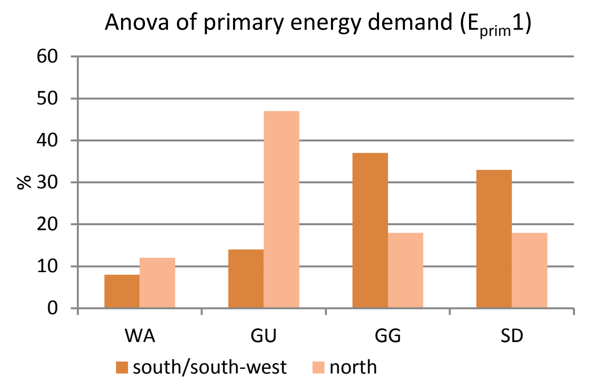
5.3.1.2.3 Input parameters window area and orientation

The main objective of the project is to clarify the question what is the best parameter choice for highly glazed buildings and steel composite structures depending on a given orientation. Therefore in this analysis only the band window (77% ratio) and the highly glazed facade (100% ratio) have been included. South and south-west orientation are presented in one sub-model, because the previous analysis has shown similar results for both orientations.

Results

The results clearly indicate that in a highly glazed building the key parameters are the choice of the glazing type and shading device, see figure 78. The analysis has confirmed the conclusions and tendencies from the previous analyses.





Input parameter
(OR orientation)
(WA window area)
GU Ug-value of glazing
GG g-value of glazing
SD shading device
ST structure type
SL slab type
VS ventilation strategy

Figure 78: Method of constraints for input parameter window area and orientation, analysis of variance

5.3.1.3 Conclusions and key parameter

The previous analyses of variance of the surrogate model (SM) and the sub-surrogate models (SSM) have allowed identifying and quantifying key parameters that influence heating demand, overheating risk and primary energy demand, see table 23.

Table 23: Identified key parameters based on the sensitivity analysis

Key parameter	NO.	Nomen-clature	Definition
Heating demand	1	WA	Window area
	2	GU	Thermal transmittance (U_g-value) of glazing type
	3	GG	Solar energy transmittance (g-value) of glazing type
	4	SD	External shading device, radiation controlled
Overheating risk	1	SD	External shading device, radiation controlled
	2	GG	Solar energy transmittance (g-value) of glazing type
	3	OR	(Orientation)
	4	GU	Thermal transmittance (U_g-value) of glazing type
	5	WA	Window area
Primary energy demand for heating and cooling (Eprim1)	1	WA	Window area
	2	GG	Solar energy transmittance (g-value) of glazing type
	3	SD	External shading device, radiation controlled (70%)
	4	GU	Thermal transmittance (U_g-value) of glazing type

The window area and thermal transmittance of the glazing type are the key parameters as far as heating demand is concerned. The solar energy transmittance of the glazing type and the shading device are crucial for improving thermal comfort in summer. The facade related design parameters have a significant impact to optimise energy efficiency and thermal comfort in office buildings. The orientation is given based on the building site and no “real” design parameter. However, the facade design should respect the orientation of the building. The challenge with a south and south-west orientation is the reduction of the overheating risk, and with a north orientation the prevention of transmission losses.

In addition to the facade design, the slab type and ventilation strategy have an impact on the overheating risk. The results of the expertise-based parameter study showed similar results. To improve thermal comfort in summer, it is essential that a suspended ceiling is not fitted (accessibility of the slab) and that passive cooling strategies (VENT_NAT) are used, see chapter 4.2.3.1.

Differences between the solid and the steel composite structure were only found in the choice of the glazing type. The steel composite structure is more affected by the impact of solar gains and transmission losses than the solid structure. One reason for this is the lower thermal storage capacity and that the slab is usually covered. The expertise-based parameter study revealed that the overheating risk increases when there is a steel composite structure covered with a suspended ceiling. However, the differences between both structure types are low if the slab's accessibility is maintained. The same applies to heating demand; the results are similar, regardless of the structure type selected.

5.3.2 Manual optimisation method of single outputs

The aim of the manual optimisation method is to get further information about the best choice of key parameters that have already been identified. In Minamo new input parameter combinations with predicted results have been generated to find optimisation steps for one output selected. The method has been applied based on the surrogate model (SM) and the sub-surrogate models (SSM) from the previous analyses. The application during the expertise-based optimisation provides a range of solutions which are feasible and reliable from a technical and building physics point of view. The new parameter combinations and the predicted results have shown the best parameter choice with clear tendencies for improving heating demand, overheating risk and primary energy demand ($E_{prim}1$). This feature of the software does not offer a graphical presentation of the results and the optimisation steps identified. They are described below and summarised in table 24 which presents a best parameter choice for the following parameters:

- slab type (SL); suspended ceiling (SC) or no suspended ceiling (WCS)
- window area (WA); ratio in %
- external shading device (SHON) or no shading (SHOFF)
- U_g-value of glazing type (GU) in $W/(m^2K)$
- g-value of glazing type (GG)
- ventilation strategy (VS); natural ventilation strategy (VENT_NAT)

depending on the choice of orientation (OR) and structure type (ST). These inputs have been defined as fixed, because the facade design should respect the orientation provided by the construction site. The choice of structure type is defined early on in the concept phase and the recommendations should be appropriate and beneficial according to which type is selected.

Table 24: Best choice of key parameters based on the manual optimisation method of single outputs

Optimisation process	Nomen-clature	Best parameter choice					
	OR	South-west		South		North	
	ST	SOLID	STEEL	SOLID	STEEL	SOLID	STEEL
Regarding the heating demand	SL	SC	WSC/SC	SC	WSC	SC	SC
	WA	48	48	48-77	48-77	48	48
	SD	SHOFF	SHOFF	SHOFF	SHOFF	SHON	SHON
	GU	0.59	0.59	0.59	0.59	0.59	0.59
	GG	0.45-0.58	0.45-0.58	0.45-0.58	0.45-0.58	0.33-0.45	0.33-0.45
	VS	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT
	OR	South-west		South		North	
	ST	SOLID	STEEL	SOLID	STEEL	SOLID	STEEL
Regarding the overheating hours	SL	WSC	WSC	WSC	WSC	WSC	WSC
	WA	48-77	48-77	77-100	77	77	48-77
	SD	SHON	SHON	SHON	SHON	SHON	SHON
	GU	0.78-1.24	0.78-1.24	0.78-1.24	0.78-1.24	0.78-1.24	0.78-1.24
	GG	0.33	0.33	0.33	0.33	0.45-0.58	0.45-0.58
	VS	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT
	ST	SOLID	STEEL	SOLID	STEEL	SOLID	STEEL
Regarding the primary energy demand for heating and cooling ($E_{prim}1$)	SL	SC	WSC/SC	SC	WSC/SC	SC	WSC/SC
	WA	48-77	77-100	48-77	77-100	48	48-77
	SD	SHON	SHON	SHON	SHON	SHON	SHON
	GU	0.59	0.59	0.59-0.78	0.59	0.59-0.78	0.59-0.78
	GG	0.33	0.33	0.33-0.45	0.33	0.33-0.45	0.33-0.45
	VS	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT	VENT_NAT

5.3.2.1 Recommendations

The general recommendations presented below for a south, south-west and north orientation are given to optimise the office zone's heating demand or overheating risk. The primary energy demand ($E_{prim}1$) includes the demand for heating and cooling the office zone.

5.3.2.1.1 Heating demand

North orientations

To reduce heating demand with a north orientation, the best choice is a punctuated facade (48% ratio) and a glazing type which reduces thermal losses and provides the use of solar gains (U_g=0.59 W/(m^{2}K) and g=0.33-0.45). With this parameter choice, the challenge is to achieve optimal adjustment of the control systems for both the shading device and the artificial lighting so as to avoid any increase in worklight hours, see chapter 4.1.6.2.

South and south-west orientations

The heating demand for the south and south-west orientated office zone is very low. With a south-west orientation the best choice is a punctuated or band window facade, and a band window facade with a south orientation. The glazing type should have a low U_g-value of 0.59 W/(m^{2}K) and a high g-value of 0.45-0.58.

5.3.2.1.2 Overheating risk

South-west orientations

As far as the overheating risk is concerned, the most critical orientation is a south-west orientation. The best choice is a punctuated facade, an efficient external shading device and a glazing type with a high U_g-value of 0.78-1.24 W/(m^{2}K) and a very low g-value of 0.33. The manual optimisation method has indicated that the choice of a solid structure is an advantage.

South and north orientations

The south- and north-orientated office zone presents a lower overheating risk. The same parameter choice as for a south-west orientation is recommended, except for the window area. A band window facade in a north orientation and a band or highly glazed facade in a south orientation is beneficial. The choice of a solid structure is indicated as an advantage for a south orientation, while for a north orientation the choice of structure type is less decisive.

For all orientations, to improve thermal comfort in summer the accessibility of the mass and the installation of a natural ventilation system using passive cooling effects are essential, see also chapter 4.2.2.

5.3.2.1.3 Primary energy demand

A punctuated facade in a north orientation and a band window facade in a south and south-west orientation are beneficial. In all orientations, the glazing type should have a low thermal and a low solar energy transmittance (U_g=0.59-0.78 W/(m^{2}K) and g=0.33-0.45). Installing a shading device and using the natural ventilation strategy are an advantage. The choice of structure type is less decisive.

5.4 Analysis and conclusions

5.4.1 Synthesis of results

5.4.1.1 Facade design

The window area influences the energy demand for heating, cooling and artificial lighting. It is a key parameter for optimising heating demand, but less decisive as regards the overheating risk if an external shading device is installed. A band window facade is the best choice and provides a compromise for optimising the outputs: heating demand, overheating hours and primary energy demand (E_{prim}1).The shading device is the key parameter for improving thermal comfort in summer. When there is a highly insulated building with an efficient external shading device, the net and primary energy demand for heating is higher than it is for cooling – and vice versa when there is insufficient solar protection or none at all.

An optimal choice of the characteristic values of the glazing type (perfect ratio of U_g- and g-value) is crucial. In a temperate Western European climate with long transitional periods, the energy demand during the heating period is decisive. The advantage of increasing transmission losses by opting for double instead of triple glazing (in case of identical g-value) to reduce the overheating risk is lower than the increase in heating demand.

5.4.1.2 Structure and slab type

The differences between the solid and the steel composite structure are low if the accessibility of the thermal mass (i.e. it is not covered with a suspended ceiling) is maintained. However, to improve thermal comfort during cooling and heating periods, there are advantages in choosing a solid structure. The steel composite structure is more sensitive to high solar gains or high transmission losses, particularly if the slab is covered. For passive cooling concepts with enhanced natural ventilation, the accessibility of the thermal mass is crucial for both structure types so that the thermal storage capacity is used.

5.4.1.3 Ventilation strategy

The natural ventilation strategy with enhanced day- and nighttime ventilation could reduce heat loads by efficient passive cooling. It is the best choice for achieving thermal summer comfort, in combination with accessibility of the slab.

5.4.2 Application of the surrogate-based sensitivity analysis tool

The application of the tool has revealed tendencies and conclusions similar to the previous expertise-based parameter study. The results can be explained from a technical and building physics point of view and they have corroborated the robustness of the results and the reliability of the previous conclusions. The application of the self-organising maps, the analysis of variance in addition to an expertise-based optimisation has provided more precise information about the design parameters and further interesting findings about the best parameter choice. The sensitivity analysis has made it possible to identify and quantify the sensitive impact of the design parameters according to energy efficiency and thermal comfort by means of statistical and mathematical validation. One problem arises due to the definition of the input parameters as fixed, discrete and categorical inherent to building physics and so as to limit the number of simulations required. The surrogate model is easier to build and more efficient with continuous input parameters. The self-organising maps provide in a graphic manner the possibility for a planer to identify favourable/beneficial parameter combinations and to evaluate their effect on energy-efficiency and overheating risk. The maps can be a useful tool to support the decision-making process in the early planning stage. The expertise-based optimisation has shown clearly tendencies for a best parameter choice to improve the outputs. During the manual optimisation process one problem arises of an insufficient quantity of experiments if any further splitting of the main surrogate model into sub-surrogate models is intended. In a next step, the application of advanced, automated optimisation methods is recommended, e.g. multi-objective ones for a simultaneous optimisation of more than one output (Pareto Front).

5.5 Evaluation of the approach and outlook

For years computer-assisted design optimisation has relied on expertise-based decision-making to analyse relevant design parameters and parameter combinations. Nowadays, automatic optimisation tools or platforms provide advanced techniques for a simulation-based design of experiments (DoE), surrogate modelling, optimisation and data-mining methods [Minamo].

The use of automated tools for parameter analysis and optimisation in the field of building design is seldom applied, although these tools are widely available in the field of industrial design and have many applications, for example, in the automotive industry. However, in the future they will be an important tool for planners and architects because of the increase in computer-aided parametric design approaches and the need for thermal simulations. The growing importance of these tools is apparent from the developments of the optimisation platform “Minamo” presented here or of comparable software tools, e.g. "DesParO" developed by the German Fraunhofer Institute for Algorithms and Scientific Computing (SCAI). "DesParO" also includes design of experiments, global sensitivity analysis and optimisation processes. It provides interactive design exploration to find the optimal range (Pareto Front) for a multi-criteria optimisation problem. For this purpose, a small set of simulation experiments is first determined with design of experiments techniques (DoE). The simulation results are used to generate a nonlinear meta-model, based on radial basis functions (approximation method[30]) [Fraunhofer SCAI]. Both tools have a similar structure and provide a connection to external simulation programmes (online application). In this case the software is directly connected to the simulation software making it possible to have an efficient and both time- and cost-saving application. New simulation results can be immediately implemented during the application to improve the surrogate model.

The objective of the next step in this project is to develop a decision-making tool suitable for planners to use in the concept phase. Therefore a huge amount of simulation results and an extensive, reliable database are crucial. A workflow between simulation tool and an optimisation platform or tool is recommended for a massive adoption of automated design by the building sector. The previous analyses have revealed that the optimisation potential in energy-efficient office buildings is an issue of fine-tuning. The workflow based on advanced optimisation methods and the data analysis platform has also revealed that this platform must be further developed to manage large discrepancies in the type of input parameter (continuous, integer, real, discrete or categorical which are inherent to building physics).

The planning recommendations and optimisation steps presented provide planners with important information about the facade design and construction details for their concept. Considering the configurations in this study (definition of design parameter), the general conclusions can be regarded as being representative for similar types of office buildings. The general design guidelines and recommendations are summarised in chapter 8.

[30] The method starts with an arbitrary number of solutions and generates a sequence of approximate solutions [Vetters].

6 Measurements Of Thermal Storage Effects

A series of measurements was carried out in an office at the University of Luxembourg to provide data for the metrological investigation of the actual thermal storage capacity of a solid slab and its impact on indoor climate. In addition, the results were evaluated by comparing them with thermal simulation results for the same room. The measurements took place during a typical summer period from 18th July to 13th September 2015.

6.1 Methodology

The aim is to analyse the temporal development of temperature variations in a concrete slab and to quantify the energy buffered in the slab depending on solar radiation, ambient and room air temperature. The results should clarify whether it is possible to confirm the statement that a slab must have a thermally effective mass storage as far as a depth of 10 cm and that a 20 cm slab can be activated to its core when both sides are uncovered [ABP], see chapter 2.6.4.

6.1.1 Test room

The office is located in the second floor of the main building at Campus Kirchberg, Luxembourg City. It is south-west orientated, has a band window facade of 66% window-to-wall ratio and a suspended ceiling, see figure 79.


Figure 79: South-west orientated office at the University of Luxembourg

The office is in a 1970s building which has not been renovated and consequently it has a poor standard of thermal insulation and airtightness, especially as far as the window elements are concerned. The office was not in use during the measurement period and no internal gains have to be taken into account. The main properties are shown in table 25.

Table 25: Properties of the office

Reference office zone	Dimension	Unit
net floor area	40.60	m^2
room height (lower edge of suspended ceiling)	2.98	m
window area	10.73	m^2
ratio of window area (calculated from inside)	66	%
U-value of window element (single glazing)	5.7	$W/(m^2K)$
g-value of window element	± 0.86	/
U-value of opaque exterior wall	± 1.0	$W/(m^2K)$
U-value of exterior roof	± 0.9	$W/(m^2K)$
building tightness (infiltration rate)	1.0/0.7	h^{-1}

In the office, four drill holes approximately 7-8 cm deep were drilled into the slab to install temperature sensors, see figure 80.

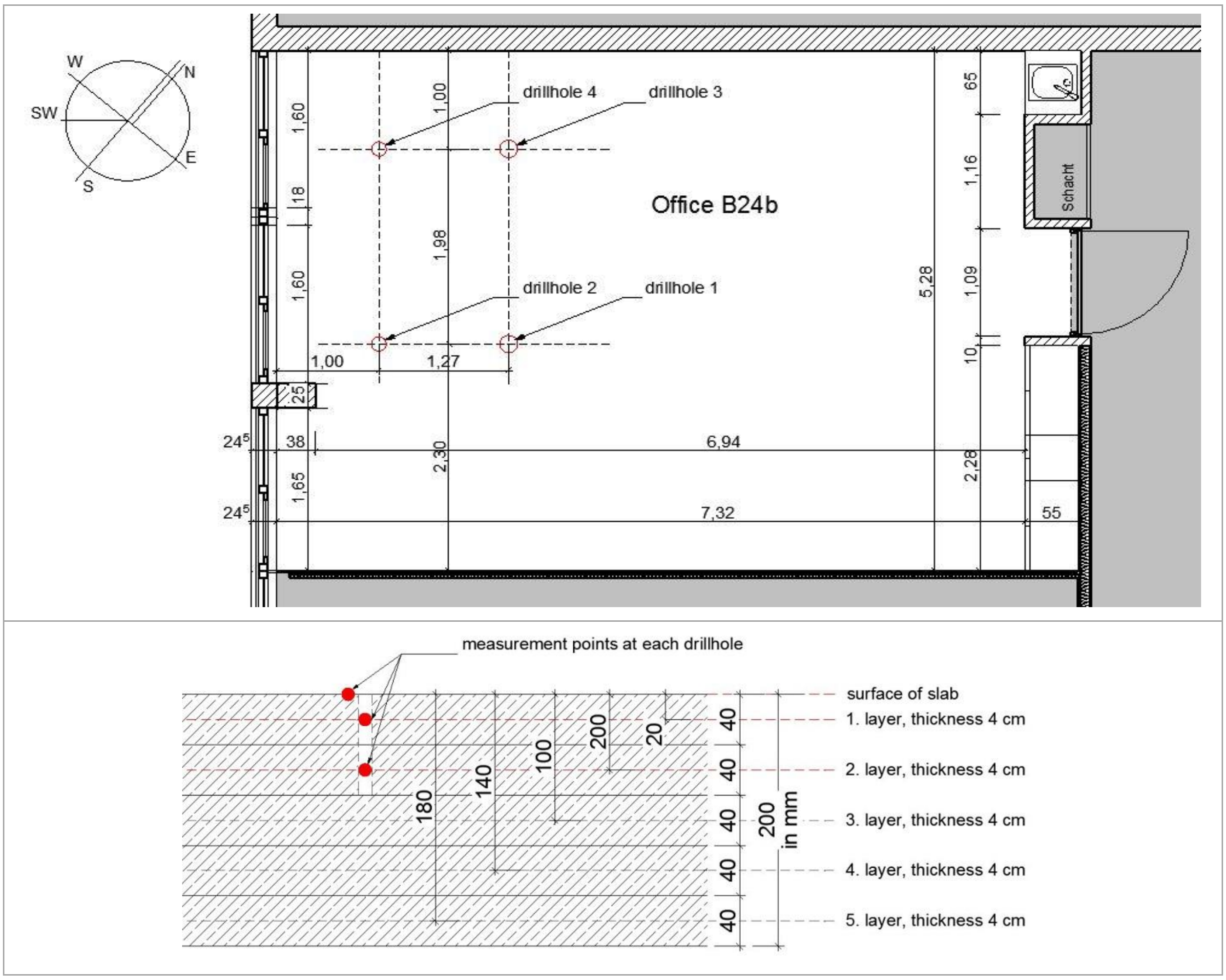


Figure 80: Office floor plan and sketch of the measurement points in the concrete slab

The above sketch shows the cross section of the 20 cm slab divided into five layers of 4 cm. In each of the four drill holes two temperature sensors were installed at a depth of 2 cm in the middle of layer 1 and of 6 cm in the middle of layer 2 (point measurements). A further four temperature sensors were placed on the surface of the floor next to each drill hole.

6.1.2 Measurement equipment

Eight NTC[31]-thermocouples, calibrated[32] before the beginning of the measurement period, were fixed in the four drill holes. Each hole was filled with a heat sink paste which has a thermal conductivity of 0.81 W/(mK) and is covered with a tape. Four NTC-sensors were used to measure the surface temperature of the floor as well as sensors to measure room air temperature, atmospheric humidity and air pressure. Furthermore, two radiation probes to determine the illuminance level were installed inside the room, see figure 81.

[31] NTC-thermistor (negative temperature coefficient): change of resistance when changing the temperature, suitable for temperature measurements.

[32] The correction values of the calibration certification have been considered in the analysis.

	
NTC-thermocouple FNA + heat sink paste (drill holes)	NTC-sensor FN 0001 K (surface)
	
radiation probe FLA 623	digital humidity-/temperature sensor FHAD 46x

Figure 81: Measurement equipment[33]

A weather station was assembled on the roof, next to the office, to measure ambient temperature, relative humidity, illuminance level and solar radiation (global and direct radiation) and air pressure. All the data was recorded using a data logger, see figure 82.

	
weather station	data logger 2890-9

Figure 82: Weather station and data logger

The four drill holes had diffuse and direct solar radiation depending on the course of the sun and the degree of cloudiness which results in no homogeneous irradiation on the slab. The NTC-sensors placed next to the drill holes were covered with tape and cardboard to avoid direct solar radiation on the sensor, see figure 83.

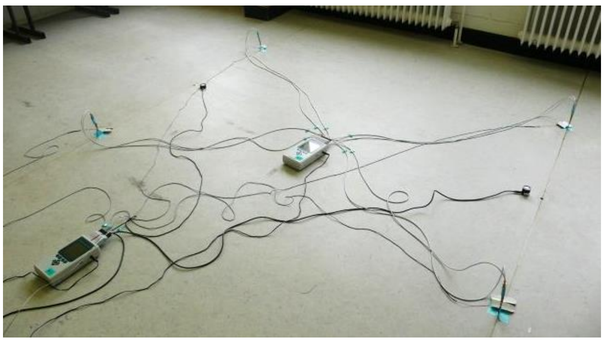
	

Figure 83: Measurement equipment installed in the office

[33] The equipment presented is manufactured by Ahlborn.

6.1.3 Evaluation steps

The aim of the evaluation is to gain deeper knowledge about the temperature fluctuations inside a concrete slab exposed to the room air temperature and solar radiation. The second objective is to quantify the energy buffered inside the different layers of the concrete slab.
The daily maximum and minimum temperatures at the surface and in the middle of each layer have been analysed to determine the temperature difference between the surface and each layer, the phase shift and the temperature amplitudes. The following graph shows exemplarily typical daily temperature fluctuations at the surface and inside a slab, see figure 84.

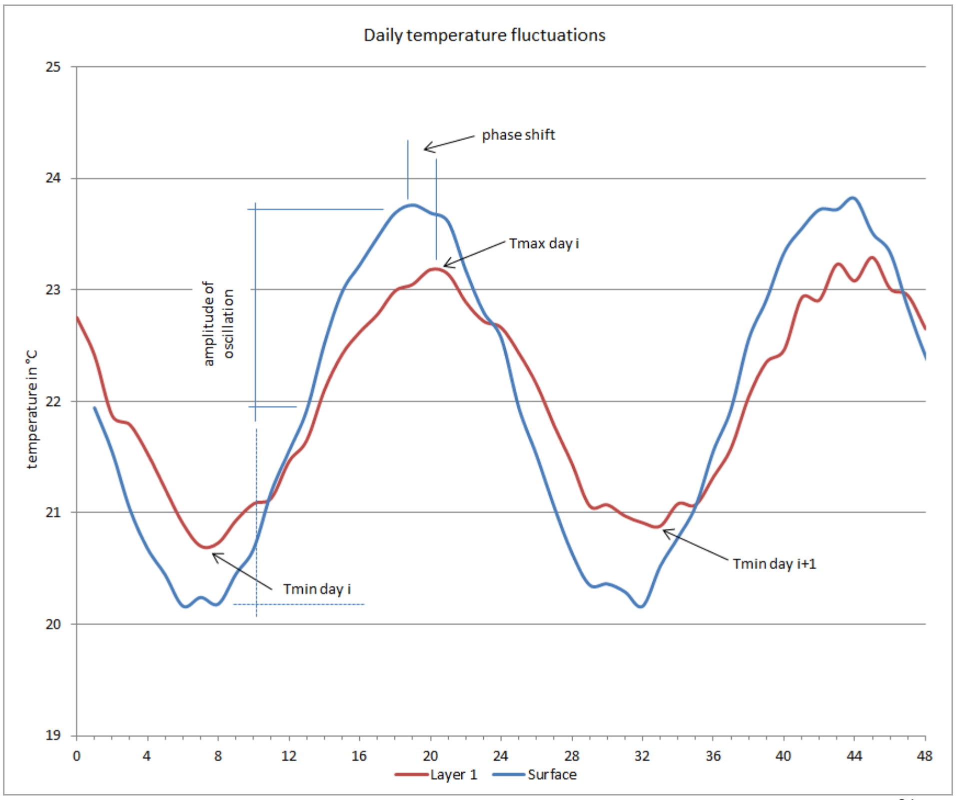


Figure 84: Example of daily temperature fluctuations at the surface and inside a slab[34]

The evaluation in this project has been divided into the following steps:

1. Qualitative analysis of the measurement results (temperature and time variations)
2. Quantitative analysis including calculation of energy buffered in the layers measured by means of daily minimum and maximum temperatures
3. Analytical analysis using the one-dimensional heat transfer equation and comparison with the results of the quantitative analysis
4. Extrapolation and calculation of the energy buffered in the entire slab thickness of 20 cm based on the analytical analysis
5. Dynamic, thermal simulation of the test room to determine:
   - solar radiation onto the facade
   - solar radiation inside through the external windows
   - solar radiation absorbed on inside surfaces and
   - energy buffered in the concrete slab based on the energy balance calculation

34 For illustrative purposes only, not based on the measurement results.

6. Comparison of extrapolated and simulated values of the energy buffered in the 20 cm concrete slab
7. Simulation of the test room adapted to the constructive and technical standard of a new office building, in this project to the reference office zone, see chapter 3.

6.1.4 Theoretical background

The quantity of energy $q_{buffered}$ in each layer of the slab in the time period between its daily temperature minimum and the following maximum is calculated by:

$$q_{buffered} = m * \mathrm{c} * \Delta T \qquad \text{(Equation 13)}$$

With:

$q_{buffered}$	[Wh/(m²d)]	specific energy buffered in 24h
m	[kg/m²]	specific mass of layer (V * ρ); ρ of reinforced concrete is 2400 kg/m³
c	[Wh/(kgK)]	specific heat capacity; c of concrete is 1000 J/(kgK) = 0.278 Wh/(kgK)
ΔT	[K]	T_{max} - T_{min}, difference of daily max and min layer temperatures

The analytical analysis is based on the one-dimensional heat transfer equation:

$$\rho c \frac{\delta T}{\delta t} = -\frac{\delta}{\delta x}\left(-\lambda \frac{\delta T}{\delta x}\right) \qquad \text{(Equation 14)}$$

With:

T	[°C, K]	temperature
t	[s]	time
λ	[W/(mK)]	thermal conductivity

The temperature profile inside the slab can be calculated as a response to the temperature profile at the surface by using the heat transfer function. The temperature profile at the surface $T_{surf}(t)$ is approximated by the following oscillation [Hagentoft]:

$$T_{surf}(t) = T_A * \sin(\frac{2\pi t}{t_p}) \qquad \text{(Equation 15)}$$

With:

T_A	[°C, K]	temperature amplitude at a time t
t_p		time period of the variation

Assuming constant material characteristics for the thermal conductivity λ(W/(mK)), the specific heat capacity c(J/(kgK)) and the density ρ(kg/m³), the temperature profile inside the slab is reduced in amplitude and phase-shifted:

$$T(x,t) = T_A * e^{-\frac{x}{dp}} * \sin(\frac{2\pi t}{t_p} - \frac{x}{d_p}) \qquad \text{(Equation 16)}$$

With:

T(x,t)	[°C, K]	time- and position-dependent temperature inside the slab
T_A	[°C, K]	temperature amplitude
$e^{-x/dp}$		reduction factor of the temperature amplitude inside the slab
d_p	[m]	periodic penetration depth
t	[s]	time
t_p		time period of the variation (wavelength), 24h=86400sec
x	[m]	position inside the slab (depth)
x/d_p		temporal phase shift

Where the periodic penetration depth d_p (m) is given by:

$$d_p = \sqrt{\frac{a\, t_p}{\pi}}; \qquad \text{(Equation 17)}$$

With:

a [m^2/s] thermal diffusivity according to:

$$a = \frac{\lambda}{\rho c} \qquad \text{(Equation 18)}$$

In case of constant λ and ρc the thermal diffusivity shows how fast the temperature changes are sustained in a material. The temperature amplitude inside the slab at a depth of x is reduced by the factor $e^{-x/dp}$ and the temporal phase shift is denoted by x/d_p when compared to the temperature at the surface. At the depth d_p the temperature amplitude is reduced to 37% [Hagentoft]. The author concludes that the temperature solution is valid as long as the thickness of the slab, d, is much greater than the periodic penetration depth d_p, at least as long as $d > 2*d_p$. For concrete the material values defined by [Hagentoft] are:

Table 26 Material properties of concrete

Material	λ in W/(mK)	ρc in J/(m^3K)	a in m^2/s
concrete	1.7	$1.8 * 10^6$	$1.0 * 10^{-6}$

In consequence, the periodic penetration depth d_p for diurnal (t_p=24h) temperature variations in concrete is 0.15 m [Hagentoft].

6.2 Metrological investigations

The measurements took place between 18 July to 13 September. This time period was characterised by several sunny days with high temperatures and high solar radiation. The amount of global radiation was mainly above 700 W/m^2 (direct radiation above 600 W/m^2).

6.2.1 Analysis of the measurement results

The temperature profiles of the surface temperature and the temperatures in layers 1 and 2 of all the drill holes showed very similar results and no outliers occurred. Therefore the measurement results will be presented using the example of drill hole 1 which has a distance from the facade of approx. 2.30 m. Two different weeks have been chosen to present the results of the first evaluation steps and a time period of one month for the analytical analysis of the energy buffered in the entire slab compared with the simulation results.

6.2.1.1 Qualitative analysis

The analysis has been focussed on one very sunny week with high temperatures, from 18 to 24 July 2015 and one week with cloudy days (three days with less than 300 W/m^2 direct solar radiation), from 2 to 8 September 2015. The week in July is hereinafter referred to as “Week1” and the week in September as “Week2”. To evaluate the effect of night ventilation three casements of the window elements (equal to 3.15 m^2 of the total window area of 10.43 m^2) were left open from 6.30 pm on 21 July until 9.30 am on 22 July (“Week1”). The daily variations of global and direct solar radiation, the ambient and the room air temperature of both weeks are presented in figure 85 and figure 86.

The maximum daily temperature of both ambient and room air temperature occurs in the late afternoon and the minimum temperature occurs in the early morning. The room air temperature varies considerably during sunny days and the variations are much lower on cloudy days, for example from 5 to 7 September ("Week2").

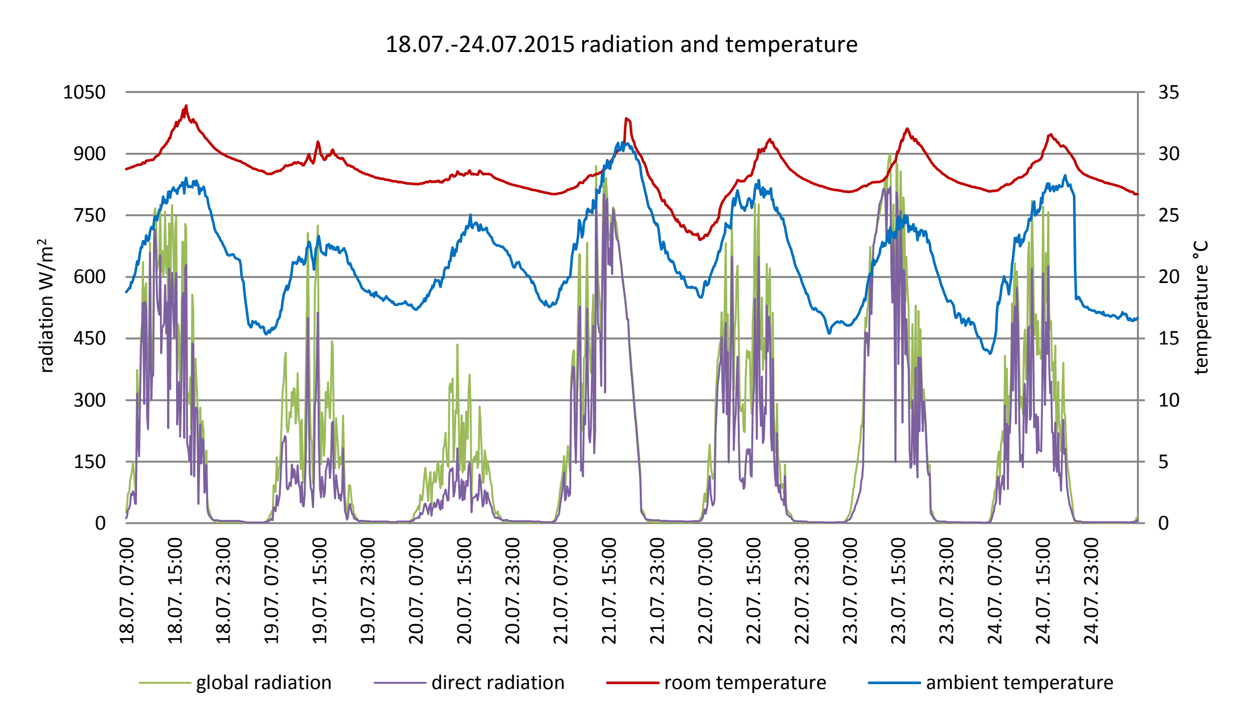


Figure 85: Solar radiation, ambient and room air temperature during "Week 1"

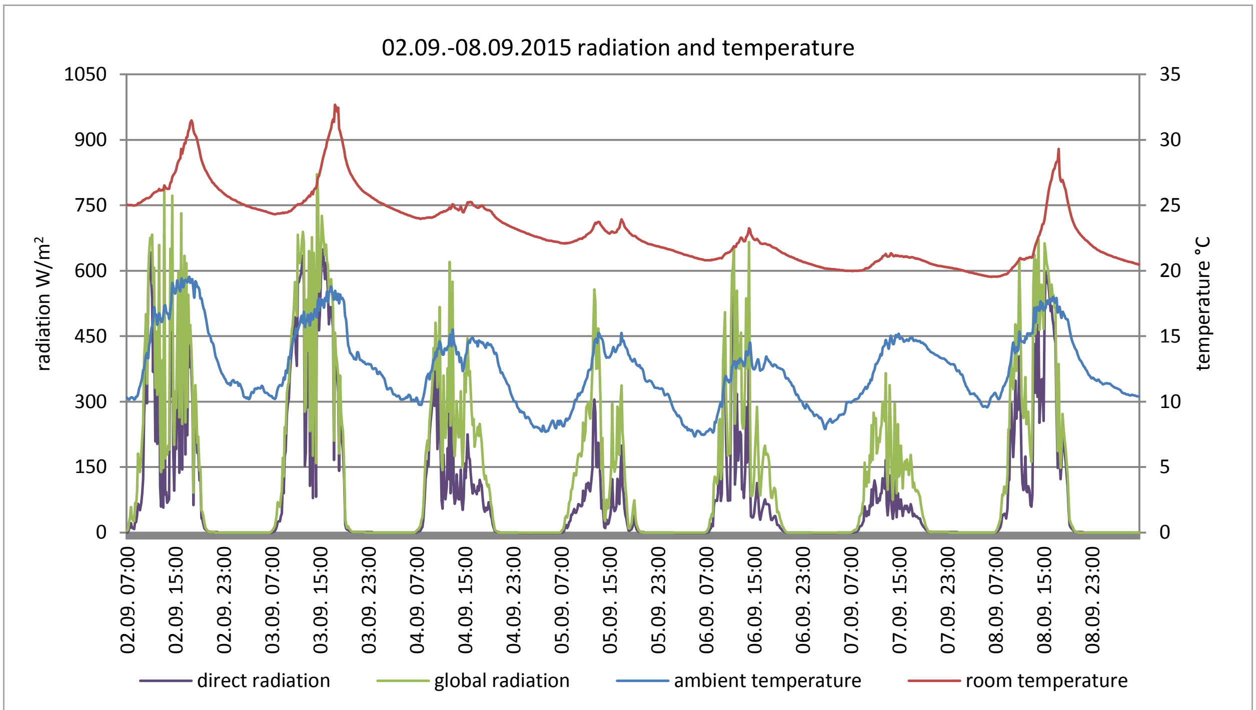


Figure 86: Solar radiation, ambient and room air temperature during "Week 2"

The following graphs present the daily temperature fluctuations of the room air temperature, the surface temperature and the temperatures inside the concrete slab of layers 1 and 2, see figure 87 and 88. The temperature fluctuations inside the slab are slightly diminished compared to the surface temperature and the temperature differences between the surface and layers 1 and 2 are low. The impact of night ventilation from 21 to 22 July is obvious and causes a room air temperature decrease of 4 K compared to the other nights during “Week1”. In “Week2” the temperatures inside the office and the slab are lower due to less solar radiation and lower ambient temperatures.

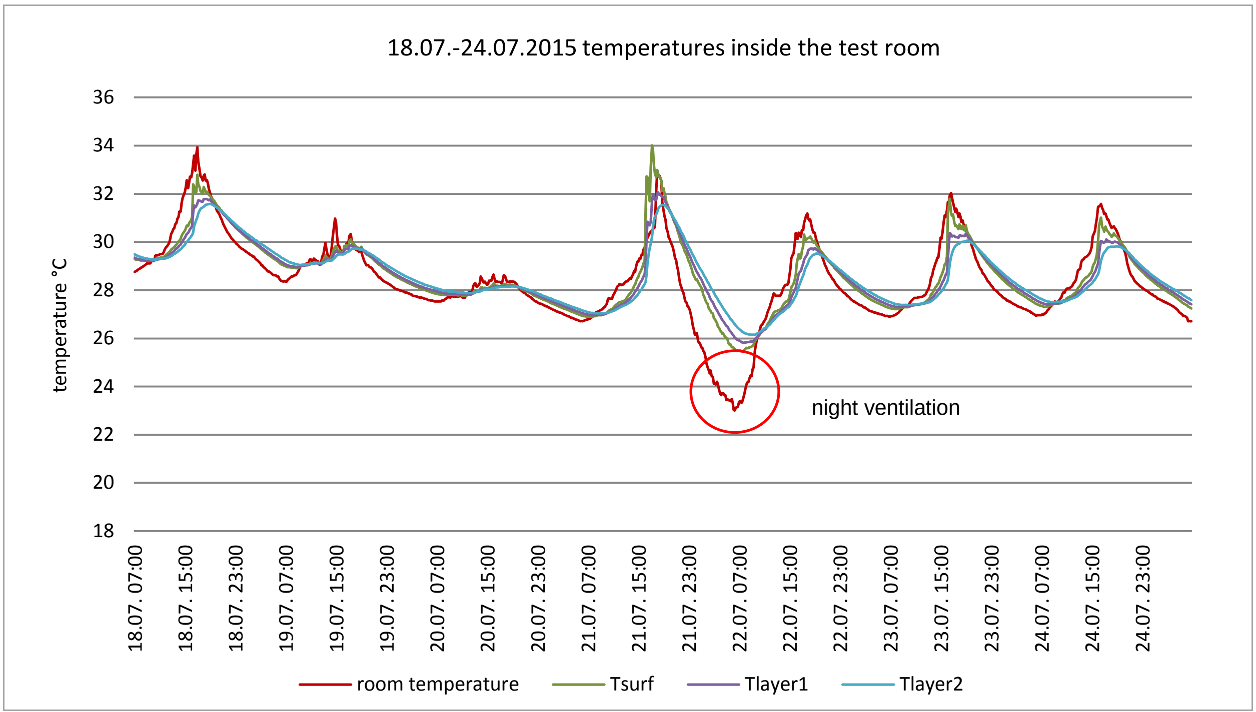


Figure 87: Room air temperature, surface and layer 1 and 2 temperatures during “Week 1”

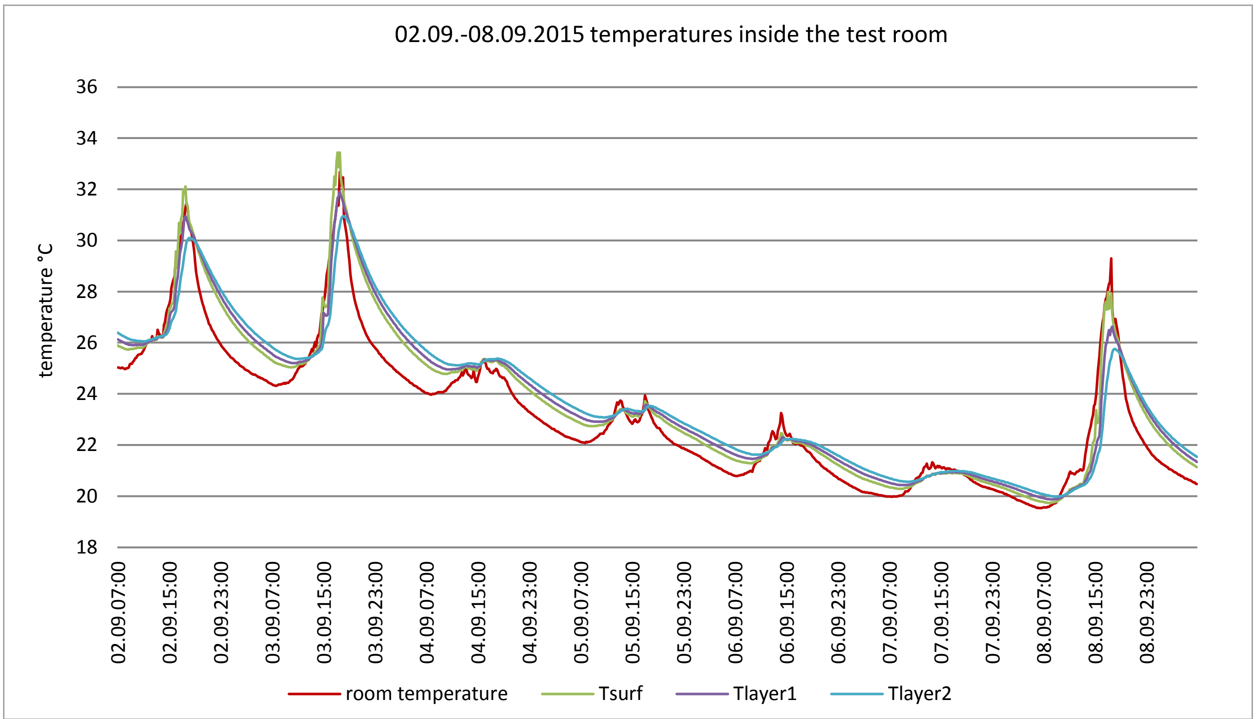


Figure 88: Room air temperature, surface and layer 1 and 2 temperatures during “Week 2”

The room air temperatures in the test room in the hot and sunny “Week1” are always above 26 °C with an average value of 28.42 °C. The average value in “Week2” is 23.20 °C. The temperature difference of the daily maximum values between surface and layer 1 is approx. 0.6 K to 0.9 K (average values) and between surface and layer 2 approx. 1 K. The phase shift between surface and layer 1 and 2 varies greatly, see table 27. The temperature difference and the phase shift are lower in the less sunny “Week2”.

Table 27: Measurement results based on qualitative analysis

Definition[35]	Surface		Layer 1		Layer 2	
	Week1	Week2	Week1	Week2	Week1	Week2
Daily maximum temperature T_{max} (average of 7 days in °C)	31.19	26.57	30.31	25.96	30.05	25.61
Daily minimum temperature T_{min} (average of 7 days in °C)	27.54	22.80	27.64	22.96	27.76	23.11
Temperature difference between layer and surface (average of daily T_{max} in K)	/	/	0.88	0.61	1.13	0.96
Phase shift of daily T_{max} (average value in min)	/	/	56	24	121	56
Daily temperature difference of T_{max}-T_{min}; heating up (average of 7 days in K)	3.65	3.77	2.67	3.00	2.30	2.49
Daily temperature difference of T_{max}-$T_{min, day+1}$; cooling down (average of 7 days in K)	-3.88	-4.28	-2.84	-3.45	-2.39	-2.87

6.2.1.2 Quantitative analysis

The quantity of energy buffered in layer 1 and 2 per day is 133 Wh/m^2 in “Week1” and 146 Wh/m^2 in “Week2” (average values of seven days). The influence of lower temperatures inside the room, for example when the windows were left open from 21 to 22 July (“Week1”) on the energy buffered in the slab is also obvious. The daily energy charge and discharge of both weeks is presented in figure 89 and 90.

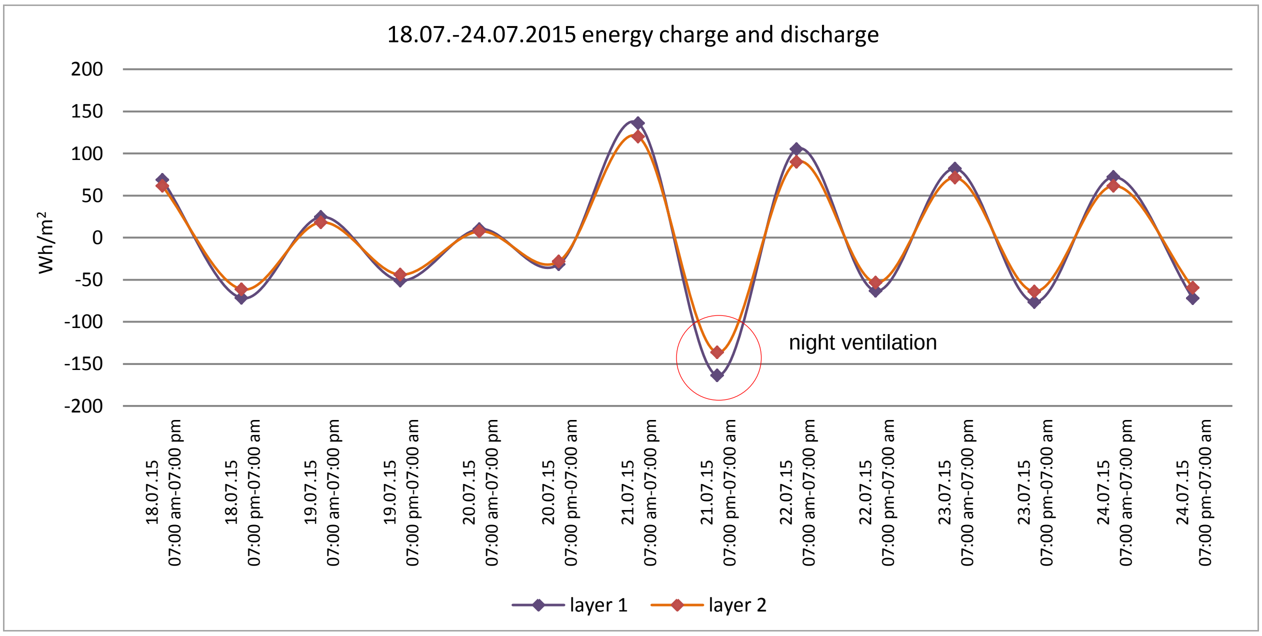


Figure 89: Energy charge and discharge in layer 1 and 2 of the concrete slab in “Week 1”

[35] Time period of 24h from 07:00 am to 07:00 am.

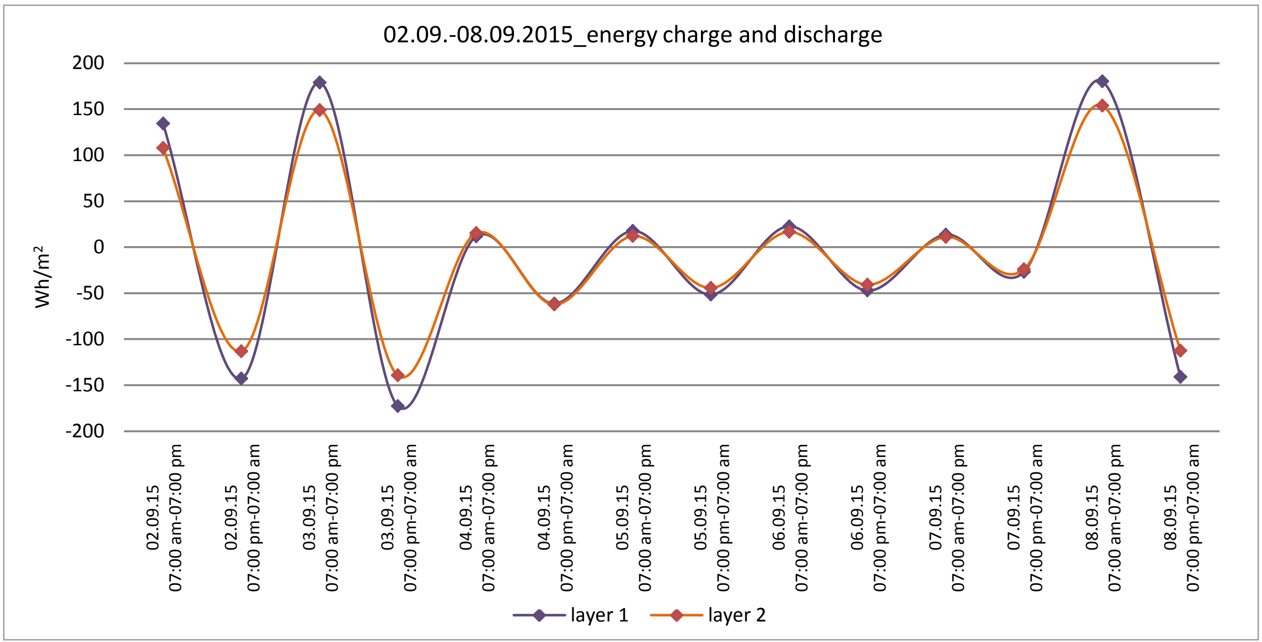


Figure 90: Energy charge and discharge in layer 1 and 2 of the concrete slab in “Week 2”

6.2.1.3 Analytical analysis

The temperatures measured at the surface have been fitted to a sine curve using the following approach:

- calculation of the measured daily average surface temperatures
- calculation of the average temperature amplitude TA per 24h (morning until the following morning), see illustratively figure 84 and the following equation:

$$T_A = 0.5 * \left(\frac{T_{max}(day_i) - T_{min}(day_i) + |T_{min}(day_i+1) - T_{max}(day_i)|}{2}\right) \quad \text{(Equation 19)}$$

- calculation of the daily surface temperatures, fitted by using equation 15 and
- analytical calculation of the temperatures inside layer 1 and 2, based on the fitted temperature profile at the surface by using equation 16.

The daily temperature variations and the phase shift between the surface temperatures and the temperatures in layer 1 and 2 are shown in figure 91 and 92. The values measured are compared to the values fitted based on the approach described above. The temperature profiles for the measured and fitted data are very similar in “Week1” and “Week2”.

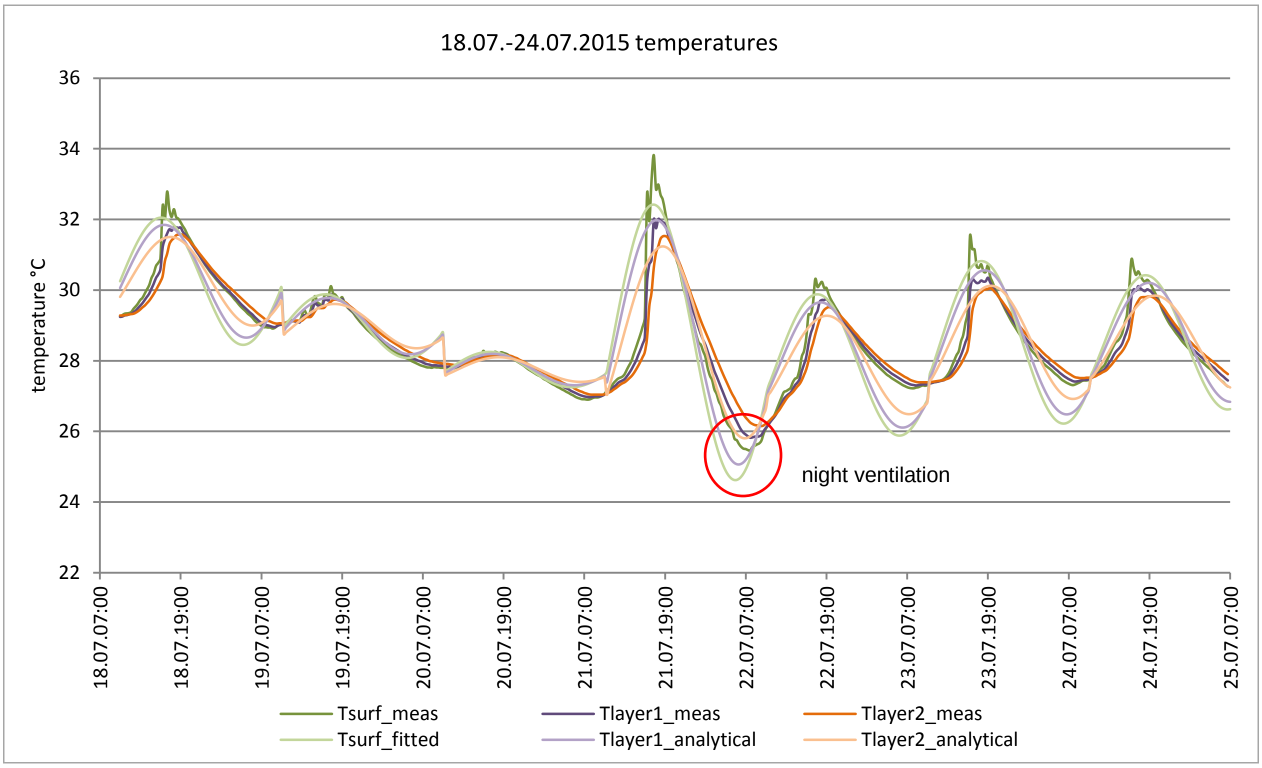


Figure 91: Measured and analytical temperature profiles during “Week 1”

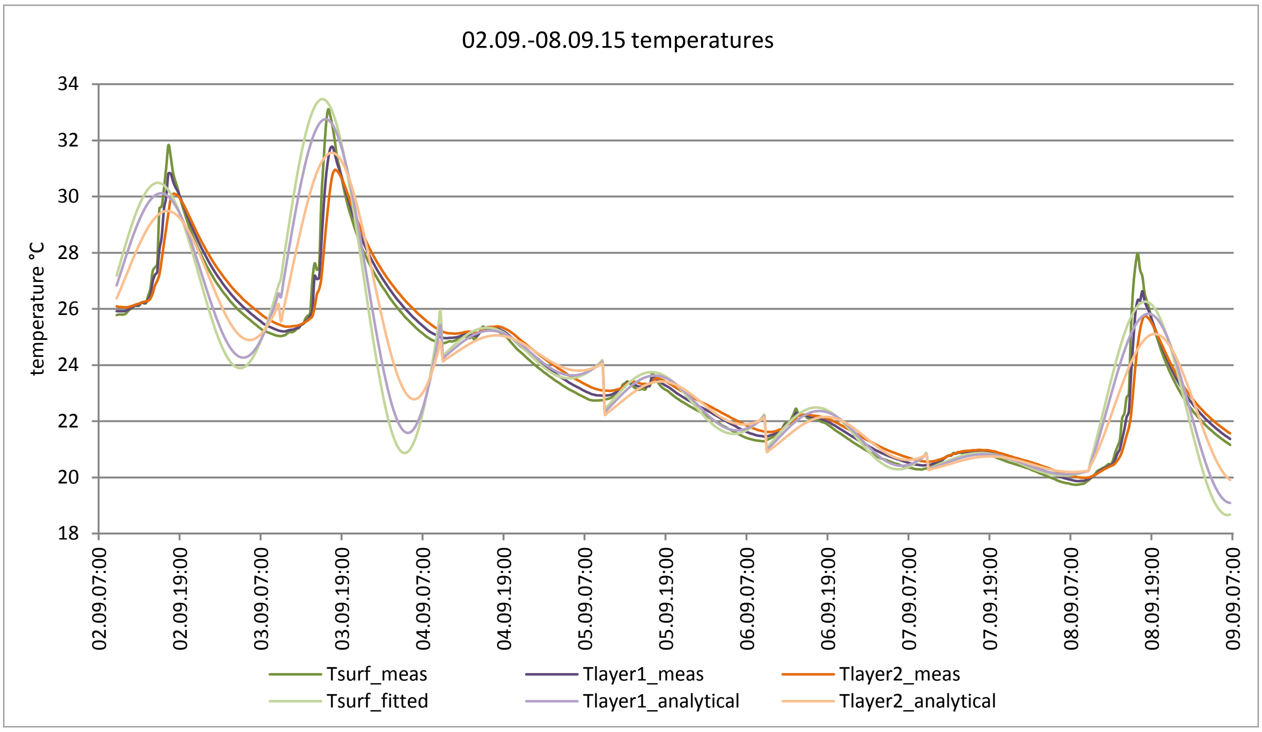


Figure 92: Measured and analytical temperature profiles during “Week 2”

The temperature profiles measured fit reasonably with the surface temperature fitted and the temperatures of layer 1 and 2 based on the analytical calculation. The temperature difference between the surface and layers 1 and 2 and the phase shift according to the analytical analysis are summarised in table 28.

Table 28: Values based on the analytical analysis

Definition	Surface		Layer 1		Layer 2	
	Week1	Week2	Week1	Week2	Week1	Week2
Temperature difference between the layer and surface (average of daily T_{max} in K)	/	/	0.23	0.32	0.57	0.79
Phase shift of daily T_{max} (average value in min)[36]	/	/	28	28	83	83
Daily temperature difference of T_{max}-T_{min} inside the layer (average of 7 days in K)	3.31	3.64	3.02	3.36	2.56	2.87
Daily temperature difference of T_{max}-$T_{min, day+1}$ inside the layer (average of 7 days in K)	-3.90	-4.97	-3.46	-4.37	-2.71	-3.44
Daily temperature amplitude at surface[37] based on measured data (average of 7 days in °C)	1.88	2.41	/	/	/	/

The temperature differences and the time shift of the data fitted are very similar to the data measured. As a consequence, the energy charged and discharged as determined by the fitted sinusoidal profiles also reasonably match the quantity of energy based on the measurements see figure 93 and 94.

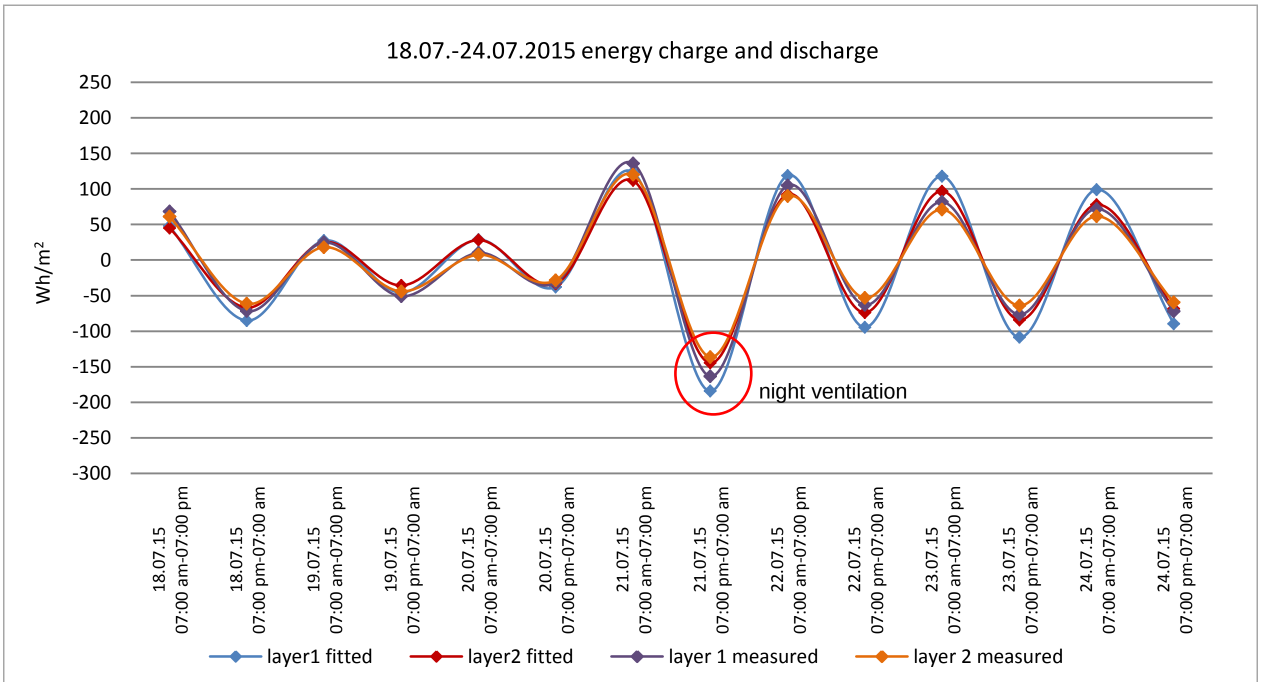


Figure 93: Energy charge and discharge based on measured and fitted values of “Week 1”

[36] The phase shift based on the fitted data is identical independently of the time period chosen.
[37] Time period of 24h from 07:00 am to 07:00 am.

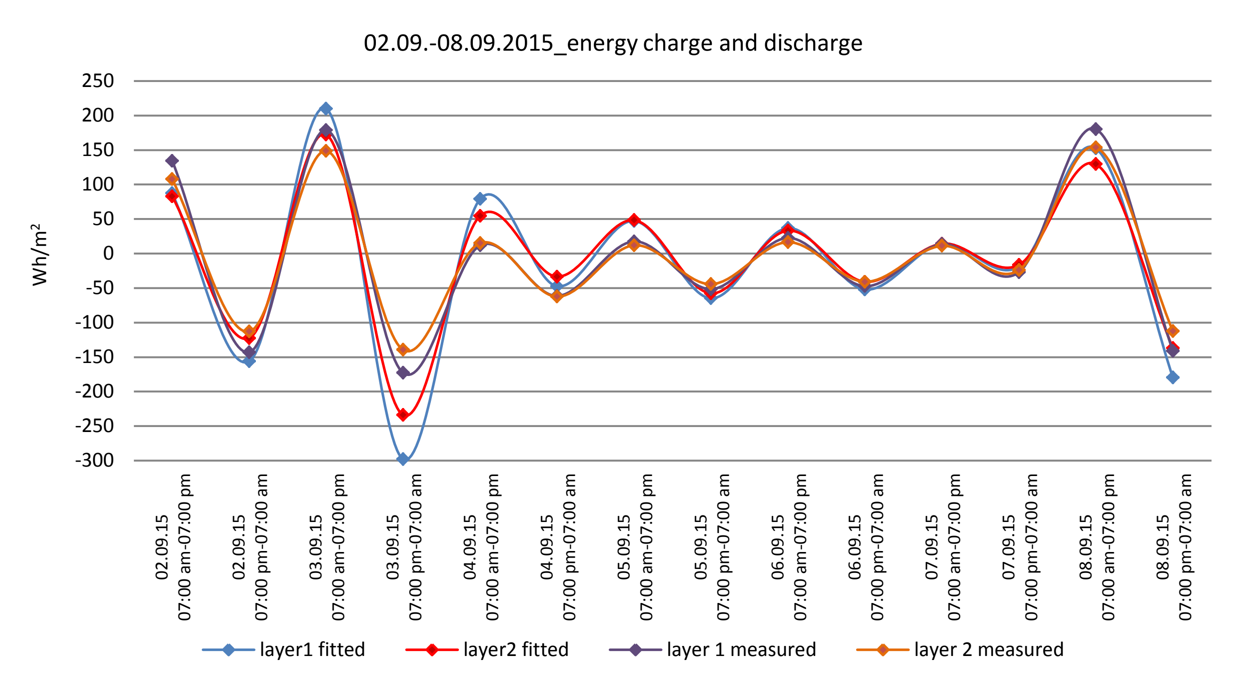


Figure 94: Energy charge and discharge based on measured and fitted values of “Week 2”

In consequence, an extrapolation based on the values of layer 1 and 2 is done to determine the quantity of energy buffered in the entire 20 cm concrete slab. An amount of approx. 300 Wh/m² to 350 Wh/m² a day can be buffered, see table 29.

Table 29: Energy buffered in the 20cm concrete slab in “Week1” and “Week2”

Energy buffered in concrete slab in Wh/m²	layer 1 + 2 (8cm) measured data	layer 1 + 2 (8cm) fitted data	Entire slab[38] (20cm) extrapolated data
Week 1 (sunny) daily average values	133	149	295
Week 2 (cloudy) daily average values	147	166	347
Daily maximum value	/	/	860
Daily minimum value	/	/	80

Further analysis of two sunny and two cloudy weeks during the measurement period has shown that in the entire slab (layer 1 to 5) a maximum value of 860 Wh/m² a day can be achieved during a sunny period and a minimum value of 80 Wh/m² a day during a cloudy period.

6.2.2 Evaluation

The quantity of energy buffered in a 20 cm concrete slab during a day of approx. 300 Wh/m² to 350 Wh/m² represents a considerable amount. These quantities have been stored and discharged when there is a building with low insulation and less airtightness and with high infiltration and transmission losses. The question is how the quantity of energy will change in a

[38] It has to be taken into account that the slab (layer 5) could be influenced by the thermal conditions of the room below which is characterized by the same properties (suspended ceiling) and thermal conditions. However, no control of temporary use or opening of doors and windows is given during the measurement period.

highly insulated and airtight new building with nearly zero losses and additionally high internal gains. Therefore a thermal simulation of the test room and an iterative adjustment to the constructive and technical standard of the reference office zone was carried out, see chapters 3 and 4.1.

6.2.3 Thermal simulation of the test room

The dynamic, thermal simulation of the office has been conducted using TRNSYS, 17.01 (2012). The aim is to cross-check the measurement results by the simulation and to corroborate the thermal storage capacity extrapolated for the 20cm concrete slab. A 3D-simulation model of the office was created to analyse the solar radiation distribution, the room conditions and the energy buffered in the slab. The weather data used were measured outside on site next to the test room for the period from 17 July to 13 September 2015. The data measured includes:

- global solar radiation in W/m^2
- direct solar radiation in W/m^2
- ambient temperature in °C
- relative humidity in %.

The properties of the test room simulated are identical to the values given in table 25 and the boundary conditions have been defined as identical to the adjacent zones. The simulated room air temperature and the surface temperatures show the same tendencies as the values measured but with diminished fluctuations. The simulation model, based on the global solar radiation measured, provides the amount of total and direct solar radiation on the facade south-west orientated in W/m^2, additionally the total short-wave radiation through the external window and the total solar radiation (direct and diffuse) absorbed on all inside surfaces. According to the solar radiation distribution, the quantity of energy buffered in the slab Q_{total}, has been calculated using the following equation (energy balance of gains and losses).

$$Q_{total} = (\mathrm{Q_{absi}} + \mathrm{Q_{abso}}) - (\mathrm{Q_{comi}} + \mathrm{Q_{como}}) \qquad \text{(Equation 20)}$$

With:

- Q_{absi}: total radiation absorbed (and transmitted) on all inside surfaces of airnode (incl. solar gains, radiative heat and internal radiative gains, but not long-wave radiation from other walls)
- Q_{abso}: total radiation absorbed (and transmitted) on all outside surfaces of airnode (incl. solar gains, radiative heat and internal radiative gains, but not long-wave radiation from other walls)
- Q_{comi}: energy from inside surface incl. convection to the air and long-wave radiation to other surfaces
- Q_{como}: energy to the outside surface incl. convection to the air and long-wave radiation to other surfaces

6.2.3.1 Time period of one week

The solar related simulation results of the test room are shown by the example of “Week1”, see figure 95 and 96.

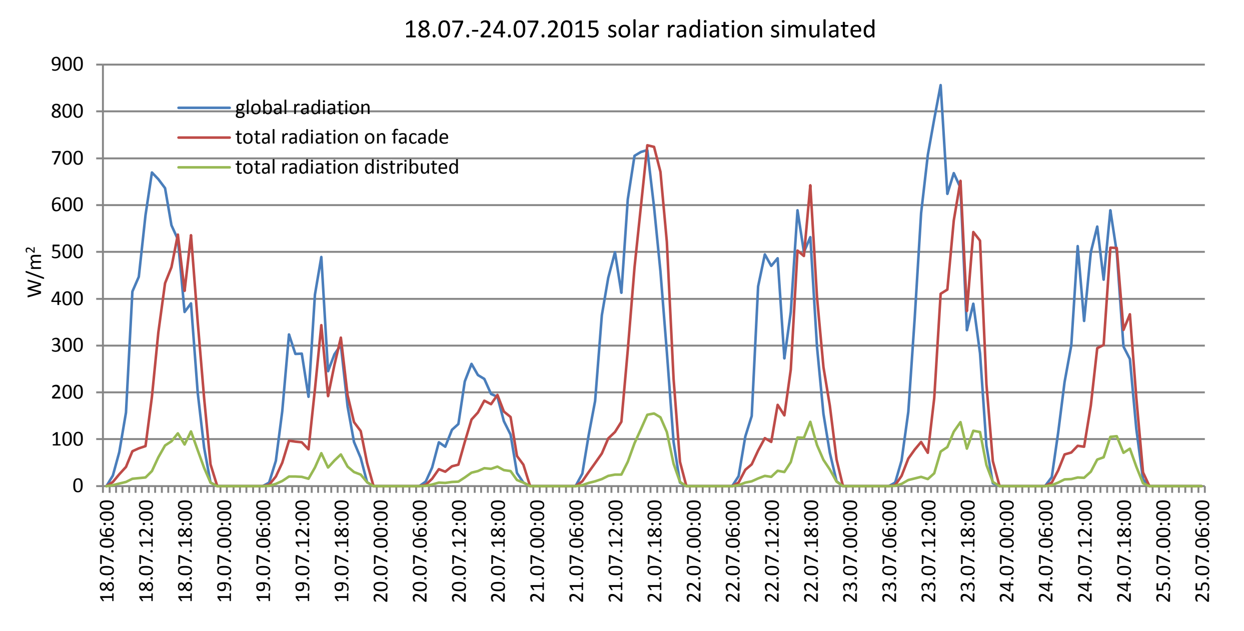


Figure 95: Simulation results for global solar radiation on the facade and inside the office

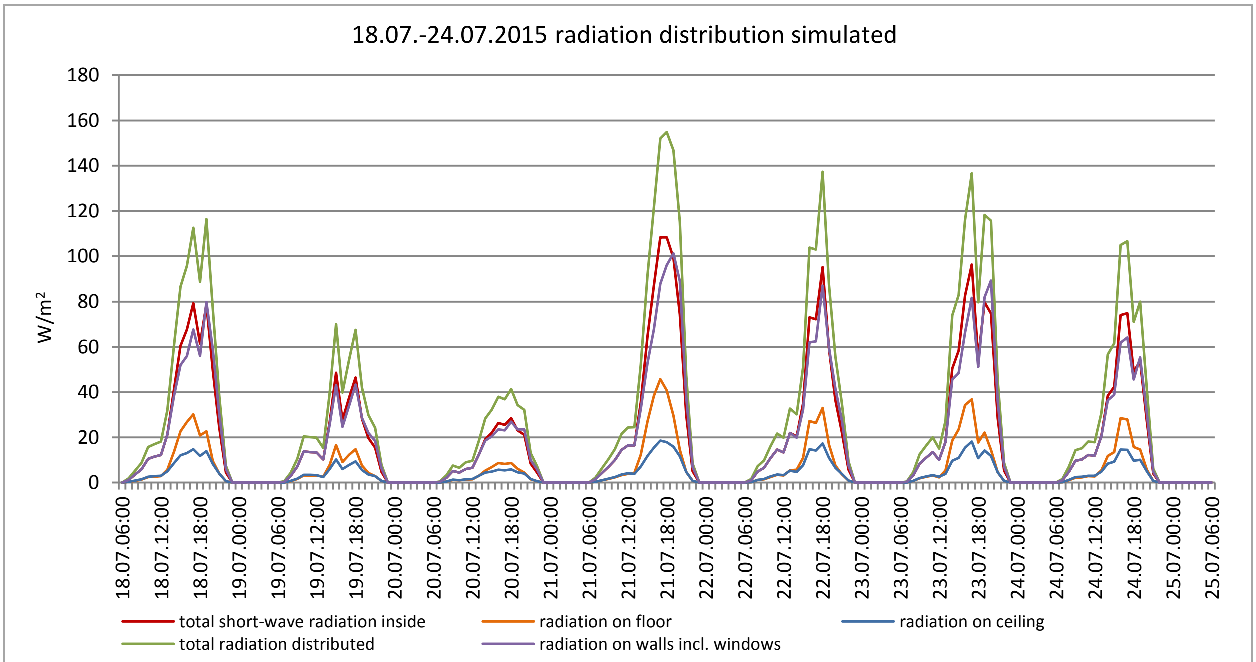


Figure 96: Simulation results for solar radiation distribution inside the office

The total solar radiation distributed and absorbed on all inside surfaces represents a proportion of approx. 15% to 20% of the outside global radiation on the horizontal. In case of a suspended ceiling the share of the solar radiation absorbed by the floor is more decisive when compared to the ceiling. If the slab is not covered the amount of radiation absorbed by the floor and the ceiling is similar.

The quantity of energy buffered in the 20cm concrete slab, based on the solar radiation distribution of the simulation model is lower than the quantity extrapolated based on the measurements. It has an average value of 225 Wh/(m^{2}d) in "Week1" and 213 Wh/(m^{2}d) in "Week2".

6.2.3.2 Time period of one month

To evaluate the quantity of energy buffered over a longer time period, a further investigation was carried out from 13 August to 9 September 2015, which is denoted as "Month1" (28 days). This month is characterised by sunny and cloudy periods. The average room air temperature is 25.05 °C. The graphical overview represents average values of each day (D) and night (N) of the ambient and the room air temperature measured, and the energy variations based on the analytical analysis as well as on the thermal simulation of the test room, see figure 97.

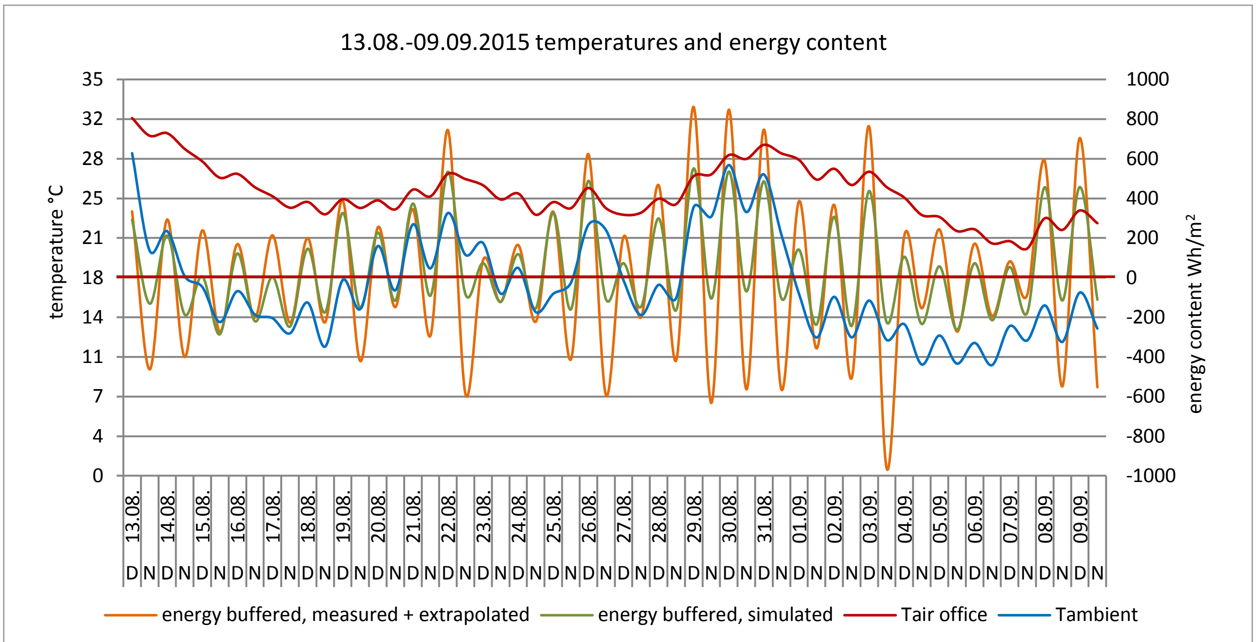


Figure 97: Daily temperature variations and energy content during a one month period

The quantity of energy buffered in the slab in "Month1" has a value of approx. 390 Wh/(m^{2}d) based on the extrapolated values of the measurements (analytical analysis) and an average value of 260 Wh/(m^{2}d) simulated (energy balance).

The variations of energy charge and discharge are similar. However, deviations of the simulation results are obvious when compared to the extrapolated values, mainly on days when the daily temperature amplitudes are higher. One reason for these simulation model deviations could be lower temperature variations, a homogeneous solar radiation distribution and consequently homogeneous heat flows inside the slab without boundary effects. Despite these facts, the results presented are physically plausible and suitable for analysing the thermal storage capacity of the slab when there are identical constructive and technical properties, for example, as in a highly insulated and airtight building.

6.2.4 Comparing the test room and reference office zone

The aim is to answer the question how the quantity of energy buffered in the 20 cm concrete slab in the test room will change in the course of an iterative adjustment to the constructional standard of the reference office zone presented in chapter 3 and the technical performance as described in chapter 4.1. The performance of the test room should be similar to that of a new, highly insulated office representing high internal gains and a natural ventilation system using passive cooling effects. The further thermal simulations are based on the following adjustment steps:

1. internal gains considering four work stations (approx. 10 m^2/person) and artificial lighting including a solar-radiation-based control system
2. external shading device (opaque fraction 70%) including a solar-radiation-based control system
3. natural ventilation strategy similar to VENT_NAT, see chapter 4.1.6.1 using passive cooling effects (no active cooling)
4. replacing the existing building envelope with a highly insulated and airtight envelope, replacing the old window elements with highly insulated windows with a triple glazing.

The thickness of the slab remains unchanged while the suspended ceiling (SC) has been removed (WSC) in the adjustment process. The evaluation was focussed on the existing test room simulated as measured and on the same room simulated according to the standard of the reference office zone. The quantity of energy buffered in the 20 cm concrete slab of “Week1” and “Week2” are presented in table 30.

Table 30: Quantity of energy buffered in the slab of the test room and according to the office zone

Definition	Test room simulated as measured		Test room simulated according to the standard of the reference office zone	
Average values	Energy buffered in the slab in Wh/(m^2d)		Energy buffered in the slab in Wh/(m^2d)	
Slab type[39]	SC	WSC	SC	WSC
Week1 (sunny)	225	151	160	87
Week2 (cloudy)	213	149	119	77

The quantity of energy based on the simulation results could be up to 225 Wh/(m^2d) in a sunny and warm summer period. When the test room is simulated according to the standard of the reference office zone, the energy buffered in the slab is reduced by approx. 38% to values between 120 Wh/(m^2d) and 160 Wh/(m^2d). By omitting the suspended ceiling, the quantity of energy is additionally reduced by approx. 42%. This is evoked by the change of solar radiation distribution inside the room and in consequence by the energy balance of gains and losses inside the slab.

In a new, highly insulated building with high internal loads, efficient sun protection and an enhanced natural ventilation strategy using passive cooling effects, the 20 cm concrete slab buffers less energy than in the poorly insulated building (test room) without shading devices. The temperature variations and in consequence the charging and discharging process inside the slab are diminished due to enhanced daytime ventilation.

[39] SC means suspended ceiling, WSC means without suspended ceiling.

6.2.5 Summary

Heat loads resulting from internal and solar gains in an office building above 250 Wh/(m^2d) are substantial and the building generally requires active cooling [Zimmermann]. The author stated that a 30 cm concrete slab will be merely warmed up by an average of 1 K when there are heat loads of approx. 225 Wh/(m^2d) and that a concrete slab can buffer up to 180 Wh/(m^2K). In comparison a light partition walls of gypsum can only buffer up to 18 Wh/(m^2K) [Zimmermann]. A heavy construction of 500 kg/m^2 is recommended when daily heat loads reach up to 300 Wh/(m^2d) [ABP]. Providing that night cooling is possible, the thermal storage capacity of the building mass should be able to buffer 40% to 60% of the total heat loads in summer [ABP].

The existing test room as measured has no internal gains, but the solar gains result in heat loads of 430 Wh/(m^2d)[40]. The test room simulated according to the standards of the reference office zone results in approx. 350 Wh/(m^2d) produced by 260 Wh/(m^2d) internal but only 90 Wh/(m^2d) solar loads due to efficient sun protection. A simulation model of the office zone, used in the previous parameter study, which was highly insulated[41] and included an external shading device and a natural ventilation system (VENT_NAT) resulted in approx. 340 Wh/(m^2d) heat loads produced by 220 Wh/(m^2d) internal and 120 Wh/(m^2d) solar loads. The results are very similar and show that heat loads between 300 Wh/(m^2d) and 360 Wh/(m^2d) are realistic values in new office buildings. The results from the measurements and the analytical analysis show that a 20 cm concrete slab can buffer a similar amount of energy, between 300 Wh/(m^2d) to 350 Wh/(m^2d). However, the test room results based on the thermal simulations are slightly lower. One reason for this could be, see also chapter 6.2.3 above, lower temperature variations, homogeneous solar radiation distribution and as a result homogeneous heat flows inside the simulation model slab. When the test room was simulated as a new building, the slab buffers up to 160 Wh/(m^2d) which corresponds to more or less 50% of the daily heat loads. The weight of the 20 cm concrete slab is approx. 480 kg/m^2 (nearly heavy construction), and in this case the requirements for passive cooling by natural night ventilation are fulfilled according to [ABP]. Heat loads of approx. 250 Wh/(m^2d) can be discharged by night cooling when the ambient temperatures are lower than 16 °C and night cooling is efficient, lasting a minimum of 5 hours with temperatures lower than 21 °C [Zimmermann].

The day-to-day temperature differences measured in layers 1 and 2 in the concrete slab of the test room are between 2 K and 2.7 K (daily minimum to daily maximum temperature). When compared with the statement of [Zimmermann] that concrete slabs can buffer up to 180 Wh/(m^2K) which means approx. 360 Wh/(m^2K) corresponding to 2 K, the quantity of energy extrapolated for the entire slab is plausible and realistic.

[40] values taken from a simulation model based on the weather data measured

[41] SOLID 1 without suspended ceiling, ratio of window area 77%, triple thermal insulation glass (EW1), south-west orientated

6.3 Conclusion

The metrological investigation approach, the results from the further analyses and the thermal simulations presented here have revealed interesting findings about:

- the temporal development of temperature variations inside a concrete slab
- the quantity of energy buffered in a slab (thermal storage capacity) depending on climatic conditions inside and outside the building
- the physical processes and the solar radiation distribution inside the test room.

The results presented are plausible and can be explained from a building physics point of view. They have confirmed that the thermal storage capacity of building materials and the addition of natural ventilation using passive cooling effects are decisive parameters for thermal comfort in summer. A huge part of heat loads resulting from internal and solar loads can be buffered in massive constructions and discharged by efficient night ventilation. A 20 cm concrete slab, representing a weight of 480 kg/m^2, can be activated to its core when it is uncovered. The measurement results have shown a remarkable temperature increase inside the first eight cm of the slab, and the results of the analytical analysis have revealed a temperature increase inside the entire slab.

A weight that is comparable to the 20 cm concrete slab which was tested is provided by the integrated floor beam system with profiled sheeting and concrete (weight 470kg/m^2) termed STEEL 2a and the system with precast concrete elements (weight 550 kg/m^2) termed STEEL 2b, see table 8, chapter 4.1.5. The parameter study has indicated, that steel composite slab systems without a suspended ceiling could lead to energy demand and overheating hours similar to solid structures, see chapter 4.2.3. It can be assumed that these slab systems behave in a similar way to a concrete slab as regards energy charge and discharge processes.

7 Environmental Evaluation

Buildings have to meet high standards in order to be officially classified as being sustainable. Their ecological, economic and socio-cultural quality can be evaluated by means of national certification systems as explained in chapter 2.4.

The most important ecological objectives of sustainable building design are the reduction of resource utilisation and correspondingly of the related environmental impacts such as the greenhouse effect, ozone depletion, waste disposal and water consumption. From an economic point of view, buildings with a high flexibility, an efficient use of space, conversion feasibility and low operating costs are considered sustainable. The socio-cultural quality stems from an optimised thermic, acoustic and visual comfort as well as from a sophisticated noise- and fire-protection concept.
A life cycle assessment (LCA), which analyses the complete life cycle of a building and its single elements, is a crucial factor for the evaluation of the ecological quality. It examines the production of construction materials, the transport, the erection on site, the use phase, possible refurbishments until the dismantling and recycling of single building components.

7.1 Methodology

The selection of the most appropriate materials not only depends on the technical and economic aspects but strongly on the increasingly important factor of the associated environmental impacts of the materials [WSA, 2011]. In addition the quality of the building materials used has a strong influence on the total energy demand and the environmental impacts during the operation of a building.

A comparative environmental study has been carried out to determine the environmental impacts and the resource requirements of different materials and structural elements. The objective is to identify optimisation potential and alternatives for the material selection and to draw up appropriate recommendations. This enables the planner to evaluate not only the energetical but also the environmental impacts of design decisions already in the concept phase. The evaluation of the ecological quality is based on the reference building and its office zone, see chapter 3.

The environmental evaluation consists of five steps:

Step 1, the material level

- evaluation of a selection of materials of building components

Step 2, the component level

- comparison of defined exterior walls, supporting structures of solid and steel composite types and interior elements

Step 3, the facade system

- combination of exterior wall and window elements to a facade system in order to determine the impact of various window-to-wall ratios

Step 4, the building level

- comparison of case studies of the entire reference zone, consisting of supporting structure, facade system and interior elements

Step 5, comparison of energy and emission characteristic values

- the energy and emission characteristic values of the product phase of case studies will be set in relation to the values of the operational energy use of the office zone.

The values of the building operation are generated in the course of the energetical evaluations, see chapter 4.2. The energy characteristic values of the primary energy demand (PE) and the emission characteristic values of the global warming potential (GWP) are the indicators judged most relevant for a direct comparison between product phase and the values related to the operational energy use.

7.2 Reference zone and choice of material

Since the objective of this project is the ecological evaluation of the reference zone and not the optimisation from a structural point of view, each element of the reference zone is based on the same technical, statical and physical properties (system boundaries) e.g. performance of elements, thermal transmittance, load assumptions.

7.2.1 Reference office zone

The reference office zone can be applied to different types of building geometry and the commonly used office organisation concepts. It is located in an intermediate storey of a typical low- or medium-rise building with a rectangular floor plan. It has a gross floor area of 120 m^2, which provides a work space for about ten persons, see figure 98. The facade grid is 1.35 m and the construction grid has been designed according to structural calculations. The opaque parts of the exterior wall are highly insulated. The U-value is 0.17 $W/(m^2K)$. For detailed building information see chapter 3.

Figure 98: Floor plan and cross section of reference office zone

7.2.2 Structure type

The most commonly used materials for supporting structures are concrete, masonry, steel and reinforced concrete. Within the framework of this project typical solid and steel composite structure types have been analysed. They are already 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 system 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 optionally a suspended ceiling, see figure 99. The structural calculations of the steel structure types[42] recommend solutions with various column grids and slab types, see appendix 4.

The opaque element of the exterior wall is a non-bearing structure with a ventilated curtain wall (cold facades) as commonly used in office buildings. These elements consist of the wall element, insulation material as well as an interior finishing and an exterior ventilated cladding. Typical wall elements, one of the solid and one of the steel composite structure types, have been examined.

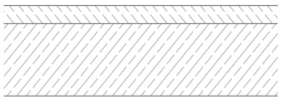
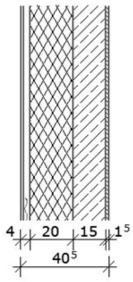
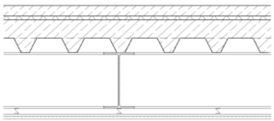
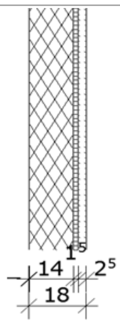
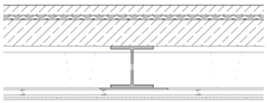
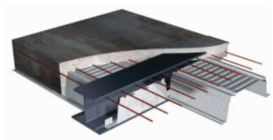
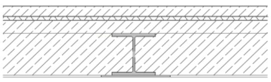
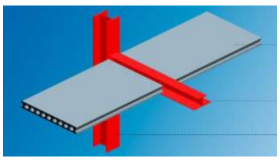
Structure type	Slab type	Sketch and image	Opaque part of exterior wall	
SOLID 1	solid reinforced concrete with screed	 		015 mm gypsum 150 mm concrete 200 mm insulation 030 mm sub-structure ventilated + cladding
STEEL 1	steel composite steel beams, profiled sheeting + concrete, floating screed, (suspended ceiling)	 		025 mm gypsum plaster board 015 mm oriented strand board 140 mm steel construction & insulation (optional 200 mm) + cladding
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)	 		

Figure 99: Structure types of the office zone

[42] calculated by M.Braun of ArcelorMittal

7.2.3 Window elements

In office buildings not only window elements are used but also curtain element facades or self-supporting frame constructions (post and beam systems) with transparent and opaque parts made of steel or aluminium. Detailed information about facade constructions can be found in chapter 2.7.1.

A self-supporting frame construction with a triple glazing has been chosen to evaluate the environmental impact of different window-to-wall ratios. The focus is on a punctuated facade with a ratio of 48% (F48), a band window facade with 77% (F77) and a fully glazed facade (F100), see figure 100. 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. The glazing has an U_g-value of 0.6 - 0.7 W/(m^2K).

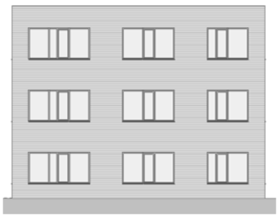
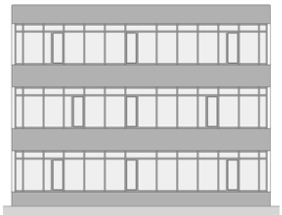
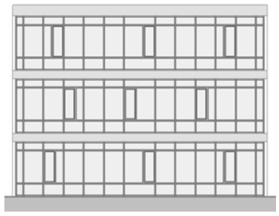
Type	F48	F77	F100
System			
Window ratio	48%	77%	100%

Figure 100: Facade systems of office building

7.2.4 Insulation material

The insulation materials of the exterior wall elements chosen are suitable for the installation in a curtain wall system of the solid as well as of the steel composite structure.

- mineral wool (rock wool)
- expanded plastic slab (PUR, polyurethane)
- expanded polystyrene (EPS)
- extruded foam (XPS, polystyrene).

The thickness of the insulation and the thermal conductivity group (WLG) depend on the U-value of the opaque exterior wall element, which was defined as 0.17 W/(m^2K) for both structure types. The calculation of the heat transition coefficient takes into account the air space according to [DIN EN ISO 6946].

7.2.5 Cladding of facade

The facade materials preselected are appropriate for the use as facade cladding in case they are typical for office buildings and can be combined with both structure types.

- fibre cement board
- glass fibre reinforced concrete panels
- flag (natural stone, e.g. granite and limestone)
- aluminium coffered panels
- steel coffer sheets
- sheet of aluminium folded profile 65/400
- sheet of steel folded profile 65/400

7.2.6 Elements of interior

The elements of the interior includes the non-load-bearing interior walls, made as metal stud partitions with double gypsum plasterboard finishing, and different floor and slab construction elements. The following elements are combined with the respective slabs of the structure types:

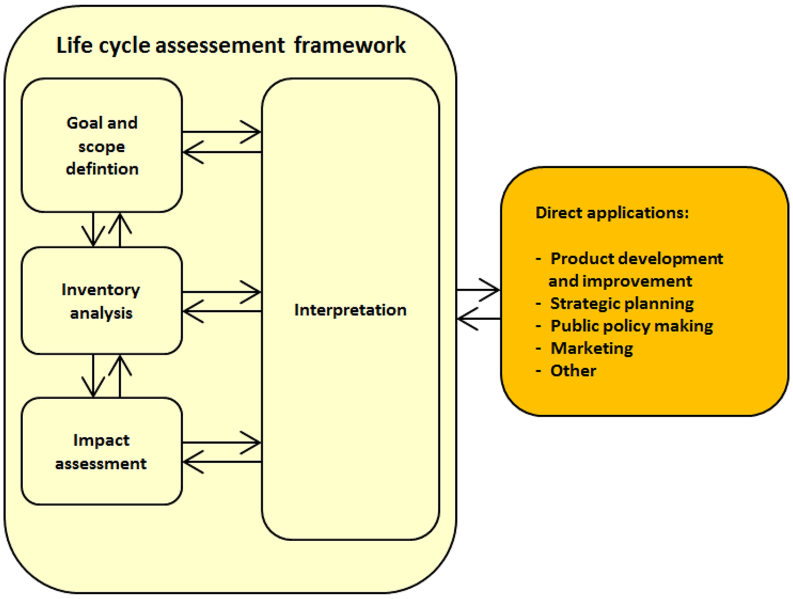
- a false floor system with a calciumsulfat board and a galvanised steel sub-structure
- a suspended ceiling with a double gypsum plasterboard and a galvanised steel sub-structure
- 70 mm cement screed with optional 30 mm sound insulation (rock wool) and
- 55 mm cement screed with 20 mm sound insulation (rock wool).

The floor covering and further finishing are not included. All selected construction materials are commonly used in office buildings, have a high market share in Luxemburg and all over Europe and can thus be regarded as being representative. Any information regarding their properties and applications in structural engineering has been taken from the information system on ecological building materials [WECOBIS] of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

7.3 Life cycle assessment

7.3.1 Structure

Life cycle assessment (LCA) is an internationally standardised methodology to quantify the environmental impacts of products taking into account benefits, trade-offs and improvements of the full life cycle of the product [EU, LCA] from the production to the end-of-life, the so called „cradle to grave“ principle [ISO 14040]. The international standards [ISO 14040] and [ISO 14044] regulate the procedure of an LCA. It is divided into four phases, see figure 101.



1. Definition of goal and scope
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Results and interpretation

Figure 101: Structure of LCA according to DIN EN ISO 14040

Additionally the international standard [ISO 21931-1] defines the objectives of the evaluation, the definition of the building’s life cycle, the definition of the system boundaries and the criteria to be evaluated.

7.3.2 Definition of goal and scope

In addition to an impact assessment of the single building materials the scope of this study also includes the analysis of various building components and supporting structures of the office zone. As a consequence the system boundaries of the building elements chosen have to be identical. The area unit of one square meter component surface is defined as functional unit, which serves as a base for the comparative analysis. Apart from the materials of step 1, the following elements of the office zone have been analysed in step 2:

- non load-bearing exterior wall elements (opaque part)
- self-supporting frame constructions with triple glazing
- supporting structures consisting of columns and slabs
- interior walls
- floor and slab construction elements (slab types).

The sub-structures, fixing and sealing materials have not been taken into consideration since their percentage by mass does not exceed 3% and thus it can be assumed that they have only little influence on the total result. Moreover, in the concept phase prior to the detailed planning process, these data are commonly not available.

Due to the fact that this study refers to a reference zone instead of a specific building, it is difficult to give generally applicable information on construction, utilisation and disassembly processes. The processes of these phases depend on the function of the relevant building component, the building concept and the implementation on site**.** However, on the basis of the available data a general illustration of the material flows is feasible for the product phase and frequently also for the recycling potential [BFS, 2010]. The end-of life status and thus the consideration of the recycling potential has increasingly gained in importance. Therefore, many databases and environmental product declarations (EPD) of various industrial associations or producers provide this information already for a huge number of materials.
This study is based on a manual “cradle to gate” analysis by means of a freely available, official database without using professional software. A detailed analysis of “cradle to grave” or “cradle to cradle” has not been carried out due to the lack of sufficient data. For those materials with sufficient data, however, the recycling potential (module D) has been taken into account. Since a direct comparison of materials with and without module D is not reasonable, in this analysis only materials and building elements with a certain base of evidence have been compared.

7.3.3 Choice of database

The data used in a life cycle assessment should be consistent, quality assured and should reflect actual industrial process chains [EU, LCA]. For the building sector a reliable environmental evaluation of the building materials depends strongly on the accessibility of the database and the availability of data for the whole life cycle. It is necessary to ensure the comparability of the data sets from lifecycle inventory analysis and impact assessment.

The data for this environmental evaluation have been taken from the “ökobau.dat” of the German BMUB (state of data May 2016), which is specialised on building materials. Missing data sets have been complemented by information gained from the environmental product declarations of the single industrial associations or producers and offered by the German institute “Bauen und Umwelt” (IBU). The creation of these data sets is based on common principles and subject to the same verification processes as the ökobau.dat.

7.3.3.1 German “ökobau.dat“ and environmental product declarations

The database “ökobau.dat” is a database designed for the ecological evaluation of building materials, construction and transportation processes [Ökobau.dat]. It contains data sets of the environmental product declarations of the IBU, which are generic and others that are specific to a manufacturer or association. The generic data sets meet the requirements of [DIN EN 15804]. This standard governs the calculation methodology, the choice of environmental indicators and the rules set up for the verification of environmental product declarations (EPD) with the objective to guarantee a harmonised, reliable and comparable creation of life cycle environmental information on a European and national level. This standard also introduces a new definition of environmental indicators and life cycle modules [BBSR]. Table 31 illustrates the definition of life cycle modules, which are assigned to the following processes:

- A1-A3 raw material supply, transport and manufacturing
- A4-A5 transport from the gate to the site and assembly
- B1-B7 use, maintenance, repair, replacement, refurbishment, operational energy use, operational water use
- C1-C4 de-construction, demolition, transport, waste processing, disposal
- D reuse-recovery-recycling potential.

Table 31: Definition of life cycle modules

Product phase	Construction process phase	Use phase	End-of-life phase	Benefits and loads beyond the system boundaries
A1 - A3	A4 - A5	B1 - B7	C1 - C4	D

Steel has shown that the data, especially those related to the recycling rate, have inconsistencies and therefore further data of the worldsteel association have been added besides the generic data of ökobau.dat and the EPD`s of the German “Bauforumstahl” (BFS).

7.3.3.2 Worldsteel data

The report supplied by the worldsteel association, see appendix 3, comprises the data of the main inputs and outputs of the steelmaking process and the following two environmental indicators:

- global warming potential (GWP 100 years), CML2001 - Dec. 07 in [kg CO2-eq.]
- primary energy demand (PE) from renewable and non renewable resources in [MJ]

The data are provided for the system boundary „cradle to gate“, including and excluding recycling for the following building products:

- hot dip galvanized steel (HDG)43, Europe average
- sections, Europe average
- rebars, World average.

[43] hot dip calvanised steel sheet (0,3-3,0 mm)

In line with the industry standard, an amount of scrap is taken into account in the production phase (A1-A3). Module D represents a benefit of further recycling potential (e.g. reuse). The data including recycling consider a debit for any steel scrap that has already been used in the steel making process and a credit for the steel that is recycled at the end of the products' life (EoL) avoiding virgin material for the production. This overall net scrap credit or burden of each product has been calculated to avoid double accounting [WSA, 2016] see appendix 3. The worldsteel methodology considers both factors in the closed material loop analysis where the net amount and the value of scrap are substracted from the „cradle to gate" product. The data have been generated based on worldsteel data collection and methodology and include steel production from the integrated route of Blast Furnace, Basic Oxygen Furnace and the Electric Arc Furnace route which is mainly based on steel scrap [WSA, 2011].

7.3.3.3 Database chosen for steel products

The data sets indicated above, cannot be directly compared as they are based on different methodologies. They will, however, be analysed in parallel to find the most suitable for the application in this study.

A life cycle assessment study of steel products should take into account the high recycling rate of steel products. The data of the worldsteel association and the generic data of the ökobau.dat consider a recycling rate of 95% (benefits of module D). However, a recycling rate of 99% is presented in the environmental product declaration for structural steel: sections and plates of the German "Bauforumstahl (BFS)" where 11% are defined as reuse and 88% as recycling. The credits of module D (reuse-recovery-recycling potential) are based on this calculation. The data of the ökobau.dat and the worldsteel association show similar values, especially in case of the sections which provide a large part of a steel composite structure, see figure 102. It has been decided to use the generic data of the ökobau.dat for the analysis of the steel products. The advantage lies in the fact that the data sets are based on the same methodology and will generate comparable results.

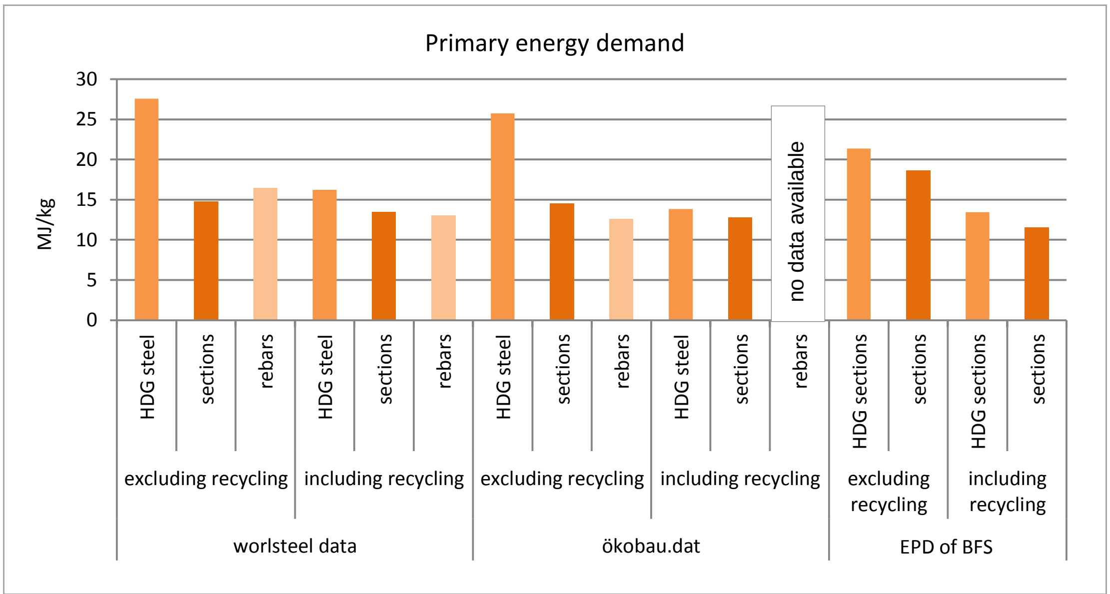


Figure 102: Primary energy demand of steel products of different databases

7.3.4 Life cycle inventory

The life cycle inventory (LCI) is the collection and development of data including all relevant mass flows, resource consumption (inputs), emissions and waste generation (output) which are associated with a product from the extraction of raw materials through production and use to final disposal, including recycling, reuse, and energy recovery [EU, LCA]. The database ökobau.dat provides this life cycle information in the shape of completed data sets.

A life cycle impact assessment (LCIA) determines the extent and significance of environmental impacts, potential damages of the eco-system or surveys on hazardous materials on the basis of the LCI data. It provides an estimation of indicators of the environmental impacts in terms of e.g. climate change, summer smog, resource depletion, acidification and human health effects and it is associated with the environmental interventions attributable to the entire life cycle of a product [EU, LCA]. In the database the LCI information is available as completed data set for a functional unit per mass, volume or surface unit.

7.3.5 Life cycle impact assessment

The international certification systems, as described in chapter 2.4, define the choice of the environmental indicators which should be used for the life cycle impact assessment (LCI). In this study the choice is based on the German system of sustainable construction for office buildings „Bewertungssystem Nachhaltiges Bauen“ [BNB]. The indicators to assess the resource requirements are:

- non-renewable primary energy demand (PE_{nren}) => method cumulative energy demand (CED) in MJ-eq.
- renewable primary energy demand (PE_{ren}) => method cumulative energy demand (CED) in MJ-eq.
- primary energy demand (PE) => addition of PE_{nren} and PE_{ren}

The indicators to assess the environmental impacts are:

- global warming potential, greenhouse warming potential (GWP) or CO_2- equivalent => method IPCC 2007 (Intergovernmental Panel on Climate Change) for 100 years (GWP 100 a) in kg CO_2-eq.
- ozone depletion potential, stratospheric ozone depletion (ODP) or R_{11}- equivalent => method CML 2001 (Institute of Environmental Sciences, Leiden University) ODP steady state in kg R_{11}-eq.
- photochemical ozone creation potential (POCP) or ethylene-equivalent => method CML 2001 (Institute of Environmental Sciences, Leiden University), category “high NOx POCP” in kg C_2H_4-eq.
- acidification potential (AP) or SO_2-equivalent => method CML 2001 (Institute of Environmental Sciences, Leiden University) in kg SO_2-eq.
- eutrophication potential (EP) or PO_4-equivalent => method CML 2001 (Institute of Environmental Sciences, Leiden University) in kg PO_4-eq.

The two abiotic indicators have recently been added to the standard [DIN EN 15804]:

- abiotic depletion potential for non fossil resources (ADPE) in kg Sb-eq.
- abiotic depletion potential for fossil resources (ADPF) in MJ-eq.

The environmental indicators can be distinguished in terms of their impact on a global, regional and local level. The global warming potential contributes to global climatic warming and in addition ozone depletion reduces the absorption of UV radiation and thus accelerates the warming of the earth's surface. Local environmental impacts that originate in production processes include acidification and eutrophication and the environmental damages involved. On a regional level one can find risks to human health caused by the so-called summer smog or the ozone creation potential.

Chosen indicators

The following study refers to the indicators listed above with a focus on the indicators primary energy demand (PE) and global warming potential (GWP). As an environmental evaluation should not be entirely based on these two indicators, a detailed analysis of the impact indicators ODPE, AP, EP and POCP has been carried out at material level. The results are not shown individually but by means of an overall indicator (I_{env}) which is part of the Luxembourgish sustainability certification for residential buildings (LENOZ) [Lichtmess]. It has been developed and revised during a study of the Luxembourg Institute of Science and Technology [Hild].

The overall indicator I_{env} is based on the harmonisation of the gross units of the materials (database ökobau.dat) and the aggregation of the environmental impacts GWP, ODP, POCP, AP end EP [Hild]. These five variables have been normalised by setting them in relation to the average emissions per capita in the European Union according to [Benini] and using weighting factors based on a study of [Huppes].

$$I_{env} = 1000 * (f_1 * \frac{GWP_{mat}}{GWP_{ref}} + f_2 * \frac{ODP_{mat}}{ODP_{ref}} + f_3 * \frac{POCP_{mat}}{POCP_{ref}} + f_4 * \frac{AP_{mat}}{AP_{ref}} + f_1 * \frac{EP_{mat}}{EP_{ref}}) \quad \text{(Equation 21)}$$

The following table 32 shows the reference values of the average emissions per capita of the European Union 2010 and the relevant weighting factors:

Table 32: Calculation of the environmental impacts of I_{env}

Environmental impact	Reference values EU25+3[44]	Unit per capita	Weighting factor[45]
GWP_{ref}	9.218	kg CO_2-eq.	$f_1 = 0{,}54$
ODP_{ref}	0.02	kg R_{11}-eq.	$f_2 = 0{,}09$
$POCP_{ref}$	32	kg C_2H_4-eq.	$f_3 = 0{,}12$
AP_{ref}	47	kg SO_2-eq.	$f_4 = 0{,}09$
EP_{ref}	1.48	kg PO_4-eq.	$f_5 = 0{,}16$

7.4 Environmental evaluation of the office zone

The environmental evaluation of the reference office zone can be divided into five steps:

- step 1, the material level
- step 2, the component level

[44] calculation of average emissions per capita of the European Union 2010 [Benini]
[45] weighting factors of I_{env} [Huppes]

- step 3, the facade system
- step 4, the building level based on the reference office zone
- step 5, comparison of energy and emission characteristic values of product phase and their correlation to the values of the operational energy use

7.4.1 Step 1, the material level

7.4.1.1 Insulation materials

Insulation materials suited for exterior wall constructions of the solid and the steel composite structure type have been analysed. The thickness of the insulation materials, their gross density and the thermal conductivity group (WLG), see table 33, were chosen in order to obtain an U-value of 0.17 W/(m^{2}K).

Table 33: Insulation materials of exterior wall

NO.	Insulation material	WLG	Thickness in mm	Density in kg/m^3
1	mineral wool (rock wool), low density	035	200	41
2	expanded plastic slab (PUR, polyurethane)	035/025	200/140	31
3	expanded polystyrene (EPS)	035	200	23
4	extruded foam (XPS, polystyrene)	035	200	35

The data available indicate the total primary energy demand and the environmental impacts for the product phase (A1-A3) as well as for the recycling potential (module D).

Total primary energy demand of insulation materials

The primary energy demand required for the production of insulation materials differs widely and only a minor share of renewable primary energy is used, see figure 103.

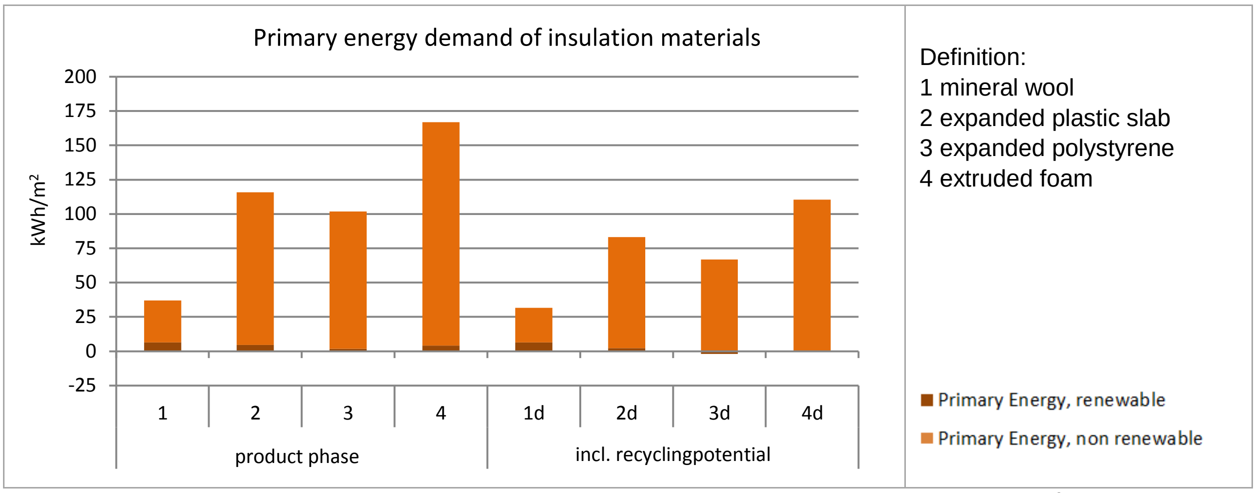
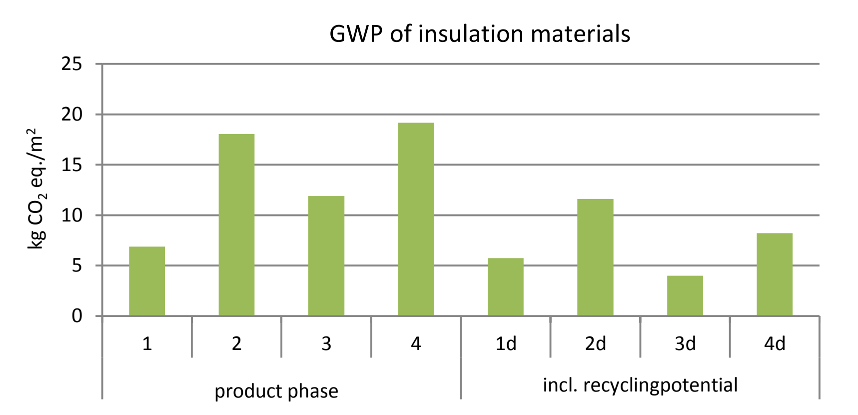


Figure 103: Total primary energy demand of insulation materials to achieve a U-value of 0.17 W/(m^{2}K)

Mineral wool has a lower primary energy demand compared to the synthetic insulation materials, even after taking into account the recycling potential. Expanded polystyrene (EPS) has the lowest demand of the synthetic insulation materials.

Environmental impacts of insulation materials

The benefits of mineral wool and EPS are also obvious regarding the global warming potential (GWP), see figure 104.

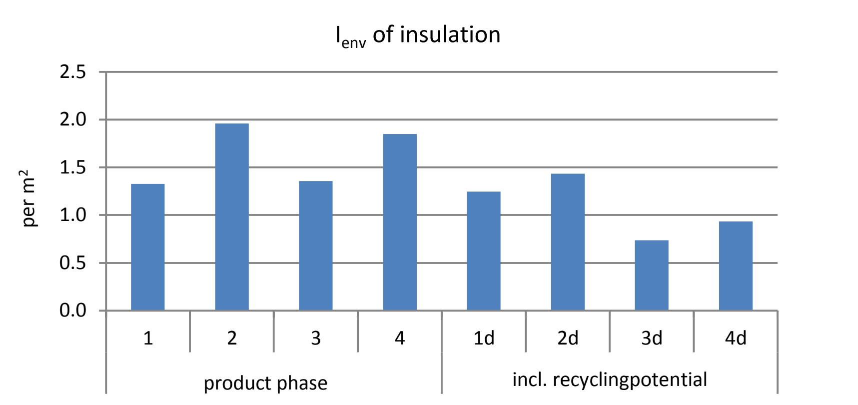


Definition:
1 mineral wool
2 expanded plastic slab
3 expanded polystyrene
4 extruded foam

Figure 104: Global warming potential of insulation materials

The CO_2 emissions of the synthetic insulation materials are higher due to the foaming agents used during the production process. However, when considering the recycling potential the GWP of EPS is lower than those of mineral wool. The higher recycling potential of synthetic insulation materials is caused by production waste of extruded polystyrene foam such as XPS and EPS which can be returned directly to the production process. Furthermore, these materials can be thermally recycled after their dismantling [ökobau.dat].

The overall indicator I_{env} of the environmental impacts leads to similar results. It shows the benefits of the higher recycling potential of synthetic insulation materials compared to mineral wool, see figure 105.



Definition
1 mineral wool
2 expanded plastic slab
3 expanded polystyrene
4 extruded foam

Figure 105: Overall indicator I_{env} of insulation materials

7.4.1.2 Cladding materials

The facade claddings chosen are technically feasible and commonly used for curtain wall systems, see table 34. The claddings have no direct influence on the physical properties of the exterior wall element. Therefore, a direct comparison of the facade materials is considered reasonable despite their different thicknesses.

Table 34: Cladding materials of exterior wall

No.	Cladding material	Thickness in mm
1	fibre cement board	12
2	aluminium coffer sheet	1.5
3	steel coffer sheets	1.5
4	flag (lime stone)	40
5	flag (granite)	30
6	glass fibre reinforced concrete panels	13
7	sheet of aluminium folded profile 65/400	0.7
8	sheet of steel folded profile 65/400	0.7

For the coffer sheets and the folded profile sheets of aluminium and steel a recycling potential (module D)[46] is included in this examination.

Total primary energy demand of cladding materials

The energy-intensive process with high electricity consumption for the production of aluminium requires a high amount of primary energy [Kolb]. The share of renewable energy, however, is also higher compared to the other facade materials. The production of fibre cement boards and flagstones of granite also lead to a high primary energy demand, see figure 106.

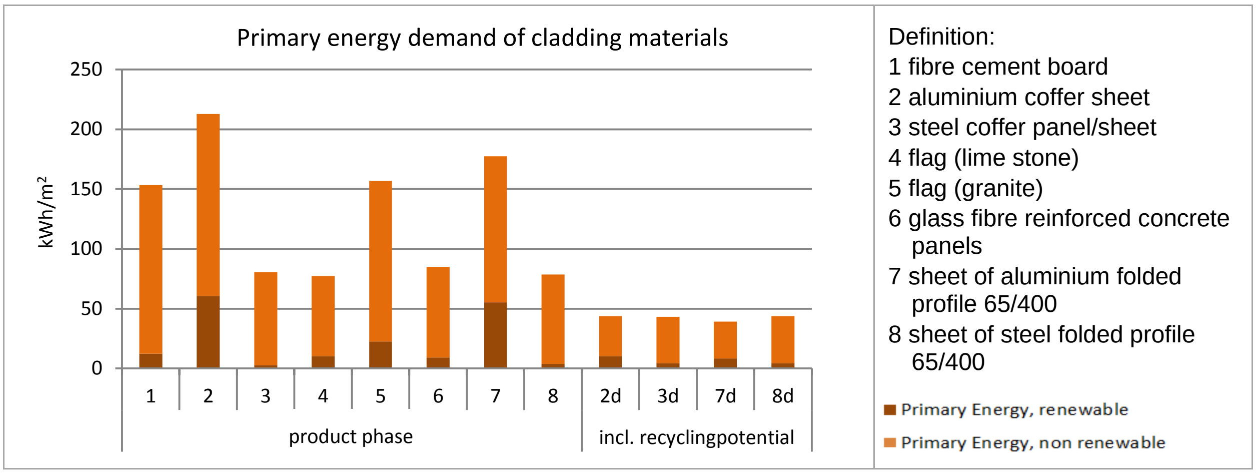


Figure 106: Total primary energy demand of cladding materials

The production of steel panels requires less primary energy compared to aluminium sheets. When considering the recycling potential, no significant differences between both metals can be observed.

Environmental impacts of cladding materials

Aluminium sheets, fibre cement board and granite cladding generate the highest GWP, see figure 107.

[46] recyclingrate of 95% for aluminium and steel coffer sheets and 90% for aluminium and steel folded profile sheets [ökobau.dat]

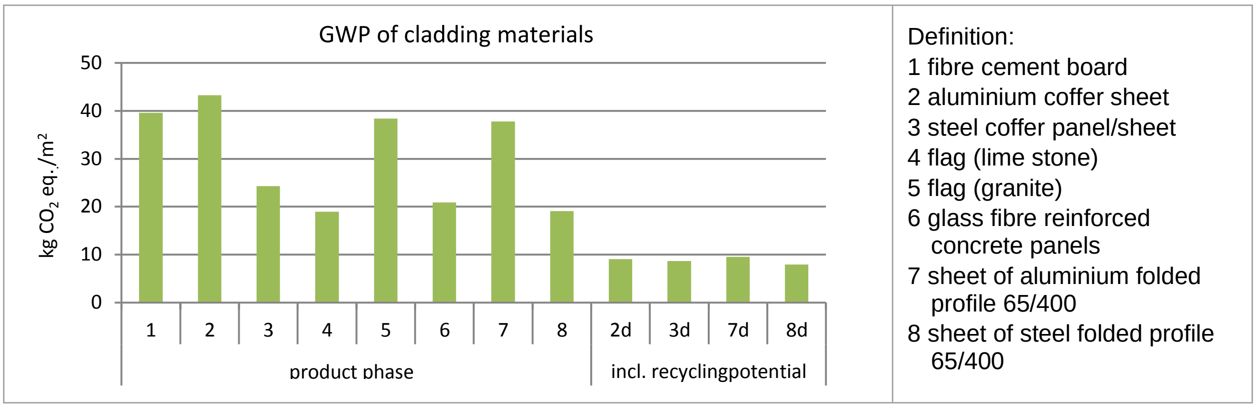


Figure 107: Global warming potential of cladding materials

Even though the weight of fibre cement board is rather low, this cladding shows enormous environmental impacts in comparison with natural lime stones and glass fibre concrete panels. After taking into account the recycling potential, the environmental impacts of the metals are the lowest.

The overall indicator I_{env} leads to similar results, see figure 108.

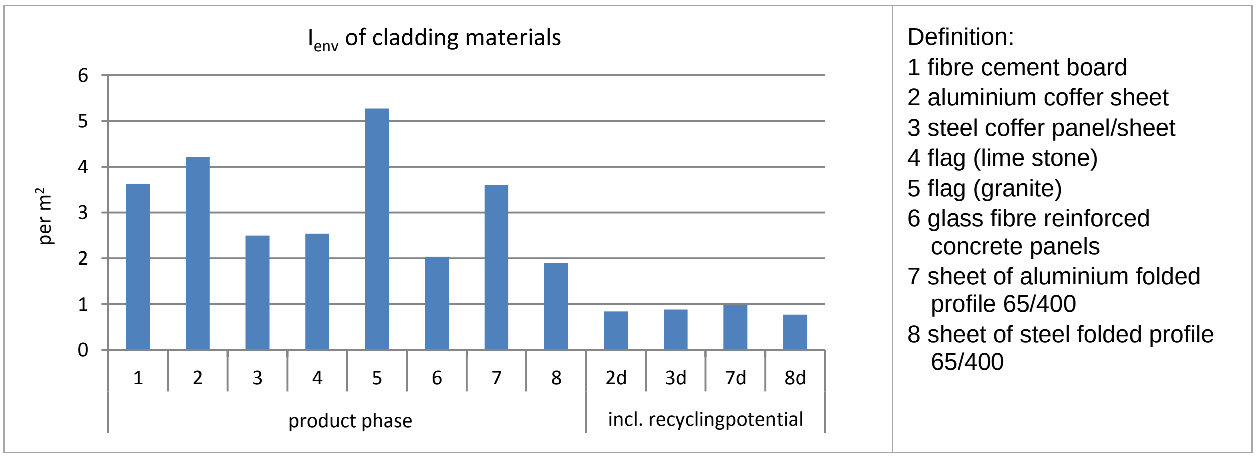


Figure 108: Overall indicator I_{env} of cladding materials

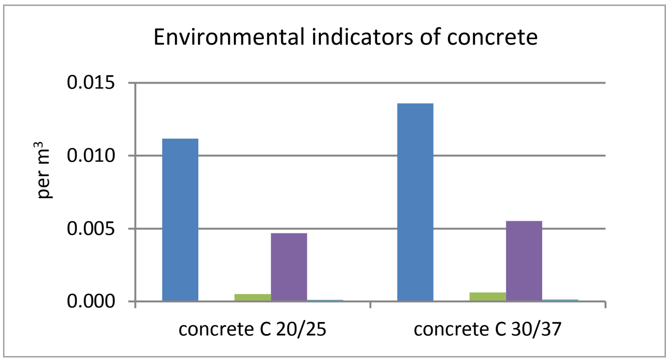
7.4.1.3 Environmental impacts of concrete and steel

The two important building materials concrete and steel have been analysed with regard to the resources required and the environmental impacts.

Concrete

The data sets used refer to unreinforced concrete for the use in building construction as ready-mixed concrete or pre-cast elements, suitable before the type of concrete has been defined. The recycling potential represents a credit for the use of demolished concrete and a potential uptake of CO_2 caused by the carbonation of concrete after the demolition [ökobau.dat].

The production process of concrete leads to high greenhouse gas emissions (GWP) and has likewise a significant influence on the eutrophication potential (EP). The effects on the other environmental indicators such as acidification (AP), photochemical ozone creation (POCP) and the ozone depletion potential (ODP) only play a minor role, see figure 109.



Definition[47]

C 20/25 compressive strength class of concrete for non-bearing exterior wall elements

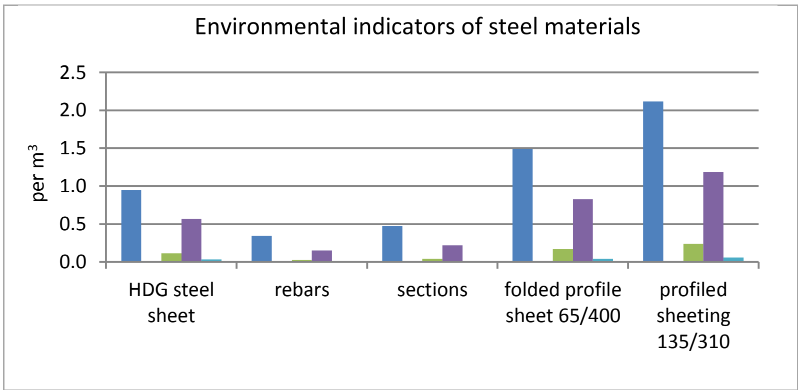
C 30/37 compressive strength class of concrete for load bearing slabs

Figure 109: Environmental impacts per m^3 concrete

The environmental impacts in terms of GWP are mainly caused by emissions during the process of cement production. Burning of cement is an energy consuming process and additionally produces large amounts of CO_2 emissions which are released from the raw limestone. The eutrophication potential (EP) is caused by production-related air pollutants and emissions in wastewater.

Steel

The generic data sets of ökobau.dat have been used for steel beams and columns as well as for steel sheets. For the galvanized profiled sheets of the slab and the exterior wall cladding the data have been collected from the EPD of the German BFS. As with concrete the results show the highest environmental impacts in terms of GWP due to the production of steel or iron from iron ore in blast furnaces. EP and AP are caused by the extraction of raw materials and the emissions produced by the sintering process, see figure 110.



Definition[48]

HDG hot dip galvanised

Figure 110: Environmental impacts per m^3 steel materials

The environmental impacts of the steel production can mainly be attributed to the supply of resources rather than to subsequent processes. The processing of raw materials causes emissions due to the thermal conversion of brown coal and the preliminary chains of the electrical energy used [BFS, 2013].

Comparison of concrete and steel

A direct comparison on material level of steel and concrete with reference to one cubic metre is not representative on building level due to the fact that concrete and steel are not used in the

[47] data including normalisation and weighting, not multiplied with factor 1000 as for I_{env}

[48] data including normalisation and weighting, not multiplied with factor 1000 as for I_{env}

same units. The specific values per volume unit differ significantly and will not be presented in one diagram. The results of the overall indicator I_{env}, however, show similar results as in the previous separate analysis, see figure 111.

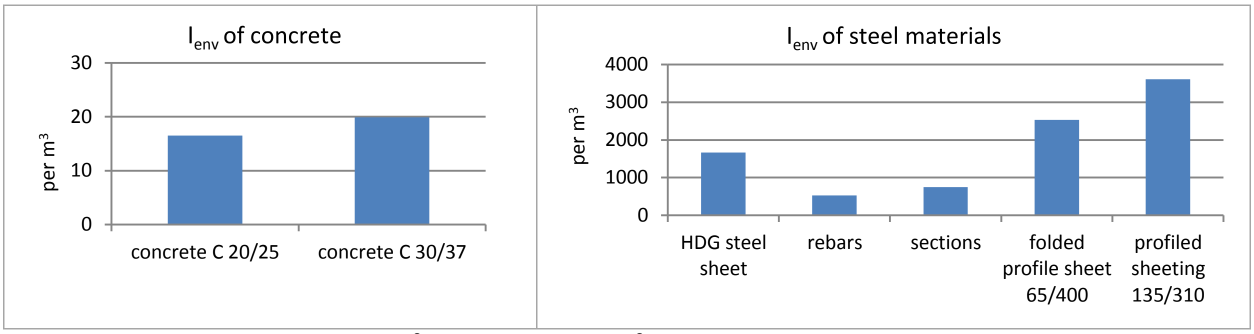


Figure 111: Overall indicator I_{env} per m^3 concrete and per m^3 steel materials

The production of folded and trapezoidal sheets leads to the highest environmental impacts compared to the other steel materials.

The results of the primary energy demand are similar and show the same tendencies as the analysis of the environmental impacts, see figure 112.

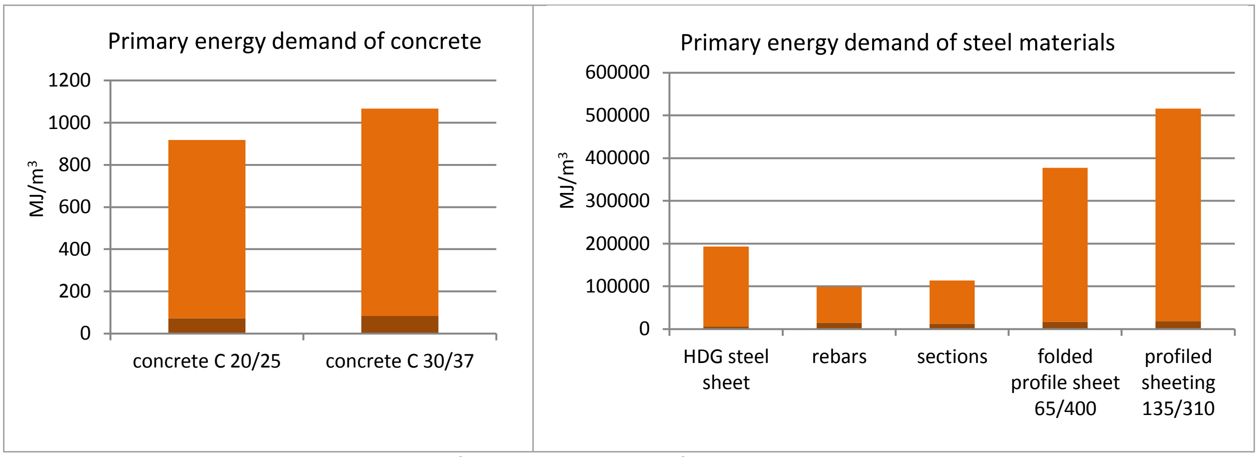


Figure 112: Primary energy demand per m^3 concrete and per m^3 steel

7.4.2 Conclusion of step 1

The examination of step 1 allows the following conclusions:

- ⇨ A direct comparison of building materials based on one cubic metre, as exemplified by concrete and steel, is not suitable for the environmental evaluation of buildings because the material thickness differs fundamentally, depending on the type of construction. The proportion of steel used e.g. in one square metre of exterior wall element is considerably lower than the amount of concrete used for solid constructions. In addition, different material thicknesses of the facade cladding and the insulation material have a strong impact on the results. Therefore, a direct comparison at component level relating to one square metre of component surface is highly recommended, see step 2.
- ⇨ Some advantages of steel become obvious when considering the recycling potential of more than 90% compared to concrete with only 10%. Furthermore, steel elements offer the possibilitiy of reuse. Nowadays, the percentage of reused steel stands at

11% and should be exploited in future. More than 80% are currently being fed back to the production process as steel scrap [BFS, 2010].

⇨ A deliberate choice of materials and the planning of slim constructions in order to save weight and mass, leads to ecologically optimised building elements. The less heavy and the more efficient a construction the lower the primary energy demand and environmental impacts. The choice of the facade cladding, e.g. is decisive due to the fact that claddings of little weight require subconstructions that are less heavy. The same applies to metal constructions, which have the lowest environmental impacts when taking into account the high recycling potential.

Due to its weighting the overall indicator I_{env} reflects the same tendencies as the GWP for nearly all materials and will therefore no longer be presented.

In addition the primary energy demand will no longer be separated into a renewable and a non-renewable share as they are related to single building materials and cannot be meaningfully allocated to building elements or at building level.

7.4.3 Step 2, the component level

In step 2 the building materials have been combined to the following structural elements:

- opaque exterior wall elements
- interior elements and
- structure types inclusive columns and slabs.

7.4.3.1 Exterior wall elements

The exterior wall elements of the solid as well as the steel composite structure are both composed by a practical and technically feasible structure, see figure 113.

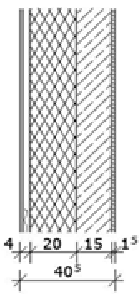
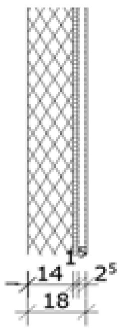
SOLID		STEEL	
	015 mm gypsum 150 mm concrete 200 mm insulation 030 mm substructure ventilated + cladding		025 mm gypsum plaster board 015 mm oriented strand board 140 mm steel construction & insulation (optional 200 mm) + cladding

Figure 113: Construction details of opaque part of exterior wall of SOLID and STEEL

The non-load-bearing concrete element consists of reinforced concrete (1% vol. steel) with a compression strength class of C 20/25 and has been combined with the following insulation materials and facade claddings:

SOLID A: EPS + fibre cement board

SOLID B: mineral wool + glass fibre concrete panel.

The interior cladding is made of gypsum plaster. The interior of the steel element consists of gypsum plasterboard and an oriented strand board (OSB). The difference between the solid and the steel element is the layer of insulation. In case of the steel structure the insulation is placed between the steel profiles. The proportion of steel related to one square metre of wall element amounts to approx. 5% and the share of insulation material 95%. This construction is combined with the following insulation materials and facade claddings:

STEEL A: PUR (140mm) + folded steel profile

STEEL B: mineral wool (200mm) + folded steel profile

An insulation material of good thermal conductivity, in order to achieve the same U-value, could reduce the thickness of the insulation layer (95% proportion) and consequently the size of the steel profile (proportion 5%). A PUR insulation of 140 mm with a thermal conductivity group of 025 (WLG 025) e.g. could replace the 200 mm mineral wool. In order to analyse the effects of this difference in terms of construction, folded steel profile was chosen as facade cladding for both steel structures. The subconstructions for the fixation of claddings as well as foils used as sealing element or vapour barrier have not been examined due to their low mass percentage.

The recycling potential (module D) of all four exterior wall elements has been considered for the wall element and for the insulation materials. In case of facade claddings the availability of data varies. Their recycling potential is not included in the assessment in order to achieve comparable results. As a consequence, the existing recycling potential of the folded steel profiles remains an additional saving potential. Data for module D do neither exist for the gypsum plaster of the solid construction, nor for the gypsum plasterboard of the steel structure.

Total primary energy demand of exterior wall elements

Less primary energy demand is required for the exterior wall elements in solid structure when compared to the steel structure, even when taking into account the recycling potential, see figure 114.

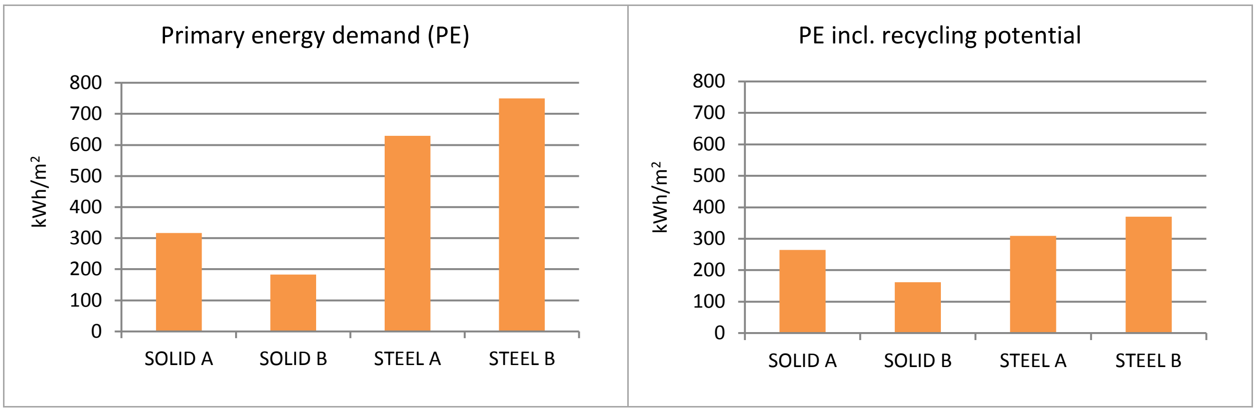


Figure 114: Primary energy demand of exterior wall elements of SOLID and STEEL

The solid element with mineral wool and a glass fibre concrete panel (SOLID B) proves to be the best choice. The steel element with PUR insulation instead of mineral wool and thus the lower proportion of steel (STEEL A) has a positive effect.

Global warming potential of exterior wall elements

The wall elements of the solid construction have a lower GWP compared to those of the steel structure. If taking into account module D, the differences between both constructions are very small, see figure 115.

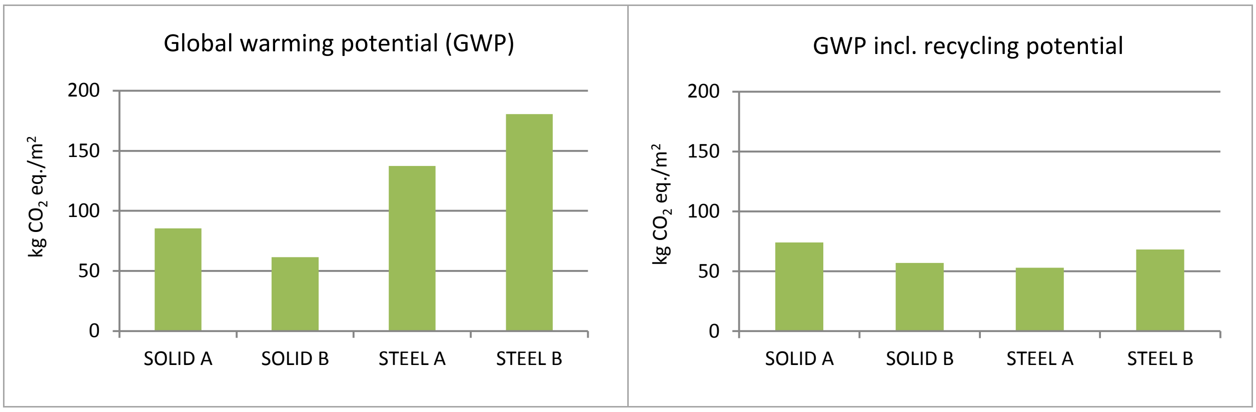


Figure 115: Global warming potential of exterior wall elements of SOLID and STEEL

The CO_2 emissions released by the exterior wall element with PUR and a folded steel profile (STEEL A) are lower than those caused by the optimised wall element of the solid construction (SOLID B). The facade cladding consisting of fibre cement board (SOLID A) has a negative impact on the GWP of the solid wall element. In this case the choice of the insulation only plays a minor role.

7.4.3.2 Interior elements

The non-load-bearing interior walls, floor constructions and the suspended ceiling are the main elements of the interior, see table 35. Floor coverings or paintings have not been considered in this study.

Table 35: Materials of interior elements

No.	Type	Definition of interior elements
1	IW	Metal stud partitions incl. mineral wool + 2*gypsum plaster boards
2.1	FF	false floor element; calcium sulphate board + sub-structure of galvanised steel
2.2	SC	suspended ceiling; 2*gypsum plaster boards + sub-structure of galvanised steel
3.1	CE 70	70mm cement screed + 30mm sound insulation (high density)
3.2	CE 55	55mm cement screed + 20mm sound insulation (high density)

The recycling potential of the materials of the interior elements has not been examined due to a lack of available data. In case of the non-load-bearing interior walls, however, the metal profiles of the subconstruction represent further recycling potential. For some materials of the interior elements minor credits are only being granted for the thermal recovery of the packaging.

Total primary energy demand and global warming potential of interior elements

The differences between the materials of the interior elements in terms of the total primary energy demand exceed those related to the global warming potential, see figure 116.

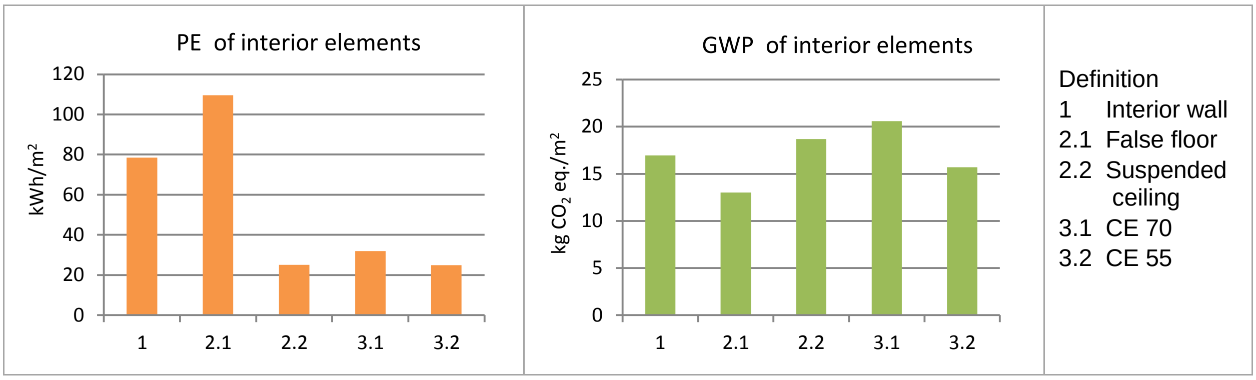


Figure 116: Primary energy demand and global warming potential of interior elements

The primary energy demand for the production of metal stud partitions and the false floor is significantly higher than for a cement screed including sound insulation board or for a suspended ceiling. One reason is the higher proportion of galvanised steel profiles for the load-bearing subconstructions.

In terms of global warming potential, constructions of cement screed cause higher environmental impacts due to the high level of CO_2 emissions released during the production of cement.

7.4.3.3 Supporting structure (structure types)

The solid and steel composite structure types consist of columns, beams and slabs. They have been examined without ceiling structures such as screeds, false floor and suspended ceiling. The ceiling structures and column grids of the supporting structure refer to the entire reference building, which is described in chapter 3. The steel and concrete masses have been converted to the gross floor area of the reference zone.

SOLID

For the solid structure (SOLID 1) two different supporting structures have been defined and referred to as Model SO 1 and Model SO 2, see table 36. The column grid is identical, only the thickness of the slab is different.

Table 36: Models of solid structures

Structure type	Model	Column grid	Slab type
SOLID 1	Model SO 1	5m/6m/5m; 5,40m	280mm reinforced concrete (2% vol. steel), C30/37
SOLID 1	Model SO 2	5m/6m/5m; 5,40m	240mm reinforced concrete (2% vol. steel), C30/37

STEEL

Precise specifications of the steel beams and columns chosen as well as the thickness of the concrete layer can be found in the tables of appendix 2 and 4. The different supporting structures are referred to as Model ST 1 until Model ST 6, see table 37.

Table 37: Models of steel composite structures

Structure type	Model	Column grid	Slab type
STEEL 1	Model ST 1	5m/6m/5m; 5,40m	steel beams, profiled sheeting C77 + reinforced concrete (1% vol. steel), C30/37
STEEL 1	Model ST 2	11m/5m; 5,40m	steel beams, profiled sheeting C77 + reinforced concrete (1% vol. steel), C30/37
STEEL 1	Model ST 3	16m; 4,05m	steel beams, profiled sheeting C60 + reinforced concrete (1% vol. steel), C30/37
STEEL 2a	Model ST 4	5m/6m/5m; 5,40m	integrated floor beams, profiled sheeting C220 + reinforced concrete (1% vol. steel), C30/37
STEEL 2b	Model ST 5	5m/6m/5m; 5,40m	integrated floor beams + precast elements of reinforced concrete (1% vol. steel), C30/37
STEEL 2b	Model ST 6	11m/5m; 5,40m	CoFSB + reinforced concrete (1% vol. steel), C30/37

Model ST 1, ST 4 and ST 5 have the same column grid as the two models of the solid structure. In case of Model ST 2 and ST 6 one and in case of Model ST 3 both rows of central post have been omitted inside the building. The slabs can be divided into the steel beam (STEEL1) and the integrated floor beam systems (STEEL 2), see also chapter 4.1.5, table 8 and 7.3.2, figure 99.

Total primary energy demand of structure type

Without taking into account the recycling potential, all models of the steel composite structure show a higher primary energy demand as the supporting structure of the solid structure, see figure 117.

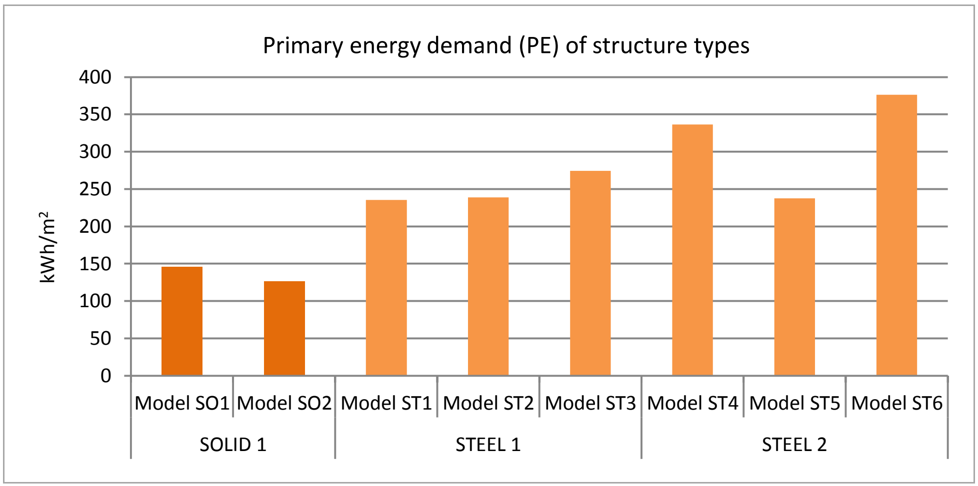


Figure 117: Primary energy demand of different structure types

The integrated floor beam systems (Model ST 4 and Model ST 6) account for the highest primary energy demand when compared to the other steel supporting structures due to a higher proportion of steel. HE-A steel beams including flat steel flanges and stronger trapezoidal sheets are used. The system with precast concrete elements (Model ST 5) has the lowest primary energy demand. For the steel beam systems (STEEL1) IPE und IPE-A rolled-form profiles have been used in case of Model ST 1, ST 2 and ST 3. Most suitable for the reference building is the choice for a smaller column grid and the selection of a slab structure with steel beams and profiled sheeting C77 (Model ST 1 and ST 2) or a SlimFloor system with precast concrete elements (Model ST 5).

The same tendencies arise when considering the recycling potential. Due to the credit of module D, however, the differences between solid and steel composite structures are less significant, see figure 118.

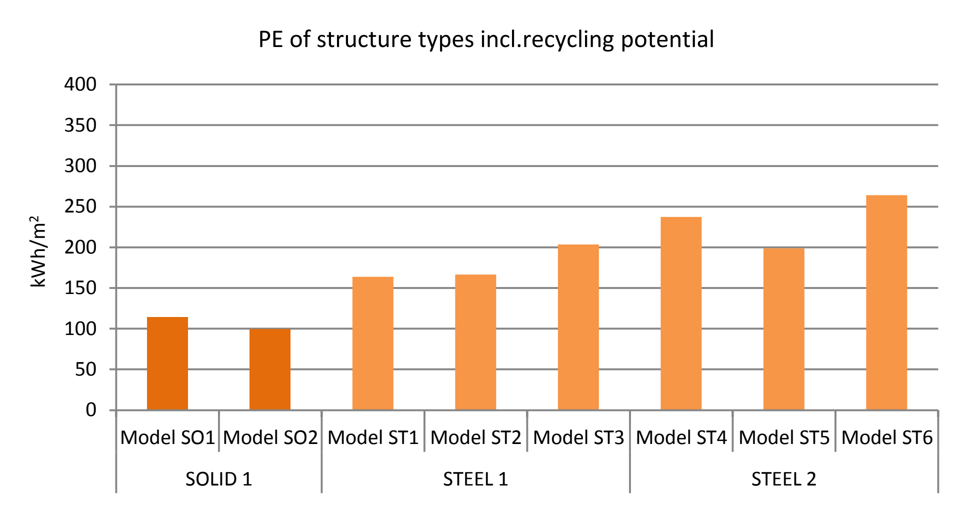


Figure 118: Primary energy demand of different structure types incl. recycling potential

Global warming potential of structure type

The global warming potential of the solid and the steel composite structures leads to similar results as the primary energy demand. Only the floor beam systems (STEEL 2) show increased CO_2 emissions, see figure 119.

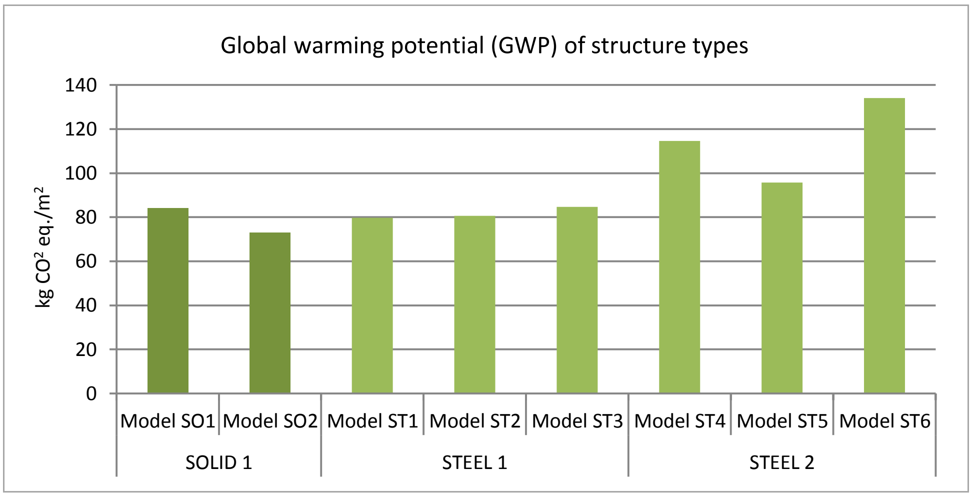


Figure 119: Global warming potential of different structure types

The solid structure with a lower slab thickness (Model SO 2) causes the smallest amount of CO_2 emissions. As with primary energy demand, both models with small column grids and profiled sheeting C77 (Model ST 1 and ST 2) show advantages compared to other models of the steel composite construction. The wider span of Model ST 3 leads to an increase in steel weight and has no advantages from an environmental point of view. The higher flexibility of the building owing to the absence of central posts, however, can be considered beneficial.

When taking into account the recycling potential, all models of the steel composite structure with steel beams (STEEL 1) lead to a lower GWP compared to the two solid structures, see figure 120.

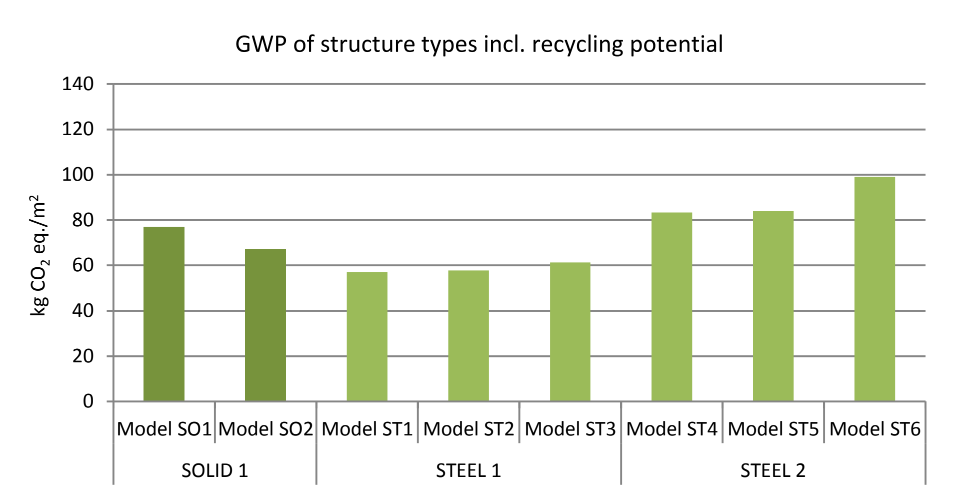


Figure 120: Global warming potential of different structure types incl. recycling potential

7.4.4 Conclusion of step 2

The examination of the building elements leads to the following conclusions:

Exterior wall

- ⇨ The choice of the facade cladding influences the environmental impacts of the opaque exterior wall element to a greater extent than the choice of the insulation material. In case of a solid construction (SOLID A and B), the impacts are even more relevant than the wall element itself.
- ⇨ Nevertheless, a furhter reduction of environmental impacts of already optimised wall elements can be achieved by an insulation material with a high proportion of recycled content e.g. EPS or by using mineral wool.
- ⇨ In case of a steel construction, an insulation material with a very good thermal conductivity value can reduce the thickness of the insulation layer and therefore the size of the steel profile. The construction thickness of the entire wall element could be reduced.
- ⇨ Building elements built as slim and lightweight as possible could reduce weight and the associated environmental impacts.

Interior elements

- ⇨ The highest recycling potential lies in the field of sub-constructions made of profiled metals. The choice for single instead of double planking in case of metal stud partitions is advantageous.
- ⇨ A suspended ceiling should be avoided. Apart from ecological disadvantages also the energetic analyses have shown that the energy demand increases. Alternatives to improve the acoustic comfort are available on the market, e.g. partially suspended acoustic panels or wall panels. Cable arrangement of technical installations should be routed in the floor structure.

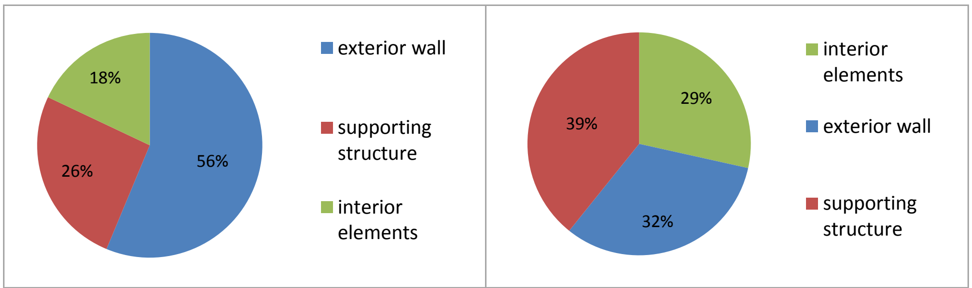
Structure type

- ⇨ The slabs of concrete constructions should be as slim as possible from an ecological point of view but also the energetic evaluation has shown that slabs thicker than 240 mm have no considerable advantage, see chapter 4.2.3.1.

- ⇨ The recycling potential of reinforcing steel (rebars) has not been taken into account and thus offers further saving potential.
- ⇨ Steel composite structures with small spans and steel beams (STEEL 1) have proved to be favourable for the reference building. However, the integrated floor beam systems (STEEL 2) can reduce the total height of the slabs and therefore the volume of a building. The CoSFB system, e.g. has been developed for large spans and offers a higher flexibility of the floor plans compared to a solid construction.
- ⇨ Detachable connections of the single materials are advisable for all building components to ensure easy dismantling and separate disposal at the end-of-life phase. In order to exploit the reuse potential of steel, screw connections should be preferred.

Comparison of building components

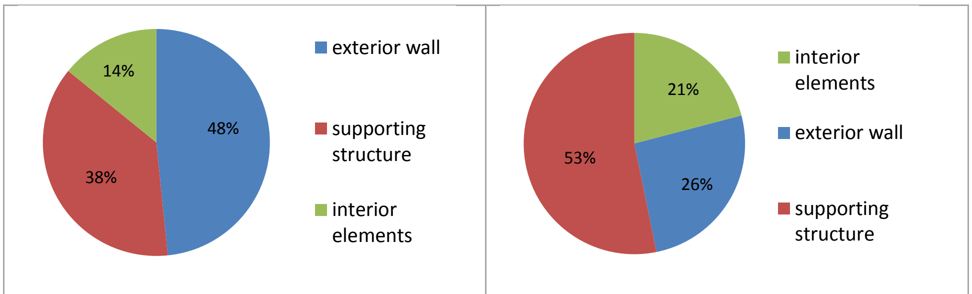
- ⇨ The direct comparison of the building components per square metre reveals that for all models observed the primary energy demand of the opaque exterior wall is higher than that of the supporting structure or the interior elements (interior walls + floor structure), see 1. of figure 121.
- ⇨ Looking at the real component surfaces of the reference office zone, the primary energy demand of the supporting structure is slightly higher than the value of the opaque exterior wall (without consideration of the ratio of window area) or the interior elements, see 2. of figure 121. The impact of the supporting structure on the primary energy demand in proportion to the external wall and interior elements is comparable to the results of [Bauer], see chapter 2.6.2.



1. Primary energy demand in kWh/m² according to building component
2. Primary energy demand in kWh according to office zone

Figure 121: Primary energy demand per m^2 and per surface area

- ⇨ In terms of global warming potential, the supporting structure has a stronger impact than the other building components of the reference zone, see figure 122.



1. Global warming potential in kg CO_2 eq./m^2 according to building component
2. Global warming potential in kg CO_2 eq. according to office zone

Figure 122: Global warming potential per m^2 and per surface area

The examination of the building components only per square metre of component surface is not suitable for an overall environmental evaluation of a building due to the different proportion of the individual components of a building. The slabs for example represent 60% - 80% of the entire shell construction volume, see chapter 2.6.2. Nevertheless, this approach by means of a direct comparison gives a good understanding of the environmental impacts of different components and facilitates the choice of structure type and building materials.
Further examinations of the office zone with reference to the real component surfaces will take place in step 4.

7.4.5 Step 3, the facade system

The influence of the ratio of window area on the primary energy demand and global warming potential has been analysed on the example of a punctuated (F48), a band window (F77) and a fully glazed facade (F100). The four opaque exterior wall elements examined in step 2 SOLID A, SOLID B as well as STEEL A and STEEL B have been combined with the following window elements:

- self-supporting aluminium frame construction incl. triple glazing
- self-supporting steel frame construction incl. triple glazing.

The combination of the opaque exterior wall elements with the window elements is referred to as „facade system“ and multiplied by the respective wall and window surfaces of the reference zone. No data are available for the recycling potential of the window profiles and the glazing. To obtain comparable results an examination of elements with and without module D is considered inappropriate. Therefore, the following facade systems have been analysed without module D:

SOLID A: SOLID + EPS + fibre cement board + aluminium frame construction

SOLID B: SOLID + mineral wool + glass fibre concrete panel + steel frame construction

STEEL A: STEEL + PUR + folded profile steel + steel frame construction

STEEL B: STEEL + mineral wool + folded profile steel + aluminium frame construction

Total primary energy demand and global warming potential of facade systems

In case of both facade systems of the solid construction the primary energy demand and the CO_2 emissions increase with a growing ratio of window area, see figure 123.

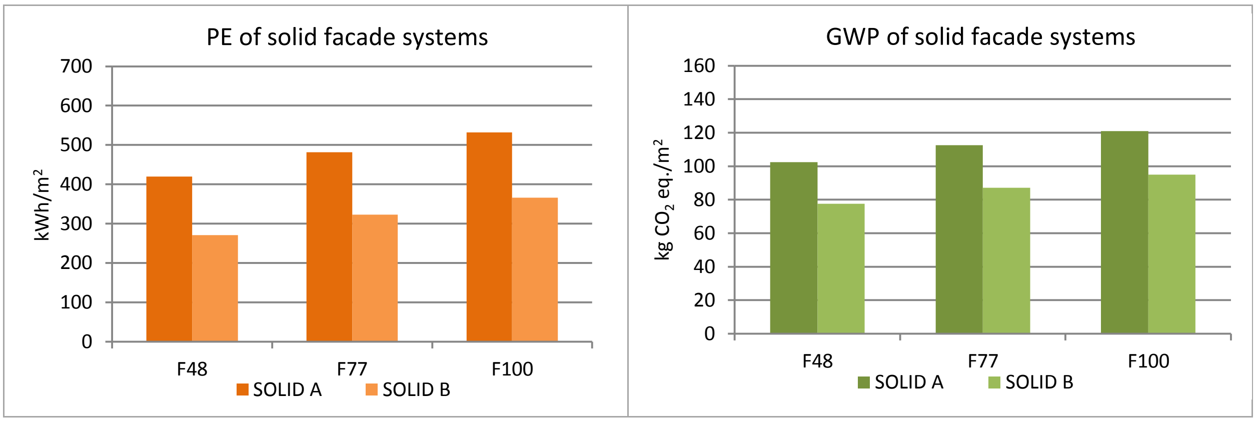


Figure 123: Primary energy demand and global warming potential of solid facade systems

High environmental impacts of the self-supporting frame constructions made of aluminium and steel have an increasing negative influence on the impacts of the entire facade system. In consequence, the impacts of the exterior wall elements decrease. The facade system with mineral wool, a glass fibre concrete panel and a steel frame construction (SOLID B) presents itself as optimised when compared to the system with EPS, fibre cement board and aluminium frame construction (SOLID A).

The window elements are more decisive than the exterior wall elements of the solid structures. The opposite effect can be observed for the facade systems of the steel composite structures, see figure 124.

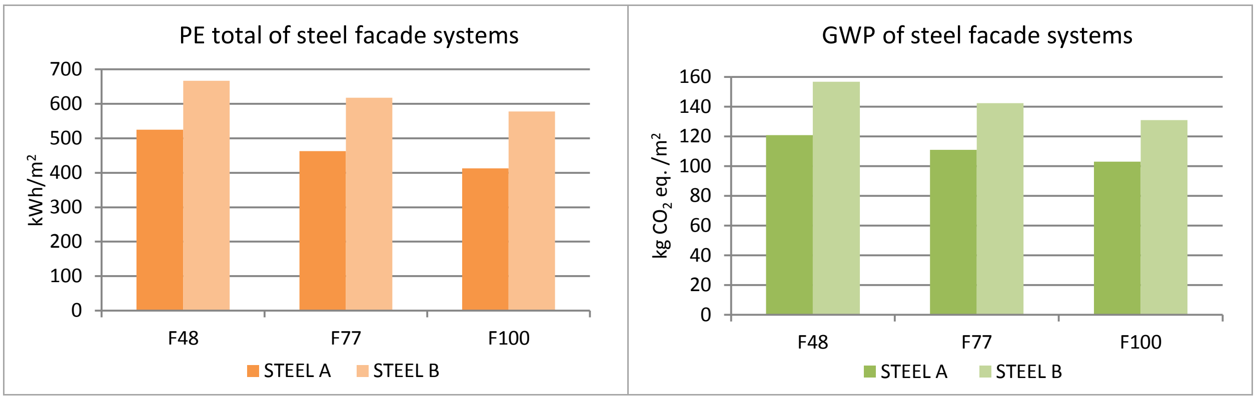


Figure 124: Primary energy demand and global warming potential of steel facade systems

The declining proportion of steel of the opaque wall element causes this effect which is stronger in case of the exterior wall element with larger steel profiles and mineral wool (STEEL B). The facade system with PUR, folded profile steel sheet and a steel frame construction (STEEL A) proves to be optimised.

The environmental impacts of the facade systems in steel composite construction are higher compared to those of the solid structure.

7.4.6 Step 4, the building level

The four facade systems of the solid and the steel composite structures of step 3 have been combined with preselected models of the supporting structure and interior elements. The combination of these building components is referred to as “case studies”, see table 38. The building materials and components selected are representing a typical choice for office buildings. The aim is to compare a well-designed and a standard case study of the entire office zone with reference to the real component surfaces.

Table 38: Case studies for the examination on building level

Case study	Exterior wall element	Window element	Models of supporting structure	Interior elements
SOLID A	SOLID + EPS + fibre cement board	Self-supporting aluminium element	Model SO 1: 5m/6m/5m; 5,40m + 280 mm reinforced concrete	CE 70 + IW
SOLID B	SOLID + mineral wool + glass fibre concrete panel	Self-supporting steel element	Model SO 2: 5m/6m/5m; 5,40m + 240 mm reinforced concrete	CE 70 + IW
STEEL A	STEEL + PUR + folded profile steel	Self-supporting steel element	Model ST 1: 5m/6m/5m; 5,40m + steel beams, profiled sheeting C77 + reinforced concrete	CE 55 + IW
STEEL B	STEEL + mineral wool + folded profile steel	Self-supporting aluminium element	Model ST 4: 5m/6m/5m; 5,40m + integrated floor beams + precast elements of reinforced concrete	CE 55 + IW

The evaluation results will be presented with and without taking into account the recycling potential. If taken into account, all building materials and components of the case studies have been considered, except the facade cladding, window elements and the interior materials for which the data availability is insufficient.

Total primary energy demand and global warming potential

The choice for a solid construction is beneficial in terms of primary energy demand as well as global warming potential when compared to the steel composite structures, see figure 125.

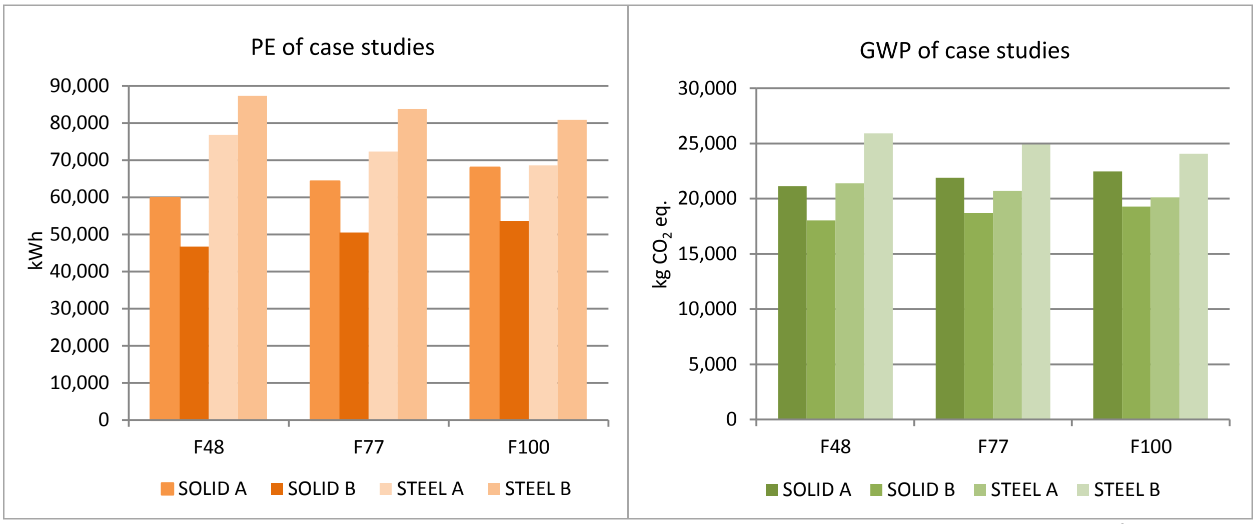


Figure 125: Primary energy demand and global warming potential of case studies for the reference zone[49]

The model built in solid construction with a slab of 240 mm reinforced concrete, an exterior wall combined with mineral wool and glass fibre concrete panel and a window element of steel (SOLID B) accounts for the lowest environmental impacts. A small window area is beneficial however, a highly glazed facade is an advantage for both steel composite structures.

If the recycling potential is taken into account, the differences between the two structure types are low, see figure 126.

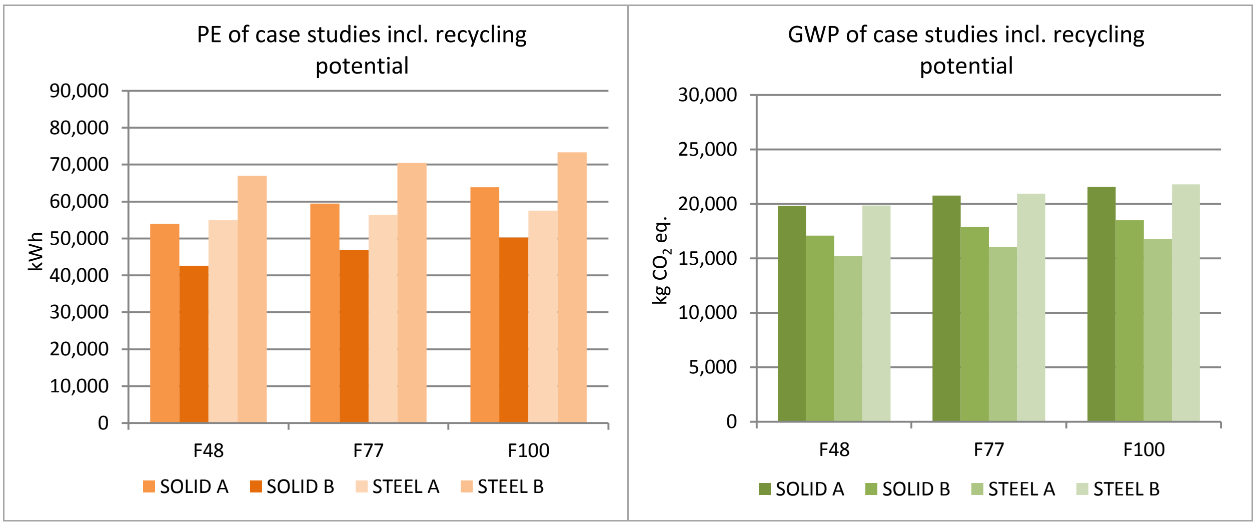


Figure 126: Primary energy demand and global warming potential of case studies for the reference zone incl. recycling potential

[49] For specific values see diagrams on page 160.

The environmental impacts of the exterior wall elements of the steel composite structures decrease and the impact of the window elements gain influence. A higher ratio of window area has a negative impact as in case of the solid constructions. The steel composite structure with a steel beam system and profiled sheeting, an exterior wall element with PUR and folded profile steel and a window element of steel (STEEL A) accounts for the smallest amount of CO_2 emissions.

The results show that the choice of structure type is less decisive than an efficient choice of building materials and well-designed components. The two optimised case studies (SOLID B and STEEL A) are used for the calculation of energy and emission characteristic values of the product phase.

7.5 Step 5, comparison of environmental and energetic evaluations

Purpose of step 5 is to determine the influence of chosen building materials and components on the eco and the energy balance of the office zone. Energy and emission characteristic values of the product phase will be developed using two case studies and set in relation to the values of the operational energy use of reference models of the office zone. The results of the energetic evaluation, see chapter 4.2, represent the primary energy demand (PE) and the corresponding global warming potential (GWP) of the reference models during the period of one year. They are referred to as follows:

- PE_{use} in kWh/(m^{2}a)
- GWP_{use} in kg CO_2 eq./(m^{2}a)

The energy and emission characteristic values of the product phase of the case studies are determined by the primary energy demand and the CO_2 emissions according to [Lützkendorf]:

$$PE_{product} = \frac{\text{primary energy demand of product phase}}{\text{reference area} * \text{reference period}} \qquad \text{(Equation 22)}$$

$$GWP_{product} = \frac{\text{global warming potential (CO2 emissions) of product phase}}{\text{reference area} * \text{reference period}} \qquad \text{(Equation 23)}$$

With:

$PE_{product}$	[kWh/(m^{2}a)]	energy characteristic value of product phase
$GWP_{product}$	[kg CO_2 eq./(m^{2}a)]	emission characteristic value of product phase
reference area	[m^2]	gross floor area of office zone, 120 m^2
reference period	[a]	time period, 30 years

The reference period for environmental evaluations is set at 50 years in many certification systems e.g. the German “BNB” for public office buildings [BNB]. A substitute has to be considered within this period for components and materials with a shorter life time [BMUB-3].

The components examined in this study will not need a replacement within 50 years, due to the fact that no elements such as door and window fittings, roof sealings, foils and adhesive tapes have been considered. However, it can be assumed that internal renovations or modifications of the facade will be carried out within 50 years. Therefore, a shorter period of 30 years has been chosen.

7.5.1 Reference models of energetic evaluation

The reference models chosen are energy-efficient models of the office zone with a low net energy demand and only few hours of overheating per year. The values of the operational energy use include the needs for heating and cooling and the electricity demand for artificial lighting, represented by the total primary energy demand and the resulting global warming potential.

7.5.1.1 Reference model SOLID 1

The reference model (SOLID 1) is based on the following parameter selection:

- Window area punctuated (F48), band window (F77), fully glazed (F100) facade
- Structure type 240 mm concrete slab and 70 mm screed acc. to Model SO 2
- Slab type no suspended ceiling (WCS)
- Shading device external (opaque part 70%), radiation controlled
- Glazing type triple glazing (EW1), Ug-value=0.59 W/(m^2K), g-value=0.58
- Ventilation strategy natural ventilation strategy (VENT_NAT)
- Exterior wall U-value = 0.17 W/(m^2K)

7.5.1.2 Reference model STEEL 1

The reference model (STEEL 1) is based on the following parameter selection:

- Window area punctuated (F48), band window (F77), fully glazed (F100) facade
- Structure type steel beam system with profiled sheeting C77 acc. to Model ST 1
- Slab type no suspended ceiling (WCS)
- Shading device external (opaque part 70%), radiation controlled
- Glazing type triple glazing (EW1), Ug-value=0.59 W/(m^2K), g-value=0.58
- Ventilation strategy natural ventilation strategy (VENT_NAT)
- Exterior wall U-value = 0.17 W/(m^2K)

7.5.2 Comparison of energy and emission characteristic values

The energy and emission characteristic values of the product phase have been calculated using the case studies SOLID B and STEEL A, without taking into consideration the recycling potential, see table 39.

Table 39: Case studies for the comparison of energy and emission characteristic values

Case study	Exterior wall element	Window element	Models of supporting structure	Interior elements
SOLID B	SOLID +mineral wool + glass fibre concrete panel	Self-supporting steel element	Model SO 2: 5m/6m/5m; 5,40m + 240 mm reinforced concrete	CE 70 + IW
STEEL A	STEEL + PUR + folded profile steel	Self-supporting steel element	Model ST 1: 5m/6m/5m; 5,40m + steel beams, profiled sheeting C77 + reinforced concrete	CE 55 + IW

The values ($PE_{product}$ and $GWP_{product}$) have been set in relation to the values of the operational energy use (PE_{use} and GWP_{use}) of the reference models SOLID 1 and STEEL 1 of the office zone.

7.5.2.1 Energy characteristic values

SOLID structure

The primary energy demand of the product phase ($PE_{product}$) increases with a growing ratio of window area, while the demand of the operational energy use (PE_{use}) decreases in all orientations, see figure 127.

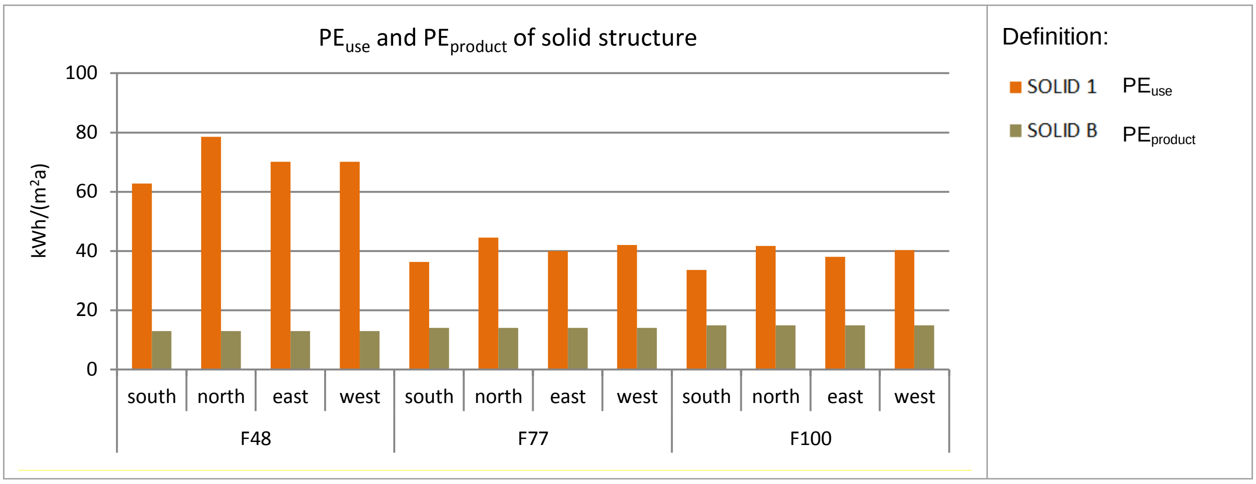


Figure 127: Energy characteristic values of product phase and operational energy use of solid structure

The primary energy demand of the production of the office zone ($PE_{product}$) accounts for a significant share compared to the demand of the operational energy use (PE_{use}), ranging between 17% - 44% with an average value of approx. 31%. A high ratio of window area is an advantage for the operation of energetically optimised buildings when taking into account the electricity demand for lighting. One reason is the efficient use of daylight, see in detail in chapter 4.3.2.

STEEL structure

The primary energy demand of the product phase ($PE_{product}$) and of the operational energy use (PE_{use}) decreases with an increasing ratio of window area, see figure 128.

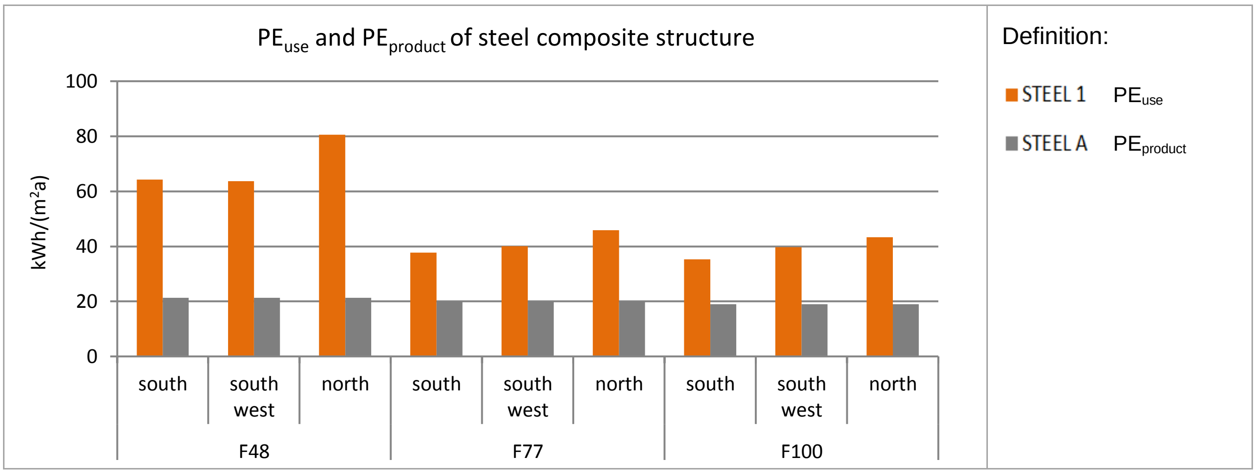


Figure 128: Energy characteristic values of product phase and operational energy use of steel composite structure

The share of the primary energy demand of the product phase ($PE_{product}$) compared to the demand of the operational energy use (PE_{use}) is higher than in case of the solid structure. The percentage lies in a range between 26% - 54% with an average value of approx. 43%. A high ratio of window area is a noticeable advantage in terms of the operational energy use also in case of steel composite structures.

7.5.2.2 Emission characteristic values

SOLID and STEEL structure

The emission characteristic values of the solid and the steel composite structures indicate that the CO_2 emissions of the product phase ($GWP_{product}$) have a share of approx. 50% compared to the emissions caused by the operational energy use (GWP_{use}), see figure 129.

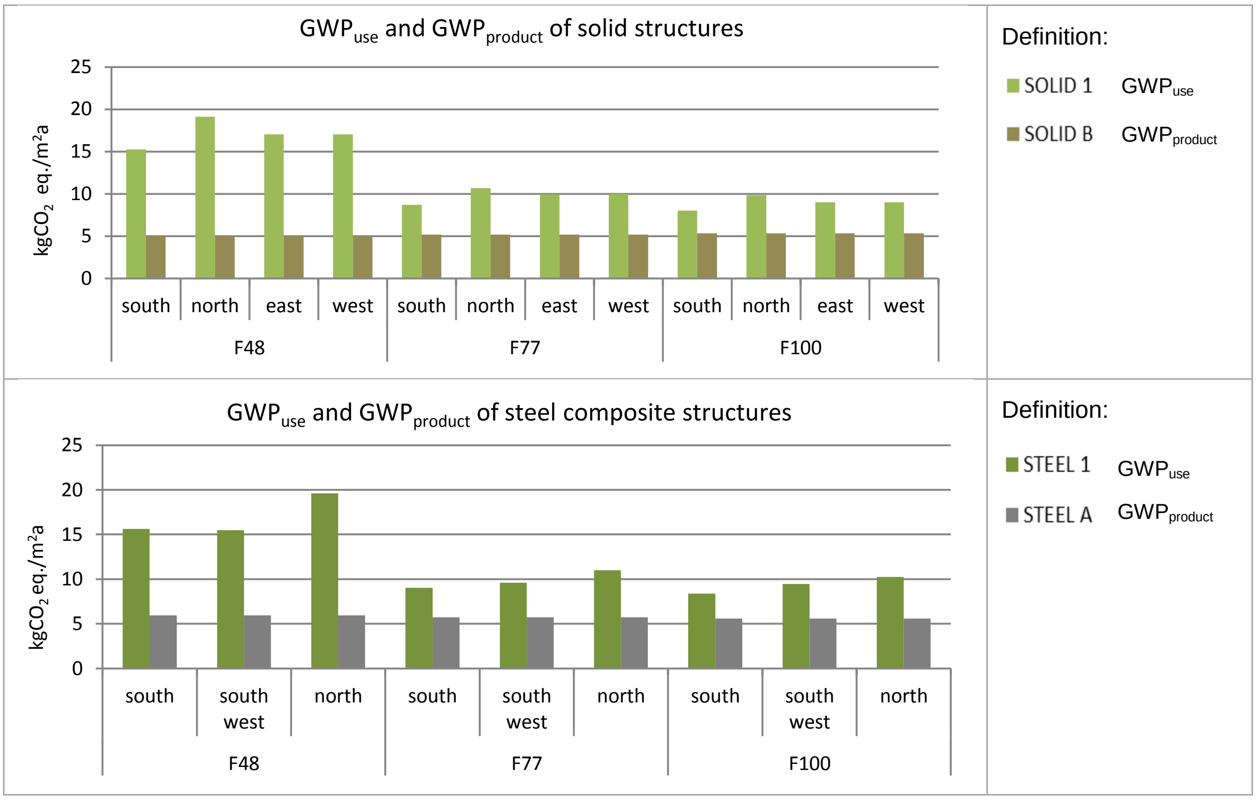


Figure 129: Emission characteristic values of product and operational energy use of solid and steel composite structure

7.5.2.3 Conclusion of step 5

The results clearly indicate the significant share of the primary energy demand of the product phase compared to the demand resulting of the building operation. They are comparable to the statement of [Hegger] that the proportion of the production of energy-efficient buildings compared to the use phase stands at approx. 40% - 50%.

Taking into account the recycling potential, has hardly any effect on the energy and emission characteristic values of the solid structure. The proportion of the primary energy demand of the production ($PE_{product}$) is reduced by approx. 3% compared to the operation of the office zone (PE_{use}). The percentage related to the steel composite structure, however, decreases by approx. 8% - 9%, see table 40. The energy characteristic values of the four case studies, SOLID A and B, STEEL A and B (see table 38) of the office zone are presented.

Table 40: Energy characteristic values of product and operational energy use of case studies with and without recycling potential (modul D)[50]

Case studies	$PE_{product}$	$PE_{product}$ incl. module D	PE_{use}	PE_{total}[51]	PE_{total} incl. module D	$PE_{product}$ compared to PE_{use}	$PE_{product}$ compared to PE_{use} incl. module D
	kWh/(m²a)	kWh/(m²a)	kWh/(m²a)	kWh/(m²a)	kWh/(m²a)	%	%
SOLID A	18	16	50	68	66	39	36
SOLID B	14	13	50	64	63	31	28
STEEL A	20	16	51	71	67	43	34
STEEL B	24	20	51	75	71	52	44

7.6 Summary and conclusion

7.6.1 Summary

The most important aspect with regard to resource requirements and environmental emissions is the reduction of masses of the entire building. The less mass and volume are being installed particularly in multi-storey buildings, the lower are the environmental impacts in terms of supporting structure, facades systems and foundations. The supporting structure has a significant impact in terms of primary energy demand and global warming potential when compared to other building components, see also chapter 2.6.2.

7.6.1.1 Structure type and supporting structure

- The differences between the solid and the steel composite structures are rather small when considering the high recycling rate of steel. Although the primary energy demand of steel composite structures is slightly higher compared to solid structures, in terms of CO2 emissions an optimised material selection offers some benefits.
- Less massivity (thickness of the slabs) and the installation of a central post in the center zone of the reference building are beneficial.
- A statical calculation and the environmental evaluation of design alternatives is crucial to find the best choice of building materials and components and a suitable supporting structure. This becomes evident by the development of the „Sustainable Office Designer" for the pre-dimensioning of the supporting structure of steel composite structures in terms of geometry and environmental impacts [Eisele], see chapter 2.10.
- The selection of the supporting structure is also determined by socio-cultural aspects such as the building and office organisation concept, comfort and economic factors related to the flexibility of floor plans and the conversion feasibility of the building.
- Due to its reuse possibilites, steel can already be categorised for the most part into the "cradle to cradle" of a closed material cycle. After the installation steel can be regarded as a „hidden steel reserve" [Bollinger]. It can be assumed that the percentage share of secondary steel will rise in future and that consequently the "cradle to cradle" material cycle will be closed.

[50] The emission characteristic values are not shown explicitly since their results reflect the same tendencies like the energy characteristic values.
[51] sum of energy characteristic values of product phase and of operational energy use

7.6.1.2 Facade system

- An optimised facade system is represented by an opaque exterior wall element as slim and light weight as possible. The same applies to the facade cladding and in consequence its sub-structure. The best insulation material should have a low thermal conductivity in order to reduce the thickness of the wall element and should provide a high recycling potential.
- The ratio of window area directly influences the primary energy demand and the environmental impacts not only of the product phase but above all of the operational energy use of a building. The window elements cause high resource requirements as well as environmental impacts during the product phase. Concerning the energy demand during building operation, however, a higher ratio of window area is an advantage for an energetically optimised building. The share of the product phase has a lower impact when compared to the impact of the building operation.

The development of energetic and environmental characteristic values of the product phase and the comparison to the values of the operational energy use of the office zone demonstrates the importance of material decisions. The proportion of the primary energy demand of the product phase is approx. between 30% and 50% compared to the operational energy use of the office zone.

7.6.2 Conclusion

The comparative environmental study reveals the significant influence of design decision in terms of building materials and components. The step-by-step analysis on material and component level, the examination of facades systems and the combination of selected components on building level has proven to be a suitable method to identify the ecological impacts and the optimisation potential of several case studies of the office zone.

7.6.2.1 Choice of indicators

The results of the energetic and environmental evaluations have shown a significant correlation between primary energy demand and environmental impacts. The total primary energy demand of the product phase as well as of the operation of a building has proven to be the relevant indicator to evaluate the energetic and ecological quality.

7.6.2.2 Data quality

The comparability of the data sets of the materials, examined in this study, is guaranteed by using only one database and environmental product declarations, which both are based on identical and commonly accepted evaluation methodologies. The quality of the data sets provided by ökobau.dat is reliable and precise. The results of the environmental evaluations are considered reproducible and representative for similar constructions of office buildings.

For the end-of-life scenarios and the recycling potential of several building materials the availability of data is not yet sufficient. Therefore, a direct comparison of the resource requirements and the environmental impacts of the whole life-cyle of a building is difficult. For the concept phase, however, the approach of this study in order to identify optimisation potential and alternatives for the selection of building materials and components is reasonable and allows the development of design guidelines and recommendations.

8 Design Guidelines And Recommendations

The objective of this research is to develop design guidelines and recommendations for office buildings. The focus is on optimisation steps for highly glazed buildings with steel composite structures and to answer the question whether and to what extent these structures are able to compete with solid structures. The extensive energetic and environmental investigations carried out during the project have finally made it possible to define general design guidelines and so called “rules of thumb” for the concept phase of office buildings. The project has focussed on design parameters related to:

- the facade design and its impact on the use of daylight and various comfort requirements and
- the structure type taking into account the thermal storage capacity of slab systems combined with passive cooling effects.

All energetic and environmental evaluations are based on the reference office building and the office zone, see chapter 3. The project is divided into four areas of examination:

1. An expertise-based parameter study to determine energy demand and overheating risk by means of dynamic, thermal simulations, see chapter 4
2. A sensitivity analysis to corroborate the simulation results and to quantify the sensitive impact of the design parameters by using statistical methods, see chapter 5
3. An experimental part to study the temporal temperature variations and quantity of energy buffered in a concrete slab by metrological investigations, see chapter 6
4. A life cycle assessment (LCA) to determine primary energy demand and the environmental impact of building materials and components taking into account product phase and end-of-life scenario (recycling potential), see chapter 7.

8.1 Synthesis of results

Design flexibility will be preserved if energy-relevant key parameters are implemented in an optimal manner. The study has clearly indicated that a high ratio of window area is feasible and that steel composite structures are competitive and offer key advantages. In Western Europe, it is possible to realize climate-adapted architecture and low-tech concepts; however, with regard to thermal comfort in summer limits are also apparent. The main results from the previous analyses can be summarized as follows:

- Annual primary energy demand lower than 100 kWh/(m^2a) for heating, cooling, ventilation and lighting is feasible in office buildings.
- The primary energy demand for artificial lighting is more decisive than the energy demand for heating and cooling in well-designed, energy-efficient buildings.
- In a temperate Western European climate, using passive cooling effects is mostly efficient compared to Northern or Southern Europe.
- The design of window area, sun protection and glazing type (facade design) works best when adapted to suit the orientation and climate conditions.
- The key parameter is ensuring efficient sun protection by using an external shading device and by also ensuring that the control system can be adjusted to the control system of artificial lighting.

- A band window facade instead of a fully glazed or punctuated facade is the best choice to gain the most benefit from use of daylight, and to provide an energy-efficient operation mode. A thermal insulation glass with high selectivity is beneficial.
- Steel composite structures representing a medium-weight construction behave similarly to solid structures. This is true from an energetic as well as from an environmental point of view. Well-designed models, which take recycling potential into account, indicate differences between the structure types lower than approx. 10%.
- A key factor is the accessibility of the mass, which means that to benefit from thermal storage capacity, the slab systems must not be covered by suspended ceilings or false floors.
- For the slab systems a construction weight between 480 kg/m^2 and 650 kg/m^2 is beneficial. Increasing the slab thickness leads to only further slight improvements in energy efficiency of the operational energy use, but to increased environmental impacts as regards the product phase.
- To improve thermal comfort in summer, a natural ventilation strategy using passive cooling effects is a key parameter in conjunction with accessibility of the mass.
- Daily heat loads (internal and solar loads) up to 360 Wh/(m^{2}d) are realistic values in new office buildings. More than 50% of these heat loads can be buffered in massive slab constructions during the daytime and this makes efficient passive cooling possible through enhanced natural night ventilation.
- The comparison of energy and emission characteristic values highlights the importance of the resource requirements and environmental impact of future office buildings. Early on in the concept phase of sustainable building design, the reuse and recycling potential of building materials and components are aspects which are becoming increasingly influential.
- The primary energy demand of the product phase represents 30% to 50% of the energy demand of the operational energy use (similar results for global warming potential).

8.2 Analysis and discussion

8.2.1 Energy efficiency

The energy demand for heating and cooling based on the simulation results can be considered as quite low or optimised. One reason is the application of the reference zone method, see chapter 3. The energy balance calculation for an entire, real building has to take into account higher losses for the entire building envelope. Otherwise, the assumptions in this project correspond to high internal loads in order to reveal the possibilities and limits of low-tech concepts (dispensing with active cooling and mechanical ventilation). In a real building, internal loads can in turn be further reduced by energy-efficient lighting systems and office equipment and a lower occupancy rate which as a consequence results in less primary energy demand for electricity.

All things considered, the results are plausible and can be explained from a building physics point of view and underline the fact that future requirements for primary energy demand of less than 100 kWh/(m²a) can be met in office buildings, see chapter 4.3.2.3 (EnOB).The primary energy demand of heating, cooling and artificial lighting ($E_{prim}2$[52]) of almost all the simulation results clearly shows that well-chosen parameter combinations selected during the expertise-based parameter study, lead to energy-efficient office buildings, see figure 130.

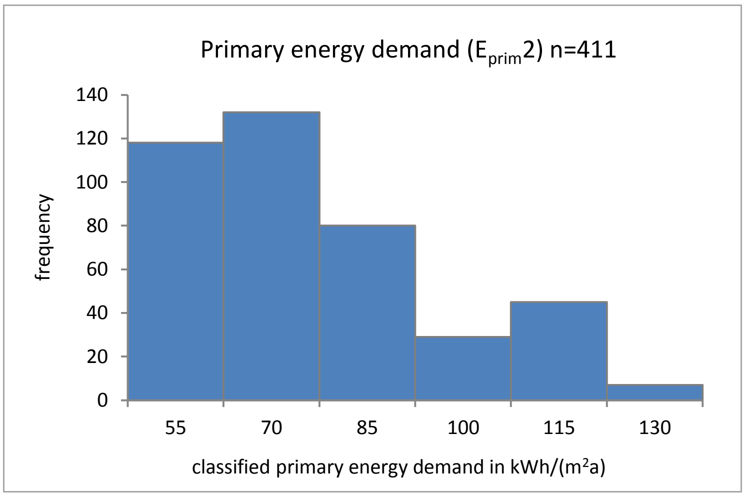


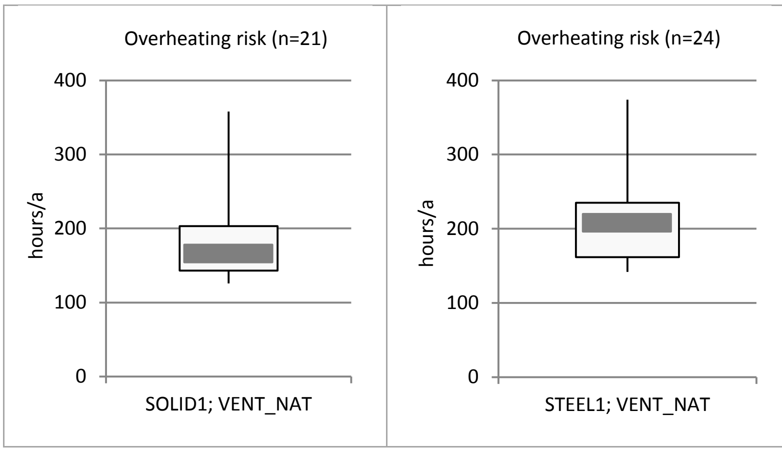
Figure 130: Frequency distribution of primary energy demand ($E_{prim}2$)

Well-considered or optimised stands for a high insulation standard of envelope and window elements, efficient, external sun protection and a natural ventilation system using passive cooling effects. Respecting these key parameters in the temperate European climate energy savings are optimised up to the limits of constructive and technical possibilities.

8.2.2 Low-tech concepts

The decision to select a low-tech concept or full air-conditioning determines the energy and technical concept. There is no doubt that an air-conditioning system, which offers many opportunities for optimising comfort (absorption of peak loads), has negative consequences in terms of electricity and primary energy demand and often reduces control options for the user. A higher standard of building technology commonly changes the operation mode of the building because the users' comfort requirements have been increased. However, dispensing with active cooling means that when considering national standards a number of annual overheating hours (> 26 °C) do fall in an acceptable range of approx. 160 hours/a - 200 hours/a (median values), but do not reach a comfortable range of less than 100 hours/a, see figure 131.

[52] not taking into account approx. 100 kWh/(m²a) electricity demand for office equipment and 15 kWh/(m²a) auxiliary energy for a mechanical ventilation strategy (VENT_MECH and VENT_NIGHT)



Parameter choice:

- SOLID 1
- STEEL 1
- no suspended ceiling (WSC)
- south, south-west + north orientation
- ratio of window area 48% +77% + 100%
- external shading device (SHON)
- triple glazing (EW1)
- natural ventilation strategy (VENT_NAT)

Figure 131: Overheating risk depending on structure type

The critical factor for low-tech concepts is being able to finely adjust the control system for the natural ventilation strategy. Further improvement has revealed that the overheating hours could be reduced to approx. 100 hours/a, see chapter 4.3.2.3. The technical feasibility of these concepts and user comfort with regard to employee well-being and performance must be carefully considered by both the planner and building owner.

8.2.3 Influence by the user

The possibility for the users to exert control is a criterion for evaluating a building's socio-cultural quality and it is assumed that the more users can influence the indoor climate the more they will be satisfied with it. In addition, users have considerable influence on a building's actual energy consumption. Depending on the user profile, average consumption may vary between 15% below or 60% above the indicative value of the standards [Hegger]. That this estimate covers such a wide range illustrates the difficulty in adequately mapping the users' influence during the planning phase. The design objective is an energy-efficient building which is highly flexible and robust as regards potential changes in its future use. To increase the planning team`s influence over the concept phase, it is essential that performance and technical specifications are defined by the building owner or user, particularly in the areas of comfort requirements and future use, e.g. the possibilities for user influence, occupancy rate, office equipment, lighting system and server rooms. Assuming a constant value of approx. 100 kWh/(m^{2}a) representing office equipment[53] and based on well-chosen constructive measures, primary energy demand could vary between 160 kWh/(m^{2}a) and 210 kWh/(m^{2}a), see figure 132.

[53] based on the simulation results, user influence not taken into account

1. Optimised design of the «office zone»	Constructive measures, potential influence of planner and design		
	+	+	+
2. Choice of energy and technical concept	Low-tech-concept, no mechanical ventilation and no active cooling	Mechanical ventilation system and active cooling + using night cooling effects	Mechanical ventilation system and active cooling
Approx. primary energy demand	**60 kWh/(m²a)**	**80 kWh/(m²a)**	**110 kWh/(m²a)**
		+	
3. Future use	User equipment, without taking into account users influence		
	primary energy demand of approx. **100 kWh/(m²a)**		
Approx. total primary energy demand	**160 kWh/(m²a)**	**180 kWh/(m²a)**	**210 kWh/(m²a)**

Figure 132: Office zone primary energy demand depending on the choice of energy concept

8.2.4 Reuse and recycling potential

For environmental evaluations, a lack of available data or consistent data makes it difficult to include the end-of-life scenario and recycling potential for all building materials. However, a comparative environmental study was feasible in this project which showed the environmental impact and the resources used to produce the main building components, facade system and supporting structure. The results reveal that the reason that there is quite a small difference between steel composite and solid structures is the substantial recycling potential of steel.

The choice of building materials, their resource requirements during the product phase as well as their recycling and reuse possibilities will become increasingly crucial for the design of future office buildings. Construction details should provide detachable material connections to ensure easy dismantling at the end-of-life phase. The aim is to increase the recycling and reuse rate of specific building materials so as to prevent most of them from ending up in landfills or thermal recycling (incineration), see figure 133.

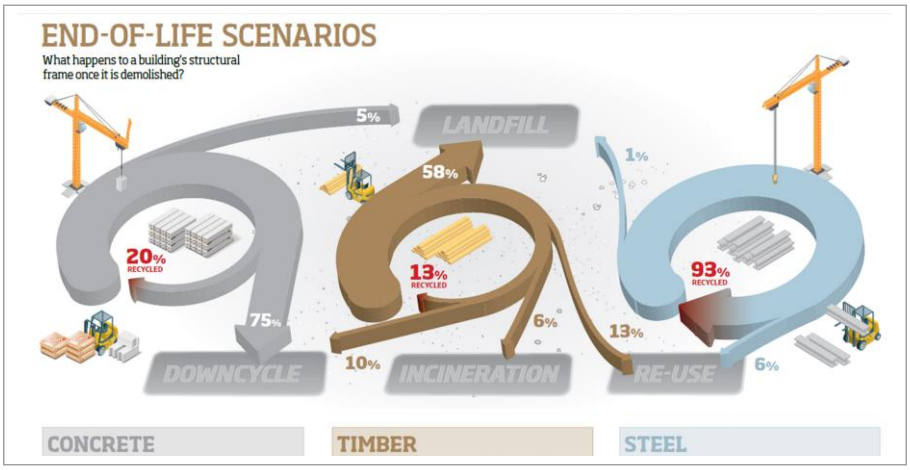


Figure 133: Example of present end-of-life scenarios for concrete, timber and steel [SCI]

The differences between steel, concrete and timber frame constructions become obvious when their end-of-life scenario is considered. The present percentage of reused steel varies between 6% [SCI] to 11% [BFS, 2010]. More than 80% is currently being fed back into the production process as steel scrap [BFS, 2010]. Structural steel is a reusable building material which can be categorised for the most part with the “cradle to cradle” principle of a closed material cycle, which in building construction means a high-quality “closed loop” in the production process. This principle is the basis of a “circular economy” and “closing the loop” means a product life cycle through greater recycling and higher reuse rates [EU, CE].

8.2.5 Cost analysis

Project costs and amortization periods are major aspects in the early planning phase, however, in the meantime the sustainability criteria that form part of national certification systems are also gaining influence, e.g. energy consumption, area efficiency or floor plan flexibility. The economic as well as the socio-cultural and ecological quality of an office building are decisive factors (monetary validation) for rentability reasons and for holding its real estate value.

Several discussions in the course of the project with experts working in the field have also confirmed that the cost of materials play a minor role when planners, investors and clients take the decision whether to build with a solid or a steel composite structure. In practice, the price difference between the two structure types is usually about 10% which is not decisive when compared with the entire cost of a building project. The decision-making depends on the project’s specific framework conditions, the building site, current national standards, specific planning and construction schedules and market prices. Due to all these factors, a cost analysis has not been included in this study.

8.3 Design guidelines

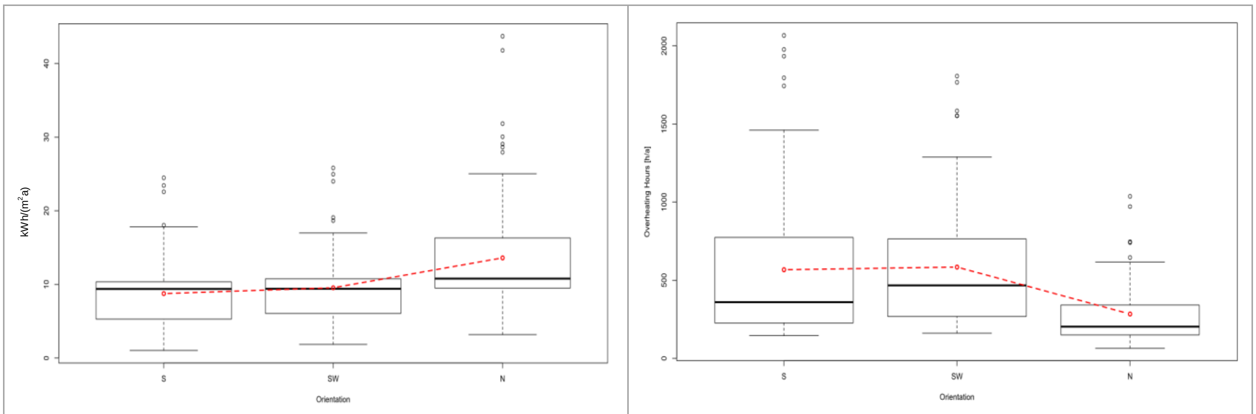
8.3.1 General recommendations

These guidelines have been developed for a temperate European climate and take into account specific recommendations for south, south-west and north facade orientations. Some suggestions will also be given for a Southern and Northern European climate.

The presentation of the recommendations focuses on facade design-related parameters which are identified as key parameters based on the sensitivity analysis (see table 22):

- ratio of window area
- shading devices
- type of glazing (U_g-value and g-value).

In addition recommendations will be given for the structure and slab type and the technical strategies for ventilation and artificial lighting. The orientation of the building should be considered as part of the facade design, because energy demand for heating and cooling (overheating risk) will vary depending on the facade orientation, see figure 134[54].



Heating demand (HD) in kWh/(m^2a)	Overheating risk (OH) in hours/a

Figure 134: Office zone heating demand and overheating risk related to orientation

8.3.1.1 Office buildings and supporting structure

Taking into consideration a number of constructive measures regarding the shape of the building and the supporting structure contributes to energy-efficient as well as to sustainable office building:

- the envelope should be highly insulated and airtight in compliance with the requirements of passive house standards
- the shape should have a compact or bar structure with a surface-to-volume ratio (A/V ratio) lower than 0.35
- a north-south orientation of the building is an advantage because east- and west-orientated facades are more critical as regards the risk of overheating.

Office building floor plans should be highly flexible so as to accommodate any future office organisation concepts and offer adaptive capacity, conversion feasibility and in consequence market value. Practicable and adequate construction and facade grids are well documented,

[54] representing median (grey line) and mean values (red dotted line) based on the sensitivity analysis database (n=201 experiments)

reference is made to [Eisele] and [Hascher] but the position of the central post has to be discussed. It is a key parameter which impacts on floor plan flexibility, the construction height of slab systems and in consequence on the entire volume of the building.

For the reference building which has a depth of 16 m, a column grid with one or two rows of central posts is favourable from an environmental point of view. Using a steel composite structure with a large span of 16m provides more floor plan flexibility but increases the environmental impact due to the heavy steel beams. Integrated floor beam systems are an interesting alternative as a way of reducing the total height of the slab. Omitting one row of central posts (column grid 11m/5m) is a good compromise and the solution can be a steel beam system or an integrated floor beam system, for example “CoSFB” which provides spans up to 14 m. Omitting one row of central posts is hardly possible with solid structures because there are spans of approx. 8m, however, these structures cause less environmental impacts compared to steel composite structures.

8.3.1.2 Facade design

Highly glazed buildings offer advantages with regard to artificial lighting, which accounts for a significant share of primary energy demand, see chapter 4.3.2. A band window facade is the best compromise and more beneficial than a fully glazed facade because further energy savings on artificial lighting are low, while at the same time the overheating risk and energy demand for heating increase, see figure 135[55]. This study has not confirmed any general recommendations for selecting a ratio of window area less than 50% or 60%.

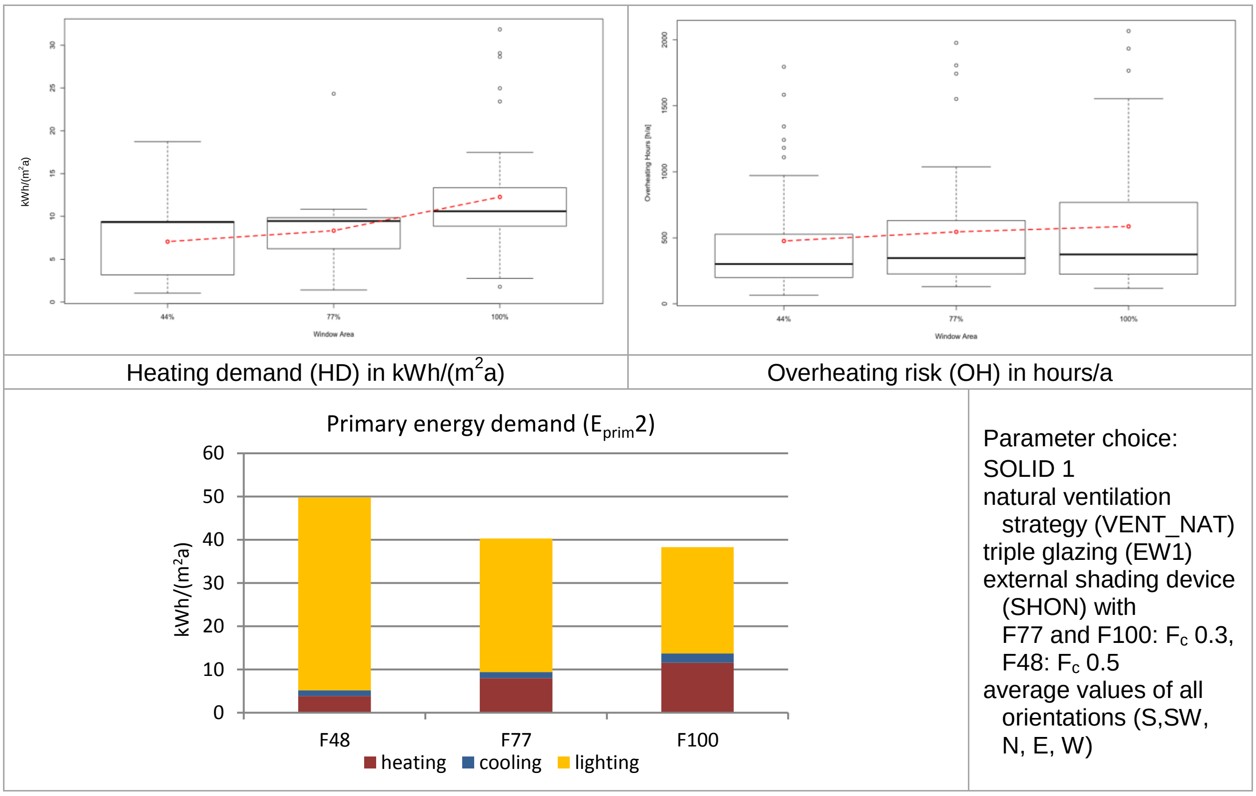


Figure 135: Heating demand, overheating risk and primary energy demand related to ratio of window area

[55] representing median (grey line) and mean values (red dotted line) based on the sensitivity analysis database (n=117 experiments)

A key parameter is achieving efficient sun protection by using an external, solar-controlled shading device. Provided that it works in an optimal manner, the impact of the orientation, the ratio of window area and the choice of glazing type become less relevant. A shading device with an opaque fraction of 70% (F_c-value of 0.3) is provided by shutters or venetian blinds and is suitable for a band window and highly glazed facade. For a punctuated facade, an opaque fraction of 50% corresponding to fixed slats, single slats or an overhang is preferable for south and north orientations.

Detailed adjustment of the control system for the shading devices and the lighting control systems is crucial in order to provide visual as well as thermal comfort. The best choice is a shading device which offers a good visual connection with the outside (transparency) and the most accurate light control, e.g. light-directing slats for efficient use of daylight. Time periods with closed shading devices and synchronous artificial lighting must be avoided. Electrochromic glazing systems offer an interesting and feasible alternative in highly glazed buildings. Installing the system leads to a similar energy demand and overheating hours when compared with the external shading device, and user acceptance is high due to the transparency. In general, it is beneficial to use internal blinds for additional glare protection in combination with external devices. The best choice is a “bottom-to-top” system which prevents direct solar radiation reaching the workplace, without restricting the use of daylight in the upper section of the window element.

In temperate climate zones with low nighttime and winter temperatures, insulating glass unit (triple glazing) is the best choice. The thermal and optical characteristic values should provide low thermal transmittance (U_g-value) and high selectivity, which means low solar energy transmittance (g-value) and high light transmittance (Tvis).

From an environmental point of view the increase in the window area has a negative impact because until today glazing offers no recycling potential. However, the impact of the building operation has a greater effect on the entire life cycle and a higher ratio of window area can therefore be recommended. The opaque part of the facade system should be as slim as possible in order to save weight and mass. Furthermore, lightweight claddings require sub-constructions which are less heavy and the same applies to metal constructions. The insulation material should have a low thermal conductivity in order to reduce the thickness of wall elements, particularly in case of stud partition elements.

8.3.1.3 Structure and slab type

In highly flexible office buildings the internal walls are commonly metal stud partitions and cannot be used for thermal storage capacity. The accessibility of the slabs systems is decisive and a suspended ceiling or a false floor (both lead to similar negative effects) has consequently to be avoided. Apart from the additional material resources required also the energy demand respectively the overheating risk strongly increases.

The slab systems should have a minimum weight of 480 kg/m^2 - 580 kg/m^2 including screed (approx. 100 kg/m^2 - 140 kg/m^2) from an energetic point of view. Increasing the thickness of the slab results in only slight improvements as far as thermal comfort is concerned, and is not advisable from an environmental point of view. The less mass and weight that is installed, particularly in multi-storey buildings, the lower the environmental impact in terms of the supporting structure, exterior walls and foundations. The evaluation of end-of-life scenarios is to be recommended and it reveals the impact of the future reuse and recycling potential of building materials or components, e.g. the fact that there are quite small differences between steel composite structures and solid structures. In the end, the choice of structure type is less decisive when the accessibiltiy of the mass is quaranteed.

In case of waiving of a suspended ceiling, there are alternatives available on the market which can provide acoustic comfort, for example, flexible sound absorber panels or acoustic measures integrated into wall elements. Cabling for technical installations should be routed in the floor structure and this is best done using e.g. floor ducts. A feasible alternative is to use additional parapet ducts or suspended ceilings merely in the corridors.

8.3.1.4 Technical measures

When a low-tech concept is planned using passive cooling effects, focusing on reducing annual overheating hours is recommended.

Cooling, heating and ventilation

In a temperate European climate, a concept using passive cooling effects, especially during nighttime, is a powerful low-tech option that allows office buildings to reduce heat loads (solar and internal loads) and it is strongly recommended. During the transition periods, additional use of natural daytime ventilation is beneficial because it is quite possible to use it throughout the year, except during a few very hot respectively very cold days. Active cooling could then be dispensed with. However, when active cooling is used, a set point temperature of 26 °C is advisable because lower set points lead directly to a two-to-threefold increase in cooling demand.

A natural ventilation system with an enhanced day- and nighttime ventilation system used in conjunction with an appropriate control system (fine adjustment) is a good choice:

- lowering the supply air temperature to 19 °C during the night and to 22.5 °C during the daytime is mostly efficient; lower temperatures can cause discomfort
- the hygienic base change rate during operation time provides constantly fresh air with ambient temperatures, the supply air grille position should not cause discomfort e.g. draught effects
- control systems inside the office space could help the user to open the windows adequately e.g. when the ambient temperatures are unfavourable or should there be a high CO_2 concentration inside the office space.

For a mechanical ventilation system with pre-heating and pre-cooling, it is advisable to have the supply air at a constant temperature at 18 °C with a heat recovery rate of more than 70% so as to further reduce energy demand for heating.

Artificial lighting

In today's energy-efficient office buildings, the specific electricity consumption for lighting is approx. 10 kWh/(m^2a) and for pure office space it is deemed to be about 7.4 kWh/(m^2a) [Voss, 2006]. The electricity demand for lighting of the office zone has an average value of approx.

13 kWh/(m^2a) in a range from 8 kWh/(m^2a) to 31 kWh/(m^2a). Lighting efficiency can be further improved by:

- best use of daylight e.g. by light-directing shading elements
- dimmable daylight-controlled systems using light sensors and presence detectors
- electrical power lower than 10 W/m^2
- lighting management in conjunction with external and internal shading device control
- using more decentralised systems e.g. individual lighting at the workplace or adjustment depending on the activity in the room (different light scene)
- reducing nocturnal, interior lighting (light pollution).

8.3.1.5 Suggestions for Northern and Southern Europe

Investigations using the highly glazed (band window facade) reference office zone, located in a continental Southern European climate (Madrid, Spain) and Northern European climate (Östersund, Sweden), show that the technical strategies used to provide heating, cooling, ventilation and sun protection need to be adapted. Other design parameters have not been investigated further in this project and reference is made to [Hausladen, 2012].

In Southern and Northern Europe, because there are long periods of time with unfavourable ambient temperatures, it is hardly advisable to use natural air exchange when a building is in operation.

In a Northern European climate, a mechanical ventilation system with supply air pre-heating and improved heat recovery rate is useful for guaranteeing thermal comfort in winter. Using passive cooling effects is only advisable during the nighttime.

In a Southern European climate, active cooling based on a set point temperature at 26 °C is necessary for the reference zone to comply with thermal comfort requirements. A mechanical ventilation system with supply air pre-cooling and that uses passive cooling effects during the nighttime and in the early morning is recommended. Apart from an external shading device, a solar control glass with a low U_g-value is the best choice for a south-west and south orientation and a thermal insulation glass for a north orientation. Electrochromic glazing is an interesting alternative as it offers a compromise between visual comfort and efficient solar protection.

8.3.2 Steel practice

The evaluation results have proven that steel composite structures are competitive compared to solid constructions from both an energetic as well as an environmental point of view. In terms of energy efficiency and thermal comfort the accessibiltiy of the mass should be quaranteed because in practice the problem of steel composite structures is the covering with a suspended ceiling or/and a false floor which is commonly used. In terms of CO_2 emissions (global warming potential) an optimised selection of building materials offers additional benefits for steel composite structures. For office buildings, considerations involving flexibility (floor plan design, office organisation), adaptive capacity and conversion feasibility are decisive when opting for a steel composite structure. These evaluation criteria form part of several national sustainability certifications and are of considerable importance for an office building’s market value. The advantages offered are substantial recycling potential and the possibilities of reuse, as well as a high degree of prefabrication and potentially large spans for column-free spaces.

8.3.2.1 Case study

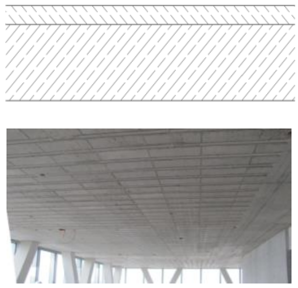
A concise presentation using a case study demonstrates the impact that gradual optimisation steps can have on energy saving potential and on reducing annual overheating hours. The case study involves a lightweight, steel composite structure with a fully glazed facade. The aim is to prove whether it is possible to achieve energy efficiency and thermal comfort in summer comparable to what a conventional solid structure can provide.

The solid structure (SOLID 1) represents a heavy construction without a suspended ceiling with a mechanical ventilation system that uses night cooling effects, see figure 136. The energy demand for heating and cooling is approx.14 kWh/(m^2a) and the amount of overheating hours per year reaches approx. 400 when the active cooling is switched off.

SOLID 1

280 mm reinforced concrete + 70 mm cement screed

weight[56] approx. 670 kg/m^2 + 140 kg/m^2



Parameter choice:

- south-west orientation
- band window facade (F77)
- external shading device (SHON)
- thermal insulation glass (EW1)
- mechanical ventilation strategy incl. night ventilation (VENT_NIGHT)
- no suspended ceiling (WSC)

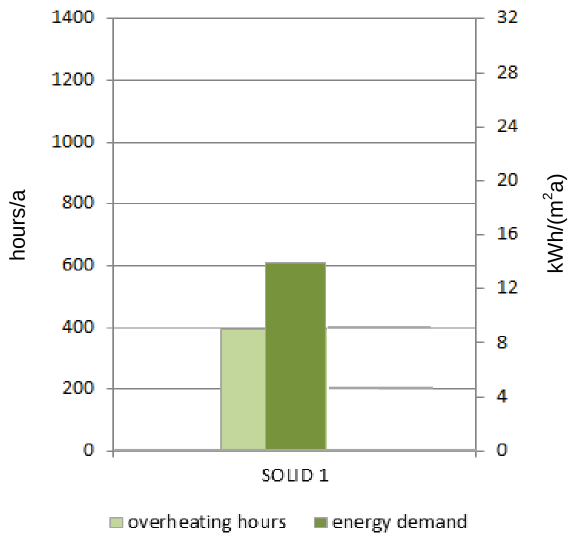


Figure 136: Energy demand (heating and cooling) and overheating hours per year for a typical solid structure

The case study presents a lightweight steel composite structure with a suspended ceiling and fully glazed facade that also has a mechanical ventilation system using night cooling effects, see figure 137. The energy demand for heating and cooling is approx. 30 kWh/(m^2a). If active cooling is switched off the amount of overheating hours per year reaches 1,370 h/a.

[56] without taking columns into account

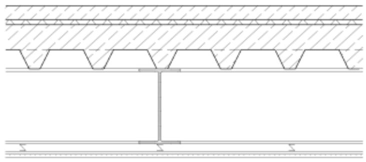
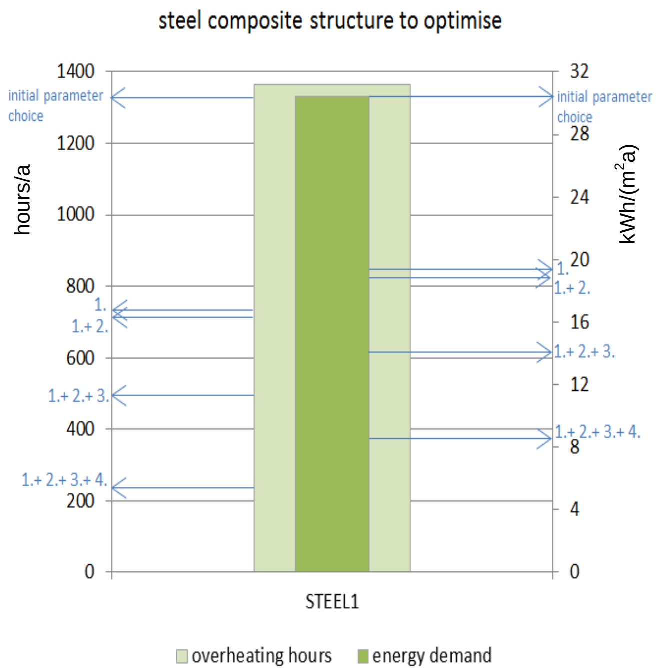
STEEL 1 steel beams, profiled sheeting C60 + 100 mm concrete, false floor, suspended ceiling weight[57] approx. 250 kg/m²	 		
Initial parameter choice: - south-west orientation - fully glazed facade (F100) - external shading device (SHON) - thermal insulation glass (EW1) - mechanical ventilation strategy incl. night ventilation (VENT_NIGHT) - suspended ceiling (SC)	 	Gradual optimisation steps[58]	
		1. Removing suspended ceiling	- 40%
		2. Increasing massivity	- 4%
		3. Decreasing window area	- 29%
		4. Natural ventilation strategy	- 47%

Figure 137: Gradual optimisation steps demonstrated using a case study

The optimisation steps indicate a substantial energy saving potential of approx. 70% and a high impact on reducing the annual overheating hours by approx. 80%. Removing the suspended ceiling (accessibility of the mass) and the ventilation strategy have a significant impact. The results confirm that the mass of the structure type is less decisive and that using a band window facade instead of a fully glazed facade is advisable. Natural ventilation using passive cooling effects during both day- and nighttime greatly improves energy efficiency and thermal comfort, see table 41.

[57] without taking into account beams and columns, false floor or suspended ceiling
[58] average values of saving potential of energy demand and overheating hours

Table 41: Impact of the gradual optimisation steps on energy demand and overheating risk using a case study

Optimisation step	Definition	Energy demand		Overheating hours	
		$kWh/(m^2a)$	Saving potential %	hours/a	Saving potential %
Base	Lightweight steel composite structure with suspended ceiling and fully glazed	30	/	1370	/
1	Removing the suspended ceiling and installing a 55 mm cement screed instead of a false floor (weight 250 kg/m^2 + 100 kg/m^2)	19.6	36	789	43
2	Increasing the massivity of the slab, opting for an integrated floor beam system (STEEL2), with 55 mm cement screed (weight 552 kg/m^2 + 100 kg/m^2)	18.4	6	777	2
3	Decreasing the ratio of window area from 100% to 77% (band window facade)	14.6	21	495	37
4	Natural ventilation strategy (VENT_NAT) with enhanced day- and nighttime ventilation instead of a mechanical ventilation strategy using night ventilation (VENT_NIGHT)	8.7	41	239	52

Further optimisation potential lies in the adjustment of the natural ventilation strategy[59] (VENT_NAT_improved, see table 16). It could reduce the overheating hours to a more comfortable range of less than 100 h/a, see chapter 4.2.6. Additionally, it can be assumed that profiled steel sheet decking provides better opportunities for passive cooling as it has a higher effective thermal capacity than conventional flat slabs [Döring].

The problem of systems with profiled sheeting is that usually they are covered to provide acoustic measures and space for technical installations, and they also fail to meet aesthetical requirements if the lower surface is not covered. There is an increased need for well-considered construction details and fire protection measures. On the other hand, a broad range of technically feasible fire protection measures are available on the market and, for example, integrated floor beam systems with precast concrete elements provide an alternative to the profiled sheeting.

8.3.2.2 Phase-change materials

A study of [Döring] has shown that to increase thermal capacity, phase-change materials (PCM) provide an interesting option for lightweight systems. The author states that a quantity of PCM of approx. 8 kg/m^2 is sufficient provided that the room air temperature remains below 26 °C. If there are higher temperature peaks, this quantity has to be substantially increased up to 20 kg/m^2. Phase-change materials are beneficial for lightweight structures and are best used when the phase-change temperature is similar to the room air temperature [Döring]. The reason why PCMs have only been sporadically used up until now in building construction is scientifically investigated in an ongoing research project “PCM-Demo II – Section Development,

[59] not shown using the case study

Optimisation and Demonstration of surface cooling systems with PCMs for non-residential buildings” [EnOB, PCM]. The aim is to evaluate the practicality of several of the products and systems available on the market. This project focuses on PCMs in surface cooling systems and ventilation systems for non-residential buildings among other areas.

8.3.2.3 Conclusion

As it turns out, the complexity of buildings and the variety of possible parameter combinations make it difficult to define statements which can be generalized. The recommendations developed do not claim to be exhaustive; however, if the key parameters are chosen based on the recommendations, a robust, energy-efficient and sustainable design for office buildings can be achieved. Finally, it can be concluded that the general statements in the parameter study, corroborated by the sensitivity analysis and the conclusions can be deemed to be universally valid for similar office building designs.

8.3.3 Graphical presentation

Already in the early concept phase, the graphical presentation in the style of a nomogram gives planners an overview of the impact of their design decisions. The following graphs show examples of the impact of the choice of structure and slab type, the ratio of window area and glazing type on overheating risk, see figure 138, and on primary energy demand, see figure 139. An external shading device and a natural ventilation strategy using passive cooling effects are fixed because they nearly always offer an advantage. The definitions SOLID, STEEL1 and STEEL2 as well as the ratio of window area correspond to the parameter introduction in chapter 4.1. The triple glazing (T) and the double glazing (D) correspond to the thermal insulation glass (EW1 and EW2).

The diagrams clearly show that the best parameter choice depends on the energy concept selected for the building. When a low-tech concept is planned, the focus should be on reducing annual overheating hours; but when there is active cooling and a mechanical ventilation system the focus should be on primary energy demand. The reduced energy demand for heating is taken as a precondition for all results presented.

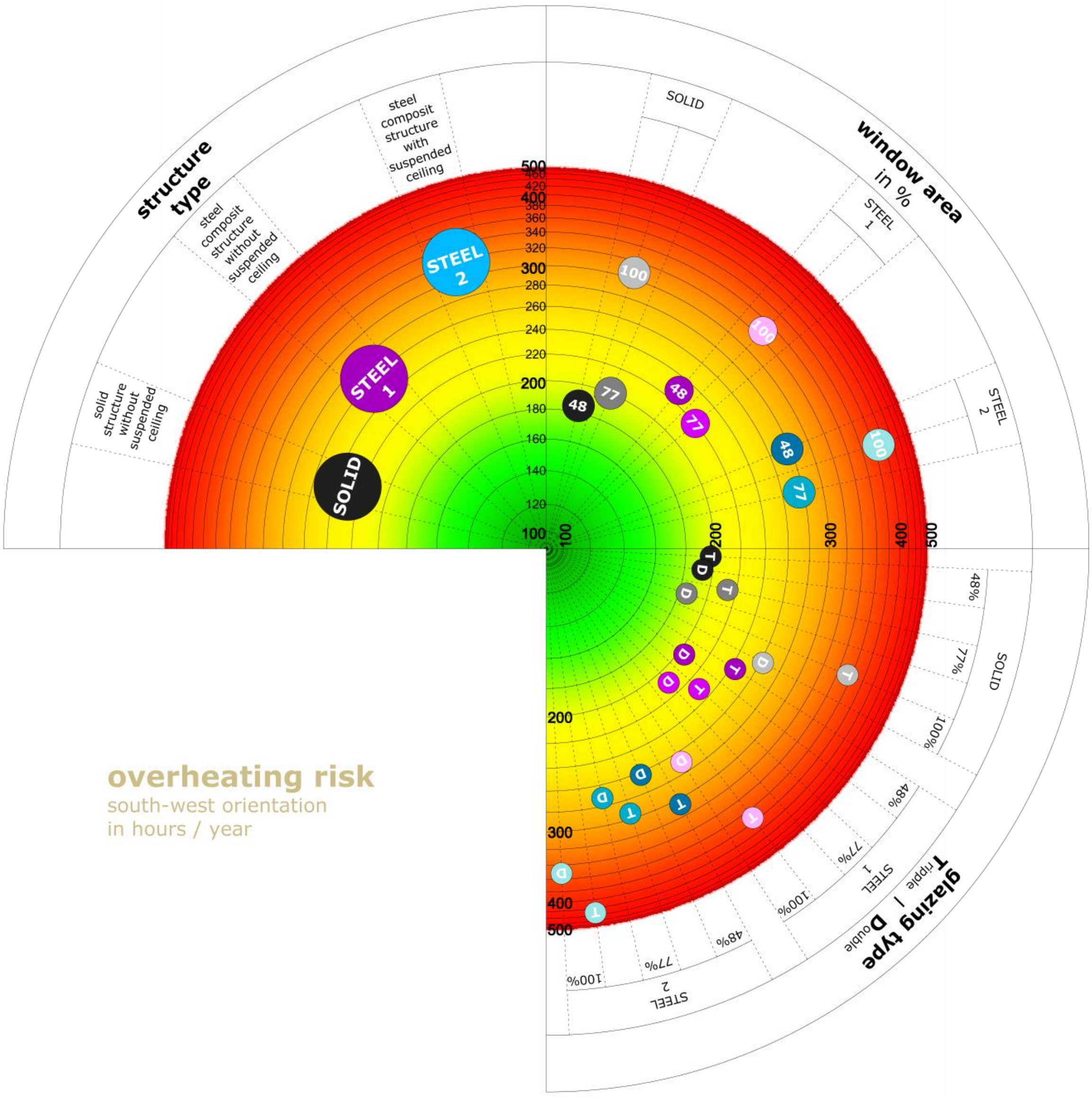


Figure 138: Overheating risk depending on the choice of structure type, window area and glazing type based on the example of a south-west orientation

The best choice for thermal comfort in summer in a south-west orientation of the facade is a solid structure (SOLID, marked in black) with a band window facade (77, marked in grey) and double glazing (D, marked in grey). This choice causes approx. 180 overheating hours per year. In case of a steel composite structure without suspended ceiling (marked in purple) the best choice is a punctuated facade (48, marked in purple) and double glazing (D, marked in purple) with approx. 210 overheating hours per year. A worst case scenario is represented by a steel composite structure with suspended ceiling (STEEL 2, marked in blue), a fully glazed facade (100, marked in light blue) and triple glazing (T, marked in light blue) which causes approx. 450 overheating hours per year.

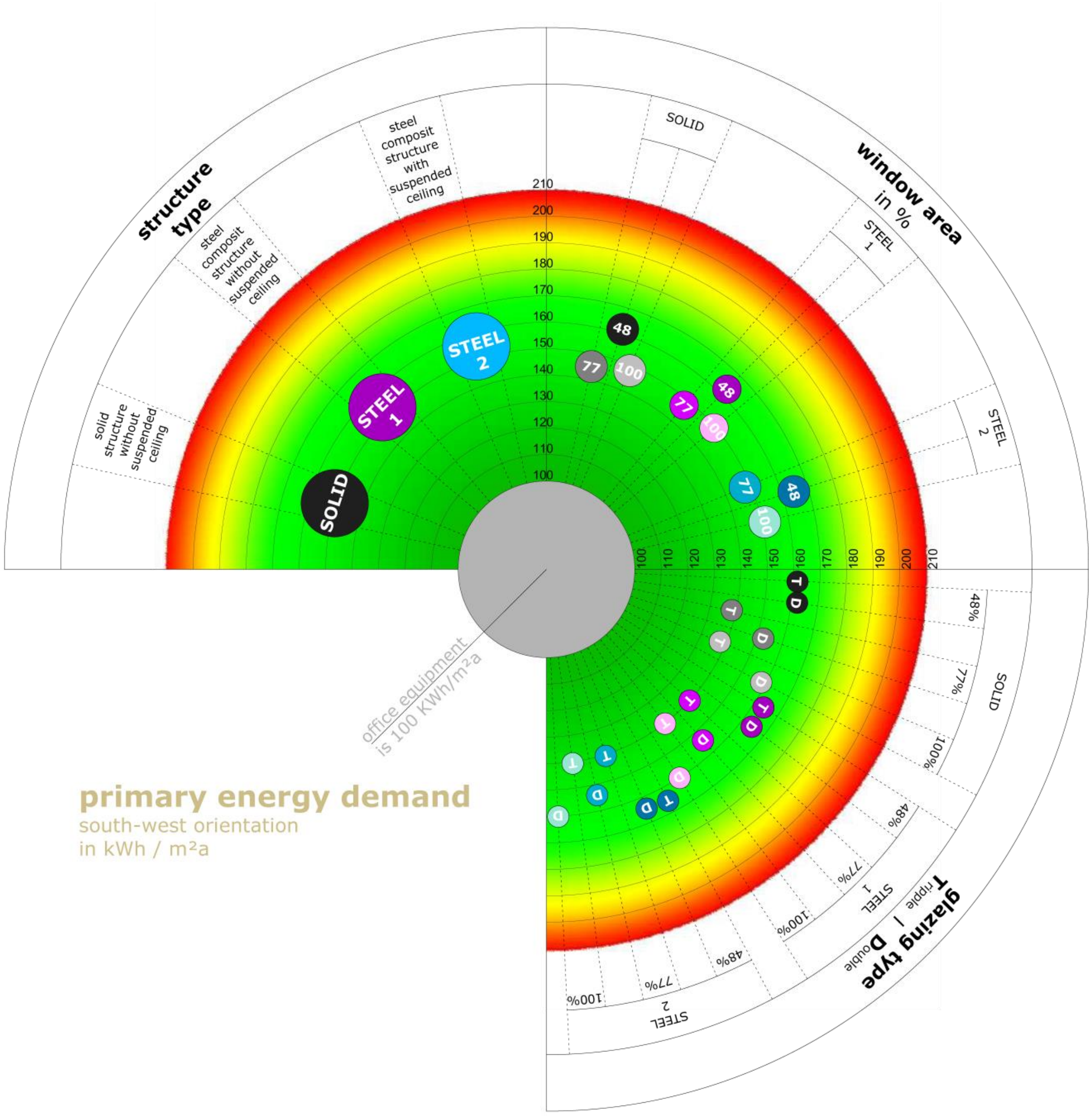


Figure 139: Primary energy demand depending on the choice of structure type, window area and glazing type based on the example of a south-west orientation

The best choice for reducing primary energy demand ($E_{prim}2$, see chapter 4.3.1) is a band window facade (77, marked in grey according to SOLID, marked in purple and blue according to STEEL 1 respectively STEEL 2) and triple glazing (T, colours according to structure type and window area). A band window facade is beneficial due to efficient daylight use and less artificial lighting. The choice of structure type is less decisive. An optimised parameter choice of the office zone causes approx. 140 kWh/m^2a of primary energy demand, taking into account an amount of approx. 100 kWh/(m^2a) for office equipment.

The graphs present the project results in a simple, structured and graphical way. Further investigations for the development of a tool are intended, and the graphical output could form the basis for the output presentation of such a tool.

9 Conclusion And Outlook

9.1 Conclusion

This study in the field of energetic and environmental assessment has revealed findings about the best parameter choice with regard to office building facade design and structure type. Design flexibility as well as the constraints for highly glazed buildings and steel composite structures became apparent. The study has proven that a parameter choice based on the recommendations presented will result in energy-efficient and sustainable building design. The optimisation potential lies in the area of fine-tuning the facade-related design parameters. To comply with energetic and lighting requirements, being able to adjust the control strategies for the shading devices and artificial lighting is essential. In addition, the application of natural ventilation strategies using passive cooling effects in conjunction with constructive measures requires detailed optimisation of all parameters. With regard to the research question ‘How and to what extent are steel composite structures competitive with solid structures?’, the holistic view based on energetic, metrological and environmental investigations has revealed a wide range of different possibilities for constructional execution. The results have clearly indicated that in case of a well-designed office building in steel composite structure the energetical and environmental impacts are very similar when compared to a solid structure.

A comparison of energy and emission characteristic values confirms the importance of the product and end-of-life phase for primary energy demand and environmental impact when compared with the building operation.

The expertise-based parameter study, the supplementary sensitivity analysis and the metrological investigations allowed a corroboration of the results and the development of generalisable guidelines and recommendations. They can be deemed to be reliable and universally valid for similar office building designs, while it remains true that the specific conditions of the urban context and complex building geometry will require detailed considerations later on in the planning process. However, for the concept phase, it is reasonable to work with guidelines and so-called “rules of thumb”. The conclusions from this study can be classified as representative for the design of office buildings in the temperate climate zone. The study induces similar results and conclusions when compared to other studies in this research field (see ABP, EnOB, Hegger, Knaack and Zimmermann).

The complexity of buildings and the vast amount of parameters involved in designing and constructing them make it difficult to evaluate the entire range of possible parameter combinations. For this reason, several design decisions and parameters were defined, based on architectural experience using typical values for office buildings. This method (expertise-based decision-making) based on predefined scenarios has proven to be valid for the analysis of specific parameters. On the other hand, this trial-and-error process is time-consuming and ineffective for an optimisation process due to the difficulties of exploring a large decision space [Asadi]. The additional application of an optimisation platform has provided new possibilities concerning the design of experiments (DoE) and the optimisation process.

9.2 Outlook

In a next step in this project, a highly automated workflow for the application of building simulation and optimisation features is intended. For complex simulation applications and simulation-based multi-objective optimisation processes, the tools are directly connected to each other, for example building thermal simulation software, generic optimisation tools (e.g. GenOpt of the University of California, Lawrence Berkeley National Laboratory) and specific optimisation techniques to run the simulation software in an automated way (parametric runs). Furthermore, evolutionary multi-objective algorithms could help to further evaluate all the possibilities for parameter combinations without causing a combinatorial explosion of the decision space which is extremely complex and time-consuming [Asadi]. The application of these methods and tools in a next step, also see chapter 5.5 (Minamo, DesParO), will make it possible to provide a larger database of energetic and environmental results for the further development of a decision-making tool. However, the planning recommendations and the characteristic values developed in this project have already contributed a simplified procedure for the evaluation of energetic and environmental impacts of design decisions in the concept phase. The graphical presentation in the style of a nomogram offers planners a decision-making aid for thermal comfort and primary energy demand.

A further objective is the development of a simple decision-making tool suitable to be used in daily practice to estimate the energy demand and environmental impact of design models. The simulation results and the energy and emission characteristic values (benchmarks) generated in this project could form the basis for such a planning tool. To develop this further, the data base has to be extended and transferred to a computer-assisted process. The correlations and dependencies between individual parameters or parameter combinations that have been established and their results must be mathematically and computationally defined in order to predict the results of possible designs, e.g. parametric dependencies of the environmental impact of building material or the energy demand caused by artificial lighting.

The need for these tools and the area of tension between developments in research and discrepancy in the field of practical application is also reflected in the topics dealt with at the Building Simulation Conference (BS2015), which are for instance in the field of improving building performance simulation tools (BPS) to close the gap between science and daily practice, the development of optimisation tools and methods to connect BPS tools with generic optimisation methods or with application software, e.g. CAD and BIM. In addition, the need for a holistic evaluation of energetic and environmental aspects can be seen in a project running currently in Luxembourg to implement a valuation basis for the environmental impact by the integration of material-specific data into energy calculation software, see [Lichtmess].

Further investigations are intended to evaluate the impact of phase-change materials and to quantify the possible optimisation potential for lightweight or medium-weight steel composite structures. Due to the fact that lighting is a key parameter in energy-efficient buildings, to complement the results from this project, it is also necessary to apply daylight simulation software that takes into account the daylight factor, autonomy, useful daylight, illuminance level and energy use for electric lighting.

An interesting study could also be in the field of office building refurbishment and conversion possibilities, given the fact that raw materials are finite and resource requirements are gaining influence. The study should evaluate whether the conclusions presented in this project are applicable for existing buildings if their refurbishment is a possibility. The study could further focus on building materials, and consider the aspects of circular economy and leasing principles, for artificial lighting or steel products, for example. In building construction, leasing recyclable materials is difficult due to the monetary valuation of utilisation cycles of more than 30-50 years. On the other hand, there are various ongoing developments, such as the so-called “circular house”, for example. The aim for a building to be made from components which can all be reused, remade or recycled once the building has reached the end of its life, was shown at the 2016 London Design Festival where a small building was exhibited as an example of this concept.

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Appendix

Appendix 1
Description of the simulation model

Reference office zone

Table A1-1: Data of the office zone

Office zone	Dimension	Unit
Dimensions	21.60 * 5.56	m
Storey height	3.35	m
Gross floor area	120.10	m^2
Net floor area/energy relevant area	110.38	m^2
Gross volume	402.32	m^3
Net volume	331.14[60]	m^3
Area of exterior wall (calculated from outside)	72.36	m^2
Area of exterior wall (calculated from inside)	64.43	m^2
Gypsum plasterboard wall inside	79.85	m^2
Climate conditions of the boundary zones are identical to those of the office zone		
Thermal capacity	2414	KJ/K
U-value of opaque exterior wall	0.17	$W/(m^2K)$
Facade system	element facade, curtain wall system, glazing types see table below	
Window-to-wall ratio (calculated from inside)	48% , 77% , 100%	
Weather data (Meteonorm / Europe database)	- Saarbrücken, Germany - Östersund, Sweden - Madrid, Spain	

Table A1-2: Shading devices of facade systems

Nomen-clature	Definition	Opaque fraction	Close if	Open when
SHON	External shading device, radiation-controlled, all times	70% (50%)[61]	total radiation on facade > 140 W/m^2	total radiation on facade < 120 W/m^2
SHON2	External shading device, radiation-controlled, all times	70%	total radiation on facade > 180 W/m^2	total radiation on facade < 150W/m^2
SHOFF	No external shading device			

Table A1-3: Glazing types of facade systems

Nomen-clature	Definition	Thermal transmittance (U_g-value in $W/(m^2K)$)	Solar energy transmittance (g-value)	Visible light transmittance (Tvis)	Selectivity (S)
EW1	Triple glazing, insulation glass unit	0.59	0.58	0.74	1.27
EW2	Double glazing, insulation glass unit	1.24	0.58	0.76	1.30
EW3	Double glazing, solar control glass	1.23	0.44	0.62	1.41
EW4	Triple glazing, solar control glass	0.59	0.45	0.66	1.46
EW6	Double glazing, insulation glass unit	0.75	0.44	0.713	1.62

[60] The gross volume of the office zone is 402 m^3. Depending on the different slab types, the net volume varies between 300 m^3 and 330 m^3, which leads to slightly higher and varying air change rates.

[61] identical with F_c-value, shutters or venetian blinds 0.3 or 0.25, fixed slats or single louvres 0.5 according to DIN 4108-2

Table A1-4: Electrochromic glazing types of facade systems

Nomen-clature	Definition	Thermal transmittance (U_g-value in W/(m^{2}K))	Solar energy transmittance (g-value)	Visible light transmittance (Tvis)	Selectivity (S)
ELEC2_120	Electrochromic triple glazing, solar radiation control, 120 W/m^2 - 420 W/m^2	0.78	0.41 - 0.05	0.33[62] (0.41 - 0.01)	1.00 - 0.16
ELEC2_380	Electrochromic triple glazing, solar radiation control, 380 W/m^2 - 780 W/m^2	0.78	0.41 - 0.05	0.38 (0.41 - 0.01)	1.00 - 0.16
ELEC3_380	Electrochromic triple glazing, solar radiation control, 380 W/m^2 - 780 W/m^2	0.74	0.37 - 0.03	0.51 (0.55 - 0.01)	1.48 - 0.32

User and occupancy concept

Table A1-5: Definition of user and occupancy concept

NO.	Parameter	Definition
1	Schedule/ Operation time (USE)	260 days/a, 7:00 am - 6:00 pm => 2.860 hours/a
2	Occupancy rate	10 people, seated, light work (ISO 7730), 75 W/person[63], 6.8 W/person and m^2 during USE
3	Internal loads	11 W/m^2 office equipment during USE + 2 W/m^2 office equipment at all times/stand-by (140 W/PC, USE *8.5 + 1.5)

HVAC concept

Table A1-6: Definition of HVAC concept

NO.	Parameter	Definition
1	Lighting system	worklight hours 7:00 am to 7:00 pm (5 days a week) => max. 3,120 h/a 10 W/m^2, fluorescent tubes, 40% convective part light control function based on shortwave solar radiation through external windows artificial lighting is turned on if solar radiation inside is ≤ 5 W/m^2, it is turned off if solar radiation inside is ≥ 10 W/m^2
2	Heating	Set point indoor temperature: 22 °C daytime, 16 °C night time, all season, unlimited heat power, no humidification
3	Cooling	**Case 1**: active cooling set point indoor temperature: 26 °C at all times, unlimited cooling power, no dehumidification **Case 2**: no cooling **Case 3**: active cooling setpoint indoor temperature: 24 °C at all times, unlimited cooling power, no dehumidification

[62] Average values depending on the control system.

[63] people are not determined with 150 W, but with 75 W; 150 W including 75 W latent (thermal conduction, cannot be measured) and 75 W sensible (convective + radiative); approx. 7 W/m^2 in single office per person [Dentel]

Table A1-6 continued

NO.	Parameter	Definition (basic strategies)
4	Infiltration rate	0,1 h^{-1} (24h, 7 days a week), high quality air-tightness of the envelope
5a	Ventilation strategy	**VENT_MECH**: mechanical ventilation system controlled, constant air flow during USE (7:00 am - 6:00 pm) supply temperature of 18 °C air change rate 1 h^{-1} and heat recovery rate of 70%
		VENT_NIGHT: identical to VENT_MECH + enhanced night ventilation controlled night-time ventilation (natural cooling by automated facade flaps) air change rate 4 h^{-1} ventilation is switched on if room air temperature is ≥ 25 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 20 °C
		VENT_NAT: natural ventilation by enhanced daytime-night time ventilation hygienic base change rate 0,7 h^{-1} during USE (7:00 am - 6:00 pm), low polluting building, equates to approx. 30 m3/person controlled daytime ventilation (automated windows and/or users) air change rate 2 h^{-1} ventilation is switched on if room air temperature is ≥ 25 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 23.5 °C controlled night-time ventilation (automated facade flaps) air change rate 4 h^{-1} ventilation is switched on if room air temperature is ≥ 25 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 21 °C
		Definition (improved strategies)
5b	Ventilation strategy	**VENT_NIGHT_24 °C**: mechanical ventilation system controlled, constant air flow during USE (7:00 am - 6:00 pm) supply temperature of 18 °C air change rate 1 h^{-}1, heat recovery rate of 70% controlled night-time ventilation (natural cooling by automated facade flaps) air change rate 4 h^{-1} ventilation is switched on if room air temperature is ≥ 23 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 20 °C
		VENT_NAT_24°C: natural ventilation by enhanced daytime-night time ventilation hygienic base change rate 0.7 h^{-1} during USE (7:00 am - 6:00 pm), controlled daytime ventilation (automated windows and/or users) air change rate 2 h^{-1} ventilation is switched on if room air temperature is ≥ 23 °C and if the internal and external temperature difference is greater than 2 K, ventilation is switched off if room air temperature is ≤ 22.5 °C controlled night-time ventilation identical as in case of VENT_NIGHT_24 °C

Appendix 2
Material list and quantities of the reference office zone

Facade system

The systems consist of:

- non load-bearing exterior wall elements (opaque part) including wall element, insulation material, interior finishing, exterior cladding
- window elements with triple glazing (window-to-wall ratio of 48%, 77% and 100%)

Table A2-1: Definition of exterior wall elements

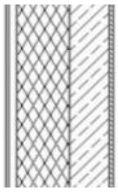
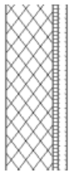
Exterior wall elements	Definition of opaque element	Sketch
SOLID	015 mm gypsum 150 mm reinforced concrete, C 20/25 (1% vol. steel) 200 mm insulation material 030 mm air layer/sub-structure ventilated + exterior cladding	
STEEL	025 mm gypsum plaster board 015 mm oriented strand board (OSB) 140 mm (optional 200 mm) steel construction (10% vol. steel) incl. insulation material + exterior cladding	

Table A2-2: Definition of insulation materials

NO.	Insulation material	WLG	Thickness in mm	Density in kg/m^3
1	mineral wool (rock wool), low density	035	200	41
2	expanded plastic slab (PUR, polyurethane)	035/025	200/140	31
3	expanded polystyrene (EPS)	035	200	23
4	extruded foam (XPS, polystyrene)	035	200	35

Table A2-3: Definition of cladding materials

NO.	Cladding material	Thickness in mm
1	fibre cement board	12
2	aluminium coffer sheet	1.5
3	steel coffer sheets	1.5
4	flag (lime stone)	40
5	flag (granite)	30
6	glass fibre reinforced concrete panels	13
7	sheet of aluminium folded profile 65/400	0.7
8	sheet of steel folded profile 65/400	0.7

Material choice for comparison of exterior wall elements on component level per m^2:

SOLID A: EPS + fibre cement board

SOLID B: mineral wool + glass fibre concrete panel

STEEL A: PUR (140mm) + folded steel profile

STEEL B: mineral wool (200mm) + folded steel profile

Table A2-4: Definition of window elements

NO.	Window elements
2.1	Self-supporting aluminium frame construction incl. triple glazing
2.2	Self-supporting steel frame construction incl. triple glazing

Material choice for comparison of facade systems, influence of window-to-wall ratio per m^2:

SOLID A: SOLID + EPS + fibre cement board + aluminium frame construction
incl. triple glazing

SOLID B: SOLID + mineral wool + glass fibre concrete panel + steel frame construction
incl. triple glazing

STEEL A: STEEL + PUR + folded profile steel + steel frame construction
incl. triple glazing

STEEL B: STEEL + mineral wool + folded profile steel + aluminium frame construction
incl. triple glazing

Interior elements

The elements are represented by:

- interior walls
- floor and slab construction elements (slab types)

Table A2-5: Definition of interior elements

No.	Type	Definition of interior elements	Total thickness in mm
1	IW	Metal stud partitions (CW 75) incl. 60 mm mineral wool + 2*gypsum plaster boards	125
2.1	FF	False floor element; calcium sulphate board + sub-structure of galvanised steel	100
2.2	SC	Suspended ceiling; 2*gypsum plaster boards + sub-structure of galvanised steel	75
3.1	CE 70	70 mm cement screed + 30 mm sound insulation (rock wool, high density)	100
3.2	CE 55	55 mm cement screed + 20 mm sound insulation (rock wool, high density)	75

Supporting structure of reference office building

The structures consist of:

- columns
- beams
- slab systems

Table A2-6: Definition of solid structure types

Structure type	Model	Column grid	Column type	Slab type
SOLID 1	Model SO 1	5m/6m/5m; 5,40m	10 * 300 mm (diameter), reinforced concrete (2% vol. steel), C 30/37	280 mm reinforced concrete (2% vol. steel), C30/37
SOLID 1	Model SO 2	5m/6m/5m; 5,40m	10 * 300 mm (diameter), reinforced concrete (2% vol. steel), C 30/37	240 mm reinforced concrete (2% vol. steel), C30/37

- Density of concrete: 2475 kg/m^3
- Density of steel reinforcement: 7850 kg/m^3

Table A2-7: Definition of steel composite structure types

Structure type	Model	Column grid	Column type	Beam type	Slab type
STEEL 1	Model ST 1	5m/6m/5m; 5,40m	20 * HE 200 A	10 * IPE 300 + 5 * IPE 300 A	9 mm profiled sheeting C77 + 130 mm reinforced concrete (1% vol. steel), C30/37
STEEL 1	Model ST 2	11m/5m; 5,40m	10 * HE 200 A + 5 * HE 240 A	5 * IPE 300 + 5 * IPE 450	9 mm profiled sheeting C77 + 130 mm reinforced concrete (1% vol. steel), C30/37
STEEL 1	Model ST 3	16m; 4,05m	12 * HE 220 A	6 * IPE A 600	9 mm profiled sheeting C60 + 100 mm reinforced concrete (1% vol. steel), C30/37
STEEL 2a	Model ST 4	5m/6m/5m; 5,40m	20 * HE 200 A	10 * HE 180 B incl. 350*10 flange + 5 * HE 220 B incl. 400*10 flange	1.13 mm profiled sheeting C220 + 190 mm reinforced concrete (1% vol. steel), C30/37

STEEL 2b	Model ST 5	5m/6m/5m; 5,40m	20 * HE 200 A	10 * HE 200 B incl. 350*10 flange + 5 * HE 220 B incl. 400*10 flange	230 mm precast elements of reinforced concrete (1% vol. steel), C30/37
STEEL 2b	Model ST 6	11m/5m; 5,40m	5 * HE 200 A + 10 * HE 240 A	5 * IPE A 240 + 5 * HE 320 A incl. 400*10 flange	1.25 mm profiled sheeting+ 250 mm reinforced concrete (1% vol. steel), C30/37

- For the structural calculations and further details concerning the steel structures see appendix 4.
- The structural design of beams and columns refers to the dimensions of the reference office building and the quantities are converted to the gross floor area of the office zone (120 m^2).
- The quantities of the steel beams and columns are calculated according to the weight in kg/m and of the profiled sheeting according to the thickness calculated and the weight in kg/m^2.

Case studies

Material choice for comparison of preselected “case studies” (incl. exterior wall elements, window elements, supporting structure and interior elements) on building level with reference to the gross floor area of the office zone (120 m^2)

Table A2-8: Definition of case studies

Case study	Exterior wall elements	Window elements	Models of supporting structure	Column grid	Interior elements
SOLID A	SOLID + EPS + fibre cement board	Self-supporting aluminium frame construction incl. triple glazing	Model SO 1: incl. columns + 280 mm reinforced concrete slab	5m/6m/5m; 5,40m	CE 70 + IW
SOLID B	SOLID + mineral wool + glass fibre concrete panel	Self-supporting steel frame construction incl. triple glazing	Model SO 2: incl. columns + 240 mm reinforced concrete slab	5m/6m/5m; 5,40m	CE 70 + IW
STEEL A	STEEL + PUR + folded steel profile	Self-supporting steel frame construction incl. triple glazing	Model ST 1: incl. steel columns and beams + slab of profiled sheeting C77 + reinforced concrete	5m/6m/5m; 5,40m	CE 55 + IW
STEEL B	STEEL + mineral wool + folded steel profile	Self-supporting aluminium frame construction incl. triple glazing	Model ST 4: incl. steel columns and integrated floor beams + slab of precast concrete elements	5m/6m/5m; 5,40m	CE 55 + IW

Appendix 3
Extracts from the Report

worldsteel
ASSOCIATION

LCI DATA FOR STEEL PRODUCTS

Report produced for:
Anja Degens
University of Luxembourg

Data provided by:
Mauro Chiappini
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2016-04-20

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Contents

1 Introduction

The following data is provided in this report:

1 kg of

- Hot dip galvanized, Europe average
- Sections, Europe average
- Rebars, World average
-

Data is provided with and without a recycling rate at end of life. Typical recycling rate is 95%.

The data provided has been generated based on the worldsteel data collection and methodology for calculating the LCI for steel products full details are available in the World Steel Association Life Cycle Inventory for Steel Products report, 2011.

2 Data description

A description of the steel products provided in this report:

HDG	Obtained by passing cold rolled coil through a molten zinc bath, in order to coat the steel with a thin layer of zinc to provide corrosion resistance. It can be found on the market in coil or in sheets and is further processed into finished products by the manufacturers. Hot Dip Galvanized Steel features excellent forming properties, paintability, weldability, and is suitable for fabrication by forming, pressing and bending. Applications include domestic applications, building applications (e.g. wall elements, roofing applications), automotive applications (e.g. bodyTypical thickness between 0.3 - 3 mm. Typical width between 600 - 2100 mm.
Sections	A steel section rolled on a hot rolling mill. Steel Sections include I-beams, H-beams, wide-flange beams, and sheet piling. It can be found on the market for direct use.This product is used in construction, multi-story buildings, industrial buildings, bridge trusses, vertical highway supports, and riverbank reinforcement.
Rebar	A steel reinforcing bar is rolled on a hot rolling mill. It can be found on the market for direct use or is further processed into finished products by the manufacturers. This product is used to strengthen concrete in highway and building construction also as primary product for the wire rod process.

The data provided is cradle to gate data. In the case recycling is included, it means that a burden is given for the steel scrap that is used as an input to the steel making process, and a credit for the end-of-life (EoL) steel that is recycled. More details about this are given in the section on methodology.

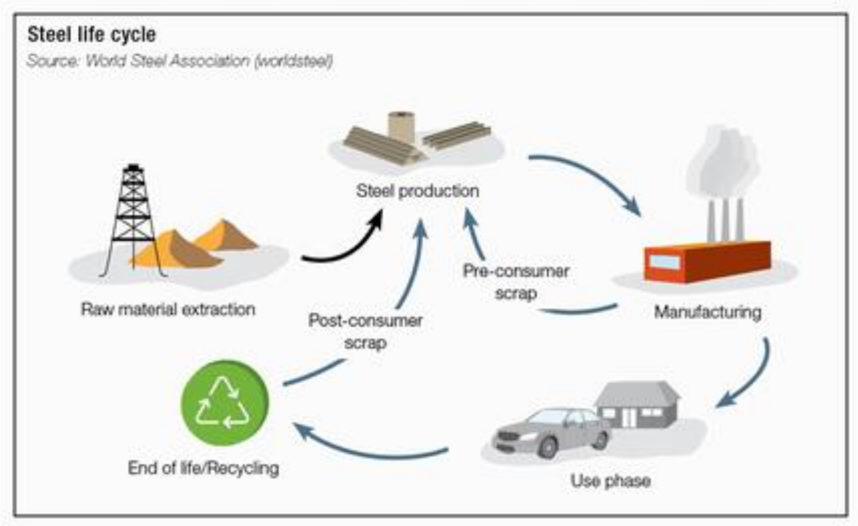
For each of the products given in this report, the recycling rates are specified with the data.

The reference year for the data is for 2005 to 2007, depending on each company providing data. Some upstream data is based on 2008 data.

The flow list includes the main inputs and outputs of the steelmaking process. Please note that, when using the data, the inputs are expressed in kg and the outputs in grams.

3 Methodology

The methodology used to develop this data is detailed in worldsteel's World Steel Life Cycle Inventory report, 2011, which is provided with this data or can be requested via the worldsteel website www.worldsteel.org.



3.1 Summary of methodology

The quality and relevance of LCA/LCI results, and the extent to which they can be applied and interpreted, depends critically upon the methodology used. It is therefore important that methodology is transparent and well documented. ISO standards have been developed to provide guidance on methodological choices and to set down rules for transparency and reporting. The relevant ISO standards are:

- ISO 14040: 2006 - Environmental management – Life cycle assessment – Principles and framework
- ISO 14044: 2006 - Environmental management – Life cycle assessment – Requirements and guidelines

The goal of collecting and developing worldsteel LCI datasets is to facilitate the range of emerging impact assessment methods in future studies.

The worldsteel LCI study has been undertaken in accordance with ISO 14040 and ISO 14044. The previous two data collections and methodology reports underwent a critical review from an independent Critical Review Panel of LCA specialists. This approach improved the integrity of the study and can help guide methodology. The full CRP Report is included in the reports. The new data collection, released February 2010, is based on the same methodology, except that now a weighted average approach is taken to determine product specific LCIs. The 2011 methodology report is available from worldsteel.

The study is a cradle-to-gate LCI study, including recycling. That is, it covers all of the production steps from raw materials 'in the earth' (i.e. the cradle) to finished products ready to be shipped from the steelworks (i.e. the gate). It also includes the credits associated with recycling the steel from the product at the end of their life. It does not include the manufacture of downstream products or their use.

The steel product manufacturing system encompasses the activities of the steel sites and all major upstream processes, including the production and transportation of raw materials, energy sources and consumables used on the steelworks. In addition the recovery and use of steel industry by-products outside of the steelworks are taken into account using in most cases the method of system expansion.

The data includes steel production from both the integrated route (Blast Furnace / Basic Oxygen Furnace) and the Electric Arc Furnace route.

3.2 Recycling methodology

Steel is one of the most recyclable materials in the world and therefore it is important to consider recycling in life cycle assessment studies involving steel, namely the steel scrap that is recycled from a product at the end of its life. In addition, steel is a vital input to the steel making process, and this input of steel scrap should also be considered in LCA studies.

The worldsteel methodology therefore considers both of these factors in the methodology (see appendix 10 of the methodology report for full details).

The general life cycle equation for the "closed material loop recycling methodology" is applied as shown by the equation below:

LCI for 1 kg of steel product including recycling = X – (RR – S) × Y(Xpr – Xre)

where:

X is the cradle to gate LCI of the product

(RR – S) is the net amount of scrap:

RR is the end of life recycling rate of the steel product

S is the scrap input to the steelmaking process

Y(Xpr - Xre) is the value of scrap:

Y is the process yield of the EAF (i.e. >1kg scrap is required to produce 1kg steel)

Xpr = the LCI for 100% primary metal production This is a theoretical value of steel slab made in the BF/BOF route, assuming 0% scrap input.

Xre = the LCI for 100% secondary metal production from scrap in the EAF (assuming scrap = 100%)

4 LCI Results: cradle to gate including recycling for 1kg steel

The data considers a burden for scrap input and a credit for the EoL recycling. These recycling rates are shown below.

Paramètres de scénario				
	Product 1	Product 2	Product 3	
Product	Hot-dip galvanised coil	Sections	Rebar	Steel product
Region	Global	Europe	Global	Region
RR	95	95	95	EoL RR %

Environmental Indicators

	Product 1	Product 2	Product 3
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	1,192476	0,9903523	0,8633513
Primary energy demand from ren. and non ren. Resources (net cal. value) [MJ]	16,22485	13,44722	13,04265

5 Data usage

A life cycle inventory (LCI) study has been carried out by the World Steel Association (worldsteel) to quantify resource use, energy and environmental emissions associated with the processing of fifteen steel industry products, from the extraction of raw materials in the ground through to the steel factory gate and including end-of-life recycling.

LCI data were calculated for products derived via the blast furnace/basic oxygen furnace route (based on iron ore and steel scrap) and the electric arc furnace route (mainly based on steel scrap).

The fifteen products included in the study are the main finished products of the steel industry. They include hot rolled coil (with and without pickling), cold rolled coil (with and without finishing), hot dip and electrically galvanised sheet, painted sheet, tinplate and tin-free sheet, welded and UO pipe, sections, plate, rebar and wire rod. The products are of general relevance to a wide range of downstream applications including those in the construction, automotive and packaging sectors.

A key goal of worldsteel is to provide support on the environmental credentials of steel to customers and users of steel, with the intention that those that specify and use materials in applications have access to relevant data to facilitate their own informed decision-making. In this regard, worldsteel is keen to support the implementation of this database in LCA software and LCA tools.

Worldsteel establishes agreement with LCA database vendors or consultants or advanced users to encourage broad use of the data in the interests of good LCA practice. The tool is fully based on the methodology for recycling that is provided with the attached methodology report.

By using the data, you agree with the following points:

- The worldsteel LCI database is provided free of charge and may not be sold to other parties.
- When the worldsteel database is included in a database for different products, it shall be supplied with the main database of the software (or tool), i.e. at no extra cost for the buyer, nor as an extra library.
- The data sheets shall include a reference source (i.e. contacts details either for the worldsteel web site or directly to the worldsteel LCA Manager: www.worldsteel.org / lca@worldsteel.org)
- The worldsteel LCI Methodology Report 2011 shall be provided on request to users of the data.
- Version updates will be available following data improvements and extra LCI information supplied by companies around the world. Please accept these updates (e.g. version changes), and update the database system as required.
- The database vendor will provide worldsteel with information about the users of the database (e.g. on a 6-monthly basis, and at least once a year).
- The datasheets are supplied only for the purpose of the study for which it was requested. Should they be required for any another purpose, worldsteel must be contacted beforehand.
- The user shall not provide the data on public websites or communicate the full inventories externally without worldsteel agreement.
- The user shall not tamper with the worldsteel data in any way.

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6 FAQ

1. What is the system boundary of the data?

The data is cradle to gate, including recycling at end-of-life. This can also be seen as cradle to grave, excluding the product manufacture (e.g. building, car etc) and use phase. Upstream processes e.g. production of raw materials, are included.

2. Are you not double accounting by including a credit for the end-of-life recycling?

No. By considering the end of life of the product, we are taking a full life cycle approach: cradle to grave. We give a credit for the scrap that is recycled at the end of the products life, based on avoiding the production of steel from virgin material, but also a burden for any scrap that has been used to make that product: thus, each product has an overall net scrap credit or burden.

3. Is the EAF route better than the BOF route?

Both EAF and BOF routes provide essential capacity for scrap recycling and the impacts of converting scrap to steel are similar for each route. At current levels of demand, there is insufficient scrap supply. Therefore there is a need to produce steel from virgin material. In life cycle terms, the two production routes are equivalent: specifying EAF steel has no net benefit to the earth. What is essential is that steel recycling is optimised so that the use of virgin material resources can be reduced and this makes the two routes complementary.

7 LCI data: cradle to gate for 1kg steel excluding recycling

The data does not consider a burden for scrap input or a credit for the EoL recycling.

Environmental Indicators

	Product 1	Product 2	Product 3
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	2,473715	1,142835	1,243977
Primary energy demand from ren. and non ren. Resources (net cal. value) [MJ]	27,58526	14,79924	16,41755

Variante	Beschreibung			Deckenstärke	Stützenraster	Spannweite Träger	Trägerabstand (~ Spannweite Decke)	Nutzlast	Doppelboden/ Estrich	Abgehängte Decke	Eigengew. Decke / Fassade	Trägerprofil	Stützen
1a.1.1	Slim-Floor mit Trapezblech (C+220)	Doppelboden 100mm	keine abgehängte Decke	30cm (mindestens 5cm Betonüberdeckung über Oberflansch)	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m	3.50 kN/m^2	0.50 kN/m^2	[-]	3.05 kN/m^2	l=6.0m: HE200B, S355M + 350x10, S355 l=5.0m: HE180B, S355M + 350x10, S355	Innenstützen (N_{Ed} = 650kN): HE200A, S355M Randstützen: (N_{Ed} = 750kN): HE200A, S355M
1a.1.4			mit abg. Decke							0.30 kN/m^2		l=6.0m: HE200B, S355M + 350x12, S355 l=5.0m: HE180B, S355M + 350x10, S355	Innenstützen (N_{Ed} = 650kN): HE200A, S355M Randstützen: (N_{Ed} = 750kN): HE200A, S355M
1a.1.2	Slim-Floor mit Trapezblech (C+220)	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	30cm (mindestens 5cm Betonüberdeckung über Oberflansch)	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m	3.50 kN/m^2	1.60 kN/m^2	[-]	3.05 kN/m^2	l=6.0m: HE220B, S355M + 400x10, S355 l=5.0m: HE180B, S355M + 350x12, S355	Innenstützen (N_{Ed} = 720kN): HE200A, S355M Randstützen: (N_{Ed} = 780kN): HE200A, S355M
1a.1.5			mit abg. Decke							0.30 kN/m^2		l=6.0m: HE220B, S355M + 400x10, S355 l=5.0m: HE200B, S355M + 350x10, S355	Innenstützen (N_{Ed} = 720kN): HE200A, S355M Randstützen: (N_{Ed} = 780kN): HE200A, S355M
1a.2.1	Slim-Floor mit Betonfertigteil	Doppelboden 100mm	keine abgehängte Decke	180mm Ortbetondecke inklusive 50mm Fertigteil	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m	3.50 kN/m^2	0.50 kN/m^2	[-]	4.50 kN/m^2	l=6.0m: HE220B, S355M + 400x10, S355 l=5.0m: HE180B, S355M + 350x15, S355	Innenstützen (N_{Ed} = 760kN): HE200A, S355M Randstützen: (N_{Ed} = 780kN): HE200A, S355M
1a.2.4			mit abg. Decke							0.30 kN/m^2		l=6.0m: HE220B, S355M + 400x10, S355 l=5.0m: HE200B, S355M + 350x10, S355	
1a.2.2	Slim-Floor mit Betonfertigteil	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	180mm Ortbetondecke inklusive 50mm Fertigteil	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m	3.50 kN/m^2	1.60 kN/m^2	[-]	4.50 kN/m^2	l=6.0m: HE220B, S355M + 400x10, S355 l=5.0m: HE200B, S355M + 350x10, S355	Innenstützen (N_{Ed} = 850kN): HE200A, S355M Randstützen: (N_{Ed} = 820kN): HE200A, S355M
1a.2.5			mit abg. Decke							0.30 kN/m^2		l=6.0m: HE220B, S355M + 400x15, S355 l=5.0m: HE200B, S355M + 350x10, S355	
1b.1.1	Stahlunterzug mit Trapezblech (C+77)	Doppelboden 100mm	keine abgehängte Decke	170mm (inklusive Blech) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m / 5.40m	3.50 kN/m^2	0.50 kN/m^2	[-]	3.25 kN/m^2	l=6.0m: IPEA300, S355M l=5.0m: IPEA300, S355M	Innenstützen (N_{Ed} = 650kN): HE200A, S355M Randstützen: (N_{Ed} = 750kN): HE200A, S355M
1b.1.4			mit abg. Decke							0.30 kN/m^2		l=6.0m: IPEA300, S355M l=5.0m: IPEA300, S355M	
1b.1.2	Stahlunterzug mit Trapezblech (C+77)	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	170mm (inklusive Blech) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m / 5.40m	3.50 kN/m^2	1.60 kN/m^2	[-]	3.25 kN/m^2	l=6.0m: IPEA300, S355M l=5.0m: IPE300, S355M	Innenstützen (N_{Ed} = 740kN): HE200A, S355M Randstützen: (N_{Ed} = 790kN): HE200A, S355M
1b.1.5			mit abg. Decke							0.30 kN/m^2		l=6.0m: IPEA300, S355M l=5.0m: IPE300, S355M	
1b.2.1	Stahlunterzug mit Betonfertigteil	Doppelboden 100mm	keine abgehängte Decke	170mm (inklusive 70mm Fertigteil) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m	3.50 kN/m^2	0.50 kN/m^2	[-]	4.25 kN/m^2	l=6.0m: IPEA300, S355M l=5.0m: IPE300, S355M	Innenstützen (N_{Ed} = 740kN): HE200A, S355M Randstützen: (N_{Ed} = 780kN): HE200A, S355M
1b.2.4			mit abg. Decke							0.30 kN/m^2		l=6.0m: IPEA300, S355M l=5.0m: IPE300, S355M	
1b.2.2	Stahlunterzug mit Betonfertigteil	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	170mm (inklusive 70mm Fertigteil) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m	5.00m / 6.00m	5.40m	3.50 kN/m^2	1.60 kN/m^2	[-]	4.25 kN/m^2	l=6.0m: IPEA300, S355M l=5.0m: IPE300, S355M	Innenstützen (N_{Ed} = 820kN): HE200A, S355M Randstützen: (N_{Ed} = 820kN): HE200A, S355M
1b.2.5			mit abg. Decke							0.30 kN/m^2		l=6.0m: IPEA300, S355M l=5.0m: IPEA330, S355M	
2.1.1	Stahlunterzug mit Trapezblech (C+60)	Doppelboden 100mm	keine abgehängte Decke	140mm (inklusive Blech) über Oberflansch	16.00m / 4.05m	16.00m	4.05m / 4.05m / 4.05m	3.50 kN/m^2	0.50 kN/m^2	[-]	2.62 kN/m^2	IPE A 550, S355M	Randstützen: (N_{Ed} = 990kN): HE220A, S355M
2.1.3			mit abg. Decke							0.30 kN/m^2		IPE A 550, S355M	
2.1.2	Stahlunterzug mit Trapezblech (C+60)	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	140mm (inklusive Blech) über Oberflansch	16.00m / 4.05m	16.00m	4.05m / 4.05m / 4.05m	3.50 kN/m^2	1.60 kN/m^2	[-]	2.62 kN/m^2	IPE A 600, S355M	Randstützen: (N_{Ed} = 1080kN): HE220A, S355M
2.1.4			mit abg. Decke							0.30 kN/m^2		IPE A 600, S355M	
2.2.1	Stahlunterzug mit Betonfertigteil	Doppelboden 100mm	keine abgehängte Decke	140mm (inklusive 60mm Fertigteil) über Oberflansch	16.00m / 4.05m	16.00m	4.05m	3.50 kN/m^2	0.50 kN/m^2	[-]	3.50 kN/m^2	IPE A 600, S275M	Randstützen: (N_{Ed} = 1050kN): HE200A, S355M
2.2.3			mit abg. Decke							0.30 kN/m^2		IPE A 600, S275M	
2.2.2	Stahlunterzug mit Betonfertigteil	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	140mm (inklusive 60mm Fertigteil) über Oberflansch	16.00m / 4.05m	16.00m	4.05m	3.50 kN/m^2	1.60 kN/m^2	[-]	3.50 kN/m^2	IPE A 600, S355M	Randstützen: (N_{Ed} = 1160kN): HE220A, S355M
2.2.4			mit abg. Decke							0.30 kN/m^2		IPE A 600, S355M	
4a.1.1	Stahlunterzug mit Trapezblech (C+77)	Doppelboden 100mm	keine abgehängte Decke	170mm (inklusive Blech) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m 16.00m / 5.40m	10.80m	5.00m / 6.00m / 5.00m	3.50 kN/m^2	0.50 kN/m^2	[-]	3.25 kN/m^2 G_F = 13.68 kN/m	l=10.80m: IPE400, S355M l=5.40m: IPE200, S355M	Innenstützen (N_{Ed} = 1300kN): HE200B, S355M Randstützen: (N_{Ed} = 750kN): HE200A, S355M
4a.1.3			mit abg. Decke							0.30 kN/m^2	3.25 kN/m^2 G_F = 14.28 kN/m	l=10.80m: IPE400, S355M l=5.40m: IPE200, S355M	
4a.1.2	Stahlunterzug mit Trapezblech (C+77)	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	170mm (inklusive Blech) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m 16.00m / 5.40m	10.80m	5.00m / 6.00m / 5.00m	3.50 kN/m^2	1.60 kN/m^2	[-]	3.25 kN/m^2 G_F = 13.88 kN/m	l=10.80m: IPE450, S355M l=5.40m: IPE200, S355M	Innenstützen (N_{Ed} = 1470kN): HE240A, S355M Randstützen: (N_{Ed} = 790kN): HE200A, S355M
4a.1.4			mit abg. Decke							0.30 kN/m^2	3.25 kN/m^2 G_F = 14.48 kN/m	l=10.80m: IPE450, S355M l=5.40m: IPE200, S355M	
4a.2.1	Stahlunterzug mit Betonfertigteil	Doppelboden 100mm	keine abgehängte Decke	170mm (inklusive 70mm Fertigteil) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m 16.00m / 5.40m	10.80m	5.00m - 6.00m	3.50 kN/m^2	0.50 kN/m^2	[-]	4.25 kN/m^2 G_F = 13.68 kN/m	l=10.80m: IPE400, S355M l=5.40m: IPE200, S355M	Innenstützen (N_{Ed} = 1450kN): HE240A, S355M Randstützen: (N_{Ed} = 780kN): HE200A, S355M
4a.2.3			mit abg. Decke							0.30 kN/m^2	4.25 kN/m^2 G_F = 14.28 kN/m	l=10.80m: IPE400, S355M l=5.40m: IPE200, S355M	
4a.2.2	Stahlunterzug mit Betonfertigteil	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	170mm (inklusive 70mm Fertigteil) über Oberflansch	5.00m - 6.00m - 5.00m / 5.40m 16.00m / 5.40m	10.80m	5.00m - 6.00m	3.50 kN/m^2	1.60 kN/m^2	[-]	4.25 kN/m^2 G_F = 13.88 kN/m	l=10.80m: IPE450, S355M l=5.40m: IPE200, S355M	Innenstützen (N_{Ed} = 1620kN): HE240A, S355M Randstützen: (N_{Ed} = 820kN): HE200A, S355M
4a.2.4			mit abg. Decke							0.30 kN/m^2	4.25 kN/m^2 G_F = 14.48 kN/m	l=10.80m: IPE450, S355M l=5.40m: IPE200, S355M	

Variante	Beschreibung			Deckenstärke	Stützenraster	Spannweite Träger	Trägerabstand (~ Spannweite Decke)	Nutzlast	Doppelboden/ Estrich	Abgehängte Decke	Eigengew. Decke / Fassade	Trägerprofil	Stützen
4b.1.1	Stahlunterzug mit Trapezblech (C+77)	Doppelboden 100mm	keine abgehängte Decke	170mm (inklusive Blech) über Oberflansch	11.00m - 5.00m / 5.40m	11.00m / 5.00m	5.40m / 5.40m	3.50 kN/m²	0.50 kN/m²	[-]	3.25 kN/m²	l=11.0m: IPE400, S355M l=5.0m: IPEA300, S355M	Innenstützen (N_{Ed} = 940kN): HE200A, S355M Randstützen: (N_{Ed} = 1100kN): HE240A, S355M Randstützen: (N_{Ed} = 750kN): HE200A, S355M
4b.1.3			mit abg. Decke							0.30 kN/m²		l=11.0m: IPE400, S355M l=5.0m: IPEA300, S355M	
4b.1.2	Stahlunterzug mit Trapezblech (C+77)	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	170mm (inklusive Blech) über Oberflansch	11.00m - 5.00m / 5.40m	11.00m / 5.00m	5.40m / 5.40m	3.50 kN/m²	1.60 kN/m²	[-]	3.25 kN/m²	l=11.0m: IPE450, S355M l=5.00m: IPE300, S355M	Innenstützen (N_{Ed} = 940kN): HE200A, S355M Randstützen: (N_{Ed} = 1100kN): HE240A, S355M Randstützen: (N_{Ed} = 750kN): HE200A, S355M
4b.1.4			mit abg. Decke							0.30 kN/m²		l=11.0m: IPE450, S355M l=5.00m: IPE300, S355M	
4b.2.1	Stahlunterzug mit Betonfertigteil	Doppelboden 100mm	keine abgehängte Decke	170mm (inklusive 70mm Fertigteil) über Oberflansch	11.00m - 5.00m / 5.40m	11.00m / 5.00m	5.40m	3.50 kN/m²	0.50 kN/m²	[-]	4.25 kN/m²	l=11.0m: IPE400, S355M l=5.00m: IPE300, S355M	Innenstützen (N_{Ed} = 1060kN): HE220A, S355M Randstützen: (N_{Ed} = 1180kN): HE240A, S355M Randstützen: (N_{Ed} = 780kN): HE200A, S355M
4b.2.3			mit abg. Decke							0.30 kN/m²		l=11.0m: IPE400, S355M l=5.00m: IPE300, S355M	
4b.2.2	Stahlunterzug mit Betonfertigteil	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	170mm (inklusive 70mm Fertigteil) über Oberflansch	11.00m - 5.00m / 5.40m	11.00m / 5.00m	5.40m	3.50 kN/m²	1.60 kN/m²	[-]	4.25 kN/m²	l=11.0m: IPEA450, S355M l=5.00m: IPE300, S355M	Innenstützen (N_{Ed} = 1190kN): HE220A, S355M Randstützen: (N_{Ed} = 1270kN): HE240A, S355M Randstützen: (N_{Ed} = 820kN): HE200A, S355M
4b.2.4			mit abg. Decke							0.30 kN/m²		l=11.0m: IPE450, S355M l=5.0m: IPEA330, S355M	
4b.3.1	Slim-Floor mit Trapezblech (C+220 mit 140mm Aufbeton über dem Blech)	Doppelboden 100mm	keine abgehängte Decke	36cm (mindestens 5cm Betonüberdeckung über Oberflansch)	11.00m - 5.00m / 5.40m	11.00m / 5.00m	5.40m	3.50 kN/m²	0.50 kN/m²	[-]	4.54 kN/m²	l=11.0m: HE320A, S355 + 450x10, S355 l=5.0m: IPEA240, S355	Innenstützen (N_{Ed} = 1100kN): HE240A, S355 Randstützen: (N_{Ed} = 1110kN): HE240A, S355 Randstützen: (N_{Ed} = 690kN): HE200A, S355
4b.3.3			mit abg. Decke							0.30 kN/m²		l=11.0m: HE320A, S355 + 450x10, S355 l=5.0m: IPEA240, S355	
4b.3.2	Slim-Floor mit Trapezblech (C+220 mit 140mm Aufbeton über dem Blech)	Trittschalldämmung 30mm + schwimmender Estrich 70mm	keine abgehängte Decke	36cm (mindestens 5cm Betonüberdeckung über Oberflansch)	11.00m - 5.00m / 5.40m	11.00m / 5.00m	5.40m	3.50 kN/m²	1.60 kN/m²	[-]	4.54 kN/m²	l=11.0m: HE320A, S355 + 450x15, S355 l=5.00m: IPEA240, S355	Innenstützen (N_{Ed} = 1230kN):HE240A, S355 Randstützen: (N_{Ed} = 1200kN): HE240A, S355 Randstützen: (N_{Ed} = 740kN): HE200A, S355
4b.3.4			mit abg. Decke							0.30 kN/m²		l=11.0m: HE320A, S355 + 450x15, S355 l=5.00m: IPEA240, S355	

Variante 4a - Randträger (Fassadenträger):

Zur Trägerdimensionierung wurde ein Fassadengewicht von 4.00 kN/m² berücksichtigt.
Die Fläche der Fassade wurde mit einer lichten Geschoßhöhe von 2.75m berechnet.
Beispiel zu Variante 4a1.1: 4.00kN/m² x (2.75m + 0.4m + 0.17m + 0.10m) = 4kN/m² x 3.42m = 13.68kN/m
Beispiel zu Variante 4a1.3: 4.00kN/m² x (2.75m + 0.15m + 0.4m + 0.17m + 0.10m) = 4kN/m² x 3.57m = 14.28kN/m - zusätzliche Höhe abgehängte Decke = 150mm
Durchbiegungsbegrenzung der Randträger, welche Fassadenlasten aufnehmen: unter Nutzlast L/500 bzw. max. 2cm (inkl. Kriechen und Schwinden bei Verbundträgern) -> bei 5.40m Trägerlänge maximale Durchbiegung = 1.08cm (= L/500)