COMPUTER SIMULATIONS
FOR ENERGY-EFFICIENT ARCHITECTURE

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Introduction

This presentation is intended to give some relevant ideas and information about the important role which computer simulations can play for architectural design and for quality control in the architectural planning process. However, before any special and detailed treatment of this topic will be elaborated, one has to clarify the proper meaning of the term “simulation”. This includes questions of modelling, accuracy, validation and sensitivity analysis. Although simulations are applicable in many more fields, we restrict our contribution for reasons of time and space to “thermal modelling” mainly, as this aspect is especially important for the energetic issues of buildings. Required data input, principal methods and typical results are illustrated and discussed. In a further chapter we give a short survey of available programs in this section and refer about the problem how to select a commercial or scientific program for own purposes. Criteria are given and illuminated from several practical aspects. An additional short comment is devoted to the topic of “solar urban planning”, which has to be considered carefully for passive-solar house designs. We finally conclude with a reference to our web-sites, which give a wealth of information about the addressed items.

Simulations

The word “simulation” comes from the Latin “simulare” which means “to do *similar* things”. *Similar* is not *the same* ! Simulation is, therefore, a mapping of reality into a theoretical “model space”, for which we can make assumptions and can do calculations according to the rules chosen for the model. As any model is an abstraction from reality, the art of “modelling”, i.e. of “describing a complex matter by a couple of equations representing the system in a simplified way” becomes crucial. Commonly, one tries to describe a system and its processes as simple as possible by inclusion of the most relevant processes only. In this case not every process within the system is considered, but the system may be easier calculated and the number of needed model-parameters is smaller and therefore more readily available. If, for the other case, more physical processes are regarded, the complexity of calculations increases and, above all, usually also the number of required model-parameters which probably are not available in practice, or not with the desired precision. Anyway, because reality is always more complex than its theoretical abstraction, the question of “model-accuracy” arises. “Accuracy” means correct description of all relevant physical laws, good compliance with all important boundary conditions of the system under investigation and reasonable coincidence of model results with measured values for a given project.

This high degree of agreement between theoretical and measured results is difficult to observe in practice for several reasons: There may be no suitable measurement results available or accessible as measurements usually are costly and time-consuming. Or such measurements are not applicable for the case considered, as special given boundary conditions differ from the case under investigation. It has become quite common, therefore, to restrict the task of checking a model on its accuracy to an “inter-comparison” of several models. This means, a new model is compared (with respect to a defined number of criteria) against the results of other existing and commonly accepted models. If the applied tests have demonstrated that the results from the new model are in reasonable agreement with those of other models, the new model is regarded as “validated”. This, of course, is also true, if the comparison was made against applicable measurements.

Our repetitive hint that models are different from reality shall underline that simulation results may differ significantly from those obtained in practice – especially if the boundary conditions (like climate, user behaviour, material data etc.) are not consistent. Therefore, the most valuable benefit of validated simulation programs is not prediction of expected results, but lies in the field of “sensitivity analysis”. This kind of investigations with the model gives an impression how strongly the different parameters of the system influence the considered results. By this way the importance of certain selected measures (e.g. material selection, construction, orientation, control, ventilation strategy etc.) can be addressed and estimated.

Nevertheless, the use of simulation programs for architectural design and planning is a considerable progress. It is always cheaper to perform calculations with a skilful program and to analyse the results than to perform physical experiments in this field. Moreover, these simulations are much faster than the evaluations of measurements. Calculations with good simulation tools offer a unique chance of quality control and assurance well in advance of the process of building where changes of plans usually become costly.

There are many detail problems within a planning process which can be asked for:
- monthly (seasonal) amount of heating/cooling energy
- maximum required heating/cooling load,
- indoor air temperatures,
- indoor wall temperature, etc.

Another question is, how some energetic figure of merit can be improved by:
- building design,
- constructional details,
- selection of materials.

Other important problems refer to:
- heat-gaps,
- thermal comfort,
- indoor air quality,
- air change rates / air flow patterns,
- day-lighting,
- external shading scenarios,
- solar urban planning,
- life-cycle-analysis,
- economic issues and evaluations.

As already mentioned above, we restrict our concern mainly to thermal simulations with special regard to energetic balances.

Influences on thermal balances of buildings

Figure 1 displays the different fields of parameters which influence the thermal and energetic behaviour of a building. The central array “overall building thermal balance / temperature field” depends mainly on four different other arrays, which are named by “meteorology“, “architectural design data”, “building materials” and “occupants”. Each of these displayed arrays/fields includes specific, relevant aspects and parameters which affect the total energy balance of a building.

Of course, “meteorology” is an important factor for the energy demand of buildings. Main parameters are outdoor air temperature (for heat losses) and global solar radiation on horizontal surfaces (for solar heat gains). Wind velocity and direction may be important too, if airtightness of a building is not very well performed. Similarly, “architectural design data” are responsible for the energy balances of buildings. Areas of facades, windows, fabrics, roof, basement, orientations, thickness of walls, surface-to-volume ratio, etc. are determining for a building’s heat losses and its ability to collect solar gains. The thermo-physical properties of “building materials” like mass density, specific heat capacity and thermal conductivity are determining for the propagation and storage of thermal energy within the constructive masses of a building. Between “occupants” and “overall building thermal balance / temperature field” exist interactions in two ways: “...thermal balance...” is very much influenced by the “occupants” through user profiles of presence, activities, artificial illumination, other kinds of internal loads, intended ventilation/air change rates, setting heating controls and so on. In turn, the “occupants” are subjected to the existing “...../ temperature field” which may be comfortable or not.

This short and rough discussion may illustrate that thermal behaviour and balance of buildings is not at all a simple topic. It is, instead, rather complex, as a lot of parameters are involved, which even can interact (occupants). For this level of discussion we still did not consider the physical processes or technical details which are dominant for the problem.

Modelling the mechanisms of heat transfer in buildings

Figure 2 gives a scheme of the relevant heat transfer mechanisms which have to be considered for buildings. Almost all of the existing mechanisms of heat transfer are involved: **Conduction** through walls, windows, floors, ceilings - with more complicated calculation efforts also through “heat gaps”; **solar radiation** (short wave) directly from the sun (beam radiation), scattered from the sky (diffuse) or reflected from the ground - there may be influences due to external shading (surrounding objects) or self-shading (overhangs, side wings); **infrared radiation** (long wave) from the sky, the earth or objects adjacent to the building, from the building´s envelope, inside the building, **convection** inside and outside of the building´s surfaces; **advection** (through infiltration, exfiltration, interzonal air exchange) and finally **latent heat** which may be withdrawn or added to the building. by evaporation and condensation of water vapour. This figure shows again the complexity of the general problem of the thermal analysis of buildings, for which many influences have to be considered and many external/internal data have to be fixed in order to be able to calculate simulation results for this system.

A general conclusion is valid: The more complex the model of a system or its corresponding simulation-model is, the more input data are required, and the more difficult and time-consuming the simulations are. Also, interpretation of outputs becomes more difficult, as many detailed results are obtained and many inter-dependencies and correlations between the influencing parameters and the individual simulation results can be investigated. The degree of complexity depends on:

- Which of all physical mechanisms have been considered or ignored in the mathematical model (e.g. heat gaps, shading, long wave radiation losses/gains for building surfaces, etc.),

- Whether there are introduced major simplifications for the considered mechanisms (e.g. combined heat transfer coefficient for radiation and convection for walls, uniform instead of orientation-dependent outdoor temperature, air change rates as parameters or dependent on characteristics of pressure field and building envelope, etc.),
- Spatial resolution of the building (e.g. one zone or more, temperatures of indoor air and constructional mass of the building, multi-zone model with inter-zonal air exchange, vertical stratification of air temperatures, etc.),
- Diversity of simulation results (e.g. temperatures, heat fluxes, heat flows, total energy balance, composition of energy gains, distribution of losses among building components and technical equipment, thermal comfort values, CO_2-emissions, etc.),
- Resolution in time for the several calculation results (e.g. seasonal, monthly, short-term, daily, hourly, or less).

As already mentioned, more detailed models require more detailed data input. The data have to be collected from several sources. (which may be - at least partially - already available with or even are incorporated into the programs of the simulation system, if advanced, commercial software is considered).

Data bases are required for:
- (a) Parameters of building materials and components (mass density, thermo-physical properties, moisture content, U-values, g-values, etc.),
- (b) Several types of temperatures (outdoor air, ground),
- (c) Solar radiation (global and diffuse on a horizontal plane, ground-reflected diffuse),
- (d) Internal thermal gains (number of persons, activities, electrical equipment, illumination, typical profiles in course of time),
- (e) Production of water vapour (persons, activities, plants, free water surfaces, etc.).

If these data are not already provided by the simulation system, they have to be gathered from the corresponding professional literature or from communications of public authorities. Data for (a), (d) and (e) can be found e.g. in DIN 4108 (“Wärmeschutz im Hochbau”), for (b) and (c) data can be bought e.g. from DWD (Deutscher Wetterdienst, Offenbach) or a special Swiss Database (METEONORM, Firma Meteotest, Bern) can be used.

Numerical methods

There is not enough time nor the space to discuss all existing methods and algorithms which can be used to solve the problems of building thermal analysis. We want, instead, illustrate one typical kind of solutions, where the building is modelled as a network of ***nodes***, which describe one or more ***zones***. A ***zone*** is a part of a building for which the room air temperatures are assumed to be (almost) identical. A ***node*** is a part or constructive element within a building zone with (almost) identical temperature. Both terms, zone and node, are, of course, idealizations of reality. In practice, room air temperatures are never homogeneous even within one single room (due to thermal stratification and the influence of heating equipment or walls on air temperature), nor are building components within a zone really isothermal (since there are always edge effects and inhomogenities in a temperature field). However, because it is practically impossible to calculate temperatures for a very fine-scaled 3D-grid, one is forced to introduce simplifications like those of zones and nodes.

Figure 3 gives the scheme of a two-zone-model. In this case we see the plan view of a building with two rooms, one northbound, the other in southern direction, separated by an east-west indoor wall with a door. Therefore, one expects different thermal behaviour for these two rooms (different solar gains through southern and northern window) and consequently defines two zones. In each zone, the surrounding temperatures of surfaces/the core of materials are relevant. This is true for eastern, southern, western and northern walls. For the inside wall, one expects no significant temperature profile. Core temperatures of this wall are set identical with surface temperatures. For both windows, only the inner glass temperatures are important. They are different for the southern and northern window. Finally, we assume one isotropic temperature of outdoor air. In conclusion, the system consists of two zones with fourteen nodes.

Again for the sake of simplicity we forgo to the presentation of equations. But, we feel that is important to have a basic understanding, which the essential ideas behind the equations of such simulation programs are. We, therefore, try to explain the key elements and main features of such programs verbally.

For (each zone and) every node j (j counts from 1 till N, where N is the total number of nodes) one can set up equations, which describe the thermal balances of these nodes. The equations represent a special version of the first basic law of thermodynamics: For every node j and (arbitrarily small) time step a positive difference of thermal gains minus thermal losses yields an increase of the nodal temperature j, as well as, in turn, a negative thermal balance will result in a decreasing temperature of node j. This means, that the main task is to determine for every node j its thermal gains and losses. Gains are either time-dependent variable data (e.g. solar gains) or they are dependent on (higher) temperatures of adjacent nodes (representing a net heat transfer from those nodes to the actual one). In the same way, thermal losses are proportional to positive temperature differences between the actual node j and its surroundings. This altogether leads to N linear equations with N unknown nodal temperatures T_j for every time step. Application of common mathematical algorithms for this problem leads to solutions for the time-dependent functions T_j (t), j from 1 till N, on the basis of a chosen discretization in time (e.g. every 5 minutes, 15 minutes, hourly, or more). These temperature fields $T_j(t)$ silently include the effects of thermal storage in construction elements. This storage effect, however, becomes negligible when longer periods of time are considered (because a finite capacity of storable heat has to be divided by the period of time in order to get the relevant average heat flow). Once all the temperature fields are known, other quantities like heat fluxes, heat flows and energies can be calculated.

Presentation of results

Thermal modelling of a system is one side of a problem, the presentation of simulation results is the other side. If the modelling was very specific, also the calculation results can be presented in a very detailed manner. Figure 4 displays an illustrative example of detailed results with respect to indoor air temperatures and heat loads as function of time (respectively of outdoor temperature and solar radiation) for ten days in may (day numbers 140 till 149) for a typical situation in Germany. The temporal development of indoor temperatures and heat loads can be trailed very well as consequence of the corresponding course in time of ambient temperature and solar gains. This allows a very close investigation of an object under consideration for time-dependent situations. Calculation and analysis of such time-dependent results is generally termed as **“dynamic simulation”.**

For many cases, one might not be interested in such results with high resolution in time at all. Under the aspect of an energetic evaluation, monthly contributions of useful solar gains, useful internal gains and required auxiliary heating for all months of a heating season may be more relevant. Figure 5 shows a typical course in time for such months of auxiliary heating, useful internal gains and solar gains (with units in kWh). They display the typical mid-European situation, for which solar gains from November to February are almost negligible, whereas - in the other months - they can contribute considerably to the thermal balance. This figure shows also, that useful internal gains are almost constant (with some reductions during the summer situation, where the utilizability of any gains becomes smaller).

An even more comprehensive and complete presentation of such monthly results is displayed in Figure 6, which also includes thermal losses of buildings due to transmission and ventilation. All quantities here are given in energy units, which are related to the heated floor area, in kWh/m^2. The graph shows that – even on a monthly basis – transmission and ventilation losses are almost equal to corresponding gains from solar radiation, internal sources and auxiliary heating. This means that the effects of thermal storage become almost negligible already for a monthly period of time. Therefore, a consideration of monthly (or seasonal) averaged heat flows of transmission and ventilation losses, **useful** solar and internal gains and auxiliary heating supply should be equivalent to results of dynamic simulations. This kind of approximation for longer time periods, which does not include thermal storage directly, is termed as **"quasi-static calculation".** The specification "quasi" is introduced, because solar and internal gains are not just summed up, but their sums are affected by a factor of utilizability, which, again, depends on various parameters of the building and its operation. characteristics.
Moreover, this quantitative monthly survey of all relevant heat flows allows for a general estimation of how the heating requirements of a building can be reduced in the best way (e.g. by increasing solar gains or by lowering transmission or ventilation heat losses).

As a final example of how to present simulation results, Figure 7 shows calculations of transmission losses for the individual parts of the building envelope on the basis of the whole heating season. These building parts are roof, walls, windows and ground. Ventilation losses are added. To cover all these thermal losses, on the left-hand side of the figure the corresponding supplies of heat (solar, internal, fuel-based) are listed. For the given case, also the heat for domestic hot water is included. Heat losses of the burner due to conversion of fuel energy to heat including the heat delivery system (here 9%) or due to not useable internal and solar gains (here 2%) are also displayed. In summary, a very instructive picture is produced, which gives a comprehensive survey of all heat flows in the building at a glance. This picture can easily be used to make recommendations for thermal improvements in an early design phase of a building. Of course, this kind of picture can also be obtained from static calculations.

How to select commercially available software ?

The scientific and commercial market offers a big variety of programs on the thermal modelling of buildings. Examples for dynamic simulation programs are (without any claim for completeness):

- APACHE,
- BLAST,
- DEROB,
- DOE – 2,
- ESP,
- SUNCODE,
- TAS,
- TRNSYS,
- TSBI 3.

The most of these programs (BLAST, DEROB, DOE – 2, SUNCODE, TRYNSYS) stem originally from the USA, but are in the meantime also implemented in Europe by representing companies. The other programs (APACHE, ESP, TAS) come from the UK or from Denmark (TSBI 3).

Quasi-static programs are abundantly available in several countries. Again without any claim for completeness:

- CASAnova,
- DIAS,
- ENERPAS,
- HELENA,
- LESOSAI-X,
- NESA-Datenbank,
- RESA.

The examples refer to the German (CASAnova, ENERPAS, HELENA, NESA, RESA) and the Swiss (DIAS; LESOSAI-X) scene, only. Additionally, there exist software products which are supporting the thermal analysis of buildings (meteorological data - METEONORM, shading analysis – SOMBRERO, use of earth heat exchangers – GAEA) or help to evaluate their results (estimation of thermal comfort – COMFORT, economic evaluation – ÖKORAT).

Prior to that any person or institution wants to buy a program on the thermal analysis of buildings, a careful analysis of needs and demands should be performed. This analysis should consider the fact, that increasing demands usually have to be paid by higher costs of investment for the program, and by more intensive work to operate the respective programs (detailed input data, required user knowledge, complexity of results). The initial analysis of demands should, therefore, answer the following questions:

- Which quantities have to be calculated ? (maximum heat load, monthly or seasonal energy demand, overheating hours, maximum/minimum temperature, additional costs of options, economic analyses).
- With which accuracy ? (5%, 10%, more ?, are quasi-static calculations sufficient ?).
- Which is the required resolution in time ? (hour, day, month, heating season) ?
- Is a calculation according to national standard codes (e.g. “Wärmeschutzverordnung 1995”, or Euro-norm “EN 832”) sufficient ?
- Is there a need for a multi-media information tool about energy savings and the use of regenerative energies in buildings ?

A further bulk of questions refers to the quality of the program itself:

- Is the mathematical/physical model adequate for the envisaged problem ?
- Is the source-code of the program available for own checks and improvements ?
- Are there “solar modules” existent (and which ones) ?
- How old is the program/the program language ?
- Quality of user surface ?
- Computing prerequisites ?/ Operation system ?
- Quality of handbook ?/ Hotline available?
- Costs of program ?
- Dissemination (widespread use) of the program ?

- Required input / delivered output ?
- Report generator available ?
- Data bases included ?
- Data exchange with other programs possible ?
- Expert system included ?
- Administration/comparison of several calculated variants ?

and other questions more.

This listing of possible requirements and suitable choices makes clear, that one cannot give a generally valid recommendation of any special program for all kinds of desires. Any choice will be a compromise between various required options and realized functions. However, one should always keep in mind, that one cannot demand for very detailed program features without paying for them al least with considerably increased effort for program operation. If mainly energetic aspects have to be addressed, programs with “quasi-static” calculations on basis of the European standard EN 832 are quite sufficient.

EN 832 calculates monthly or seasonal demands of heating energy for a building (which is different from the energy demand to produce this heating energy !) by means of a modified energy balance:

$$Q_{HEATING} = (Q_{TRANSMISSION} + Q_{VENTILATION}) - N * (Q_{INTERNAL} + Q_{SOLAR})$$

Transmission and ventilation losses are calculated according to physically reasonable models, especially concerning the heat losses towards the ground.. Air change rates can be chosen arbitrarily according to variable conditions of wind field, temperature difference between indoors and outside and building performance. Internal as well as solar gains can be inserted into the calculation method individually according to users, appliances, local climate and orientations of facades. Also, the number of heating degree days is kept as a variable. N, the utilization factor of internal and solar heat gains, is determined as a function of several parameters describing the building and its heating system.

Solar urban planning

Besides mere thermal analysis of individual buildings, also the impact of an urban environment on a building is rather relevant. Urban planning sets the rules for the planning of individual houses. Solar gains cannot happen if the sun cannot shine on a building´s envelope ! Of course, there is very often a dominance of problems like

- urban context,
- access to roads, and
- ground-saving arrangement of buildings.

But one should also try to avoid problems in the use of solar energy for individual houses by consideration of

- possibility of most southern direction of the facade with most windows,
- avoidance of shading from neighbouring buildings,
- consideration/minimization of topographical shading effects,
- careful planning of vegetation (kinds and locations of trees and bushes),
- compact building geometry with a minimum of self-shading.

Within the frame of a pilot project, the state of North-Rhine-Westphalia in Germany has sponsored the development of a planning tool “Sol-City”, which allows for an easy consideration of detrimental shading effects due to adjacent buildings and the given topography. Fig.

8 shows, that buildings create “butterfly”-like areas around them, which represent areas of prevented input of solar energy. These areas can be grouped by scales of Grey colours. Bright Grey means low losses of solar gains, dark Grey implies heavy reductions of solar input. Moving a building within a given topography and a built environment allows for a “best positioning” of this building under the given conditions. By this way, new settlements can be planned in a relatively easy manner in order to guarantee the best utilization of solar energy for every building.

Summary

This introductory contribution has shown, that the system “energy and buildings” is rather complex due to a variety of reasons: Some important parameters like ventilation, occupants, meteorology, etc. are not well defined nor exactly known. There exists an abundance of theoretical models and programs for the thermal and energetic analysis of buildings. However, no generally valid recommendation for one specific program can be given, as the individual demands (e.g. aspects of energy saving , supply with solar energy, environmental impact, thermal comfort, urban planning, etc.) are very widespread.

Nevertheless, thermal analysis of buildings offers a unique chance to optimise a building design well in advance of its realization. Skilful and careful modelling gives valuable predictions of energy consumption and thermal comfort. Sensitivity analysis allows to investigate the relative importance of various measures. For solar urban planning, useful guidelines of building shape, orientation and positioning of the building in a landscape and the avoidance of mutual shading exist. **In conclusion: Computer-aided analysis of the energy-efficiency of buildings is a must for advanced and sustainable building design.**

Recommendations for further information

Many more detailed information about special software was given in corresponding contributions to the workshop on “Energy–efficient buildings”, which was held during the next few days after this introductory speech. Some software has been distributed to the participants of this workshop (e.g. NESA-Datenbank, CASAnova, ÖKO-RAT, COMFORT, others). A lot of additional information is also contained in the web sites of the author given under its affiliation.

Generally, information in this field is very much time-dependent: New updates can change program features considerably, company or university based developments may not further be available after some time beyond of first results, completely new products may be under test in a few places, but not yet accessible for everyone. A look into the web for most recent information is always recommended.

An older but comprehensive survey for the German situation is also given by:
Marktspiegel “Energieeinsparung mit EDV-Unterstützung”, Energieagentur NRW, Wuppertal, September 1996.

Figure Captions

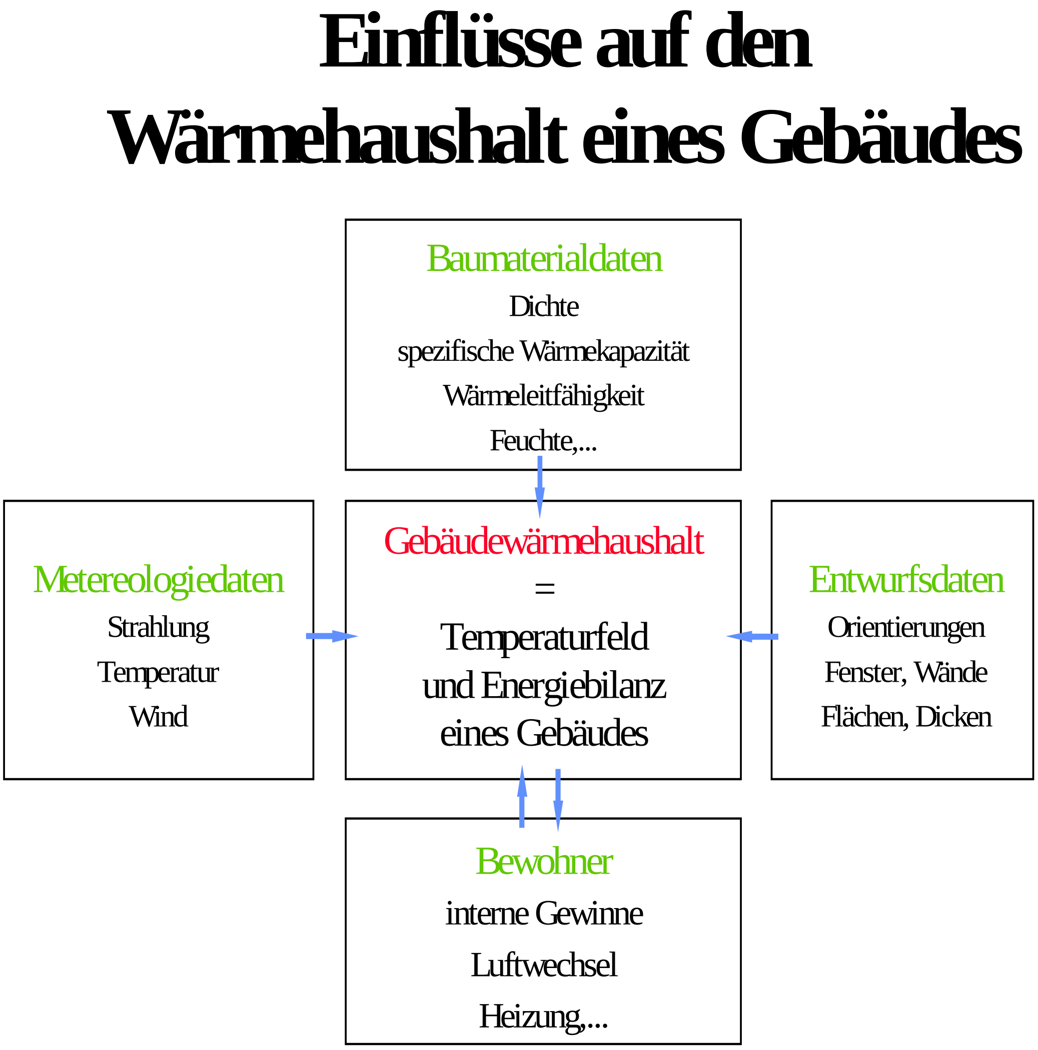


Figure 1: Influencing factors of the temperature field and the thermal energy balance in buildings.

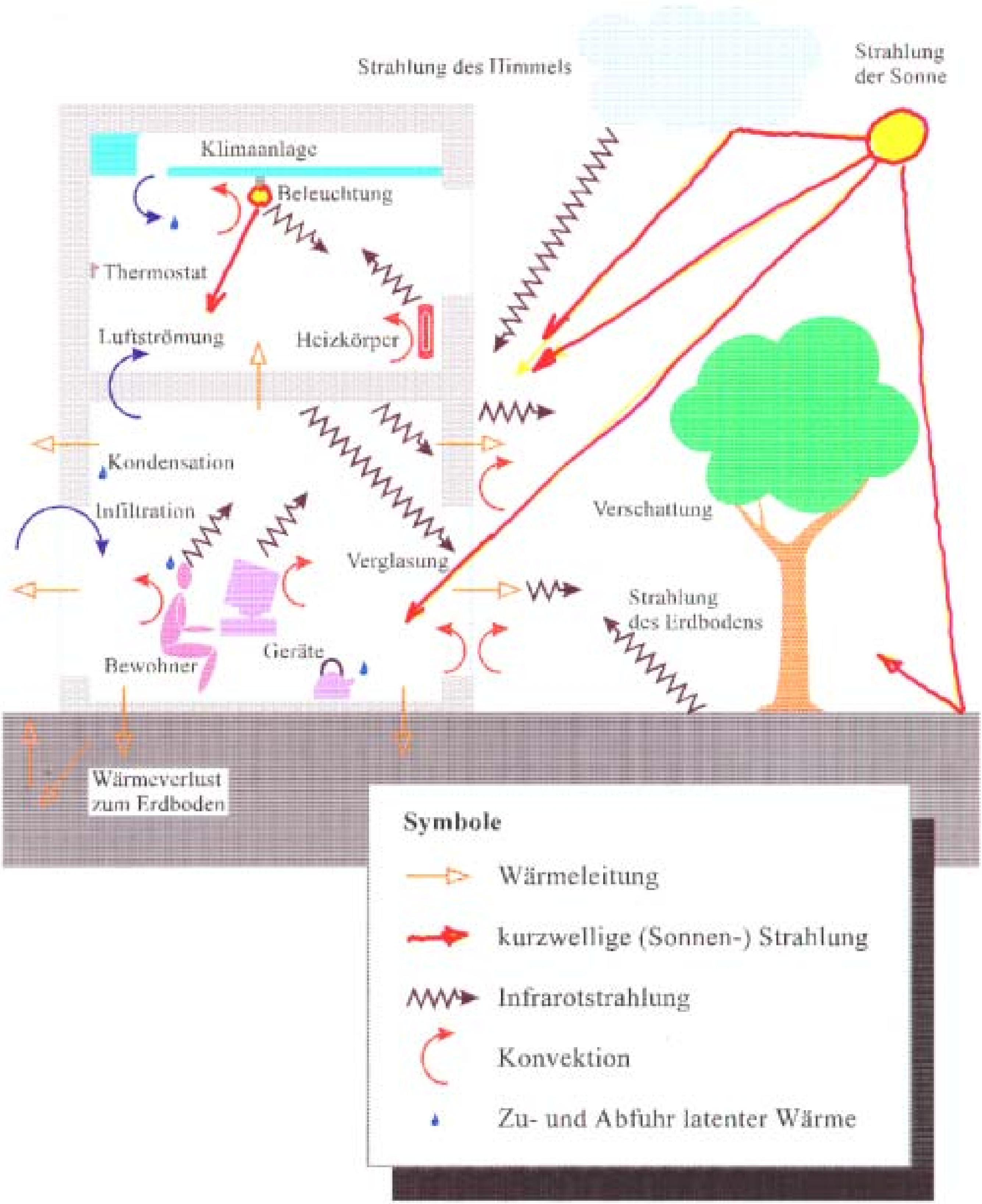


Figure 2: Illustrative presentation of heat transfer mechanisms around and inside

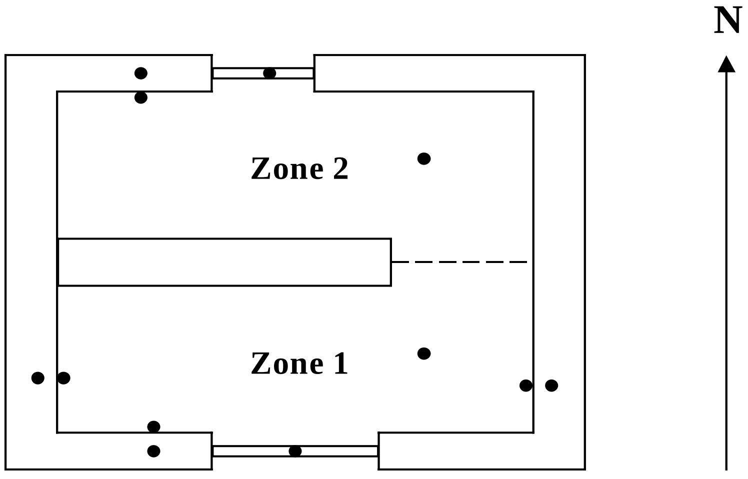
buildings.

Netzwerk- / Knoten-Modelle

Zone: Gebäudeteil mit (nahezu) identischer Lufttemperatur.

Knoten: Gebäudeteil innerhalb einer Zone mit (nahezu) identischer Temperatur.

Beispiel mit zwei Zonen:



● **Knotenpunkte**

Figure 3: Typical simplified nodal model for a two-zone presentation of a building.

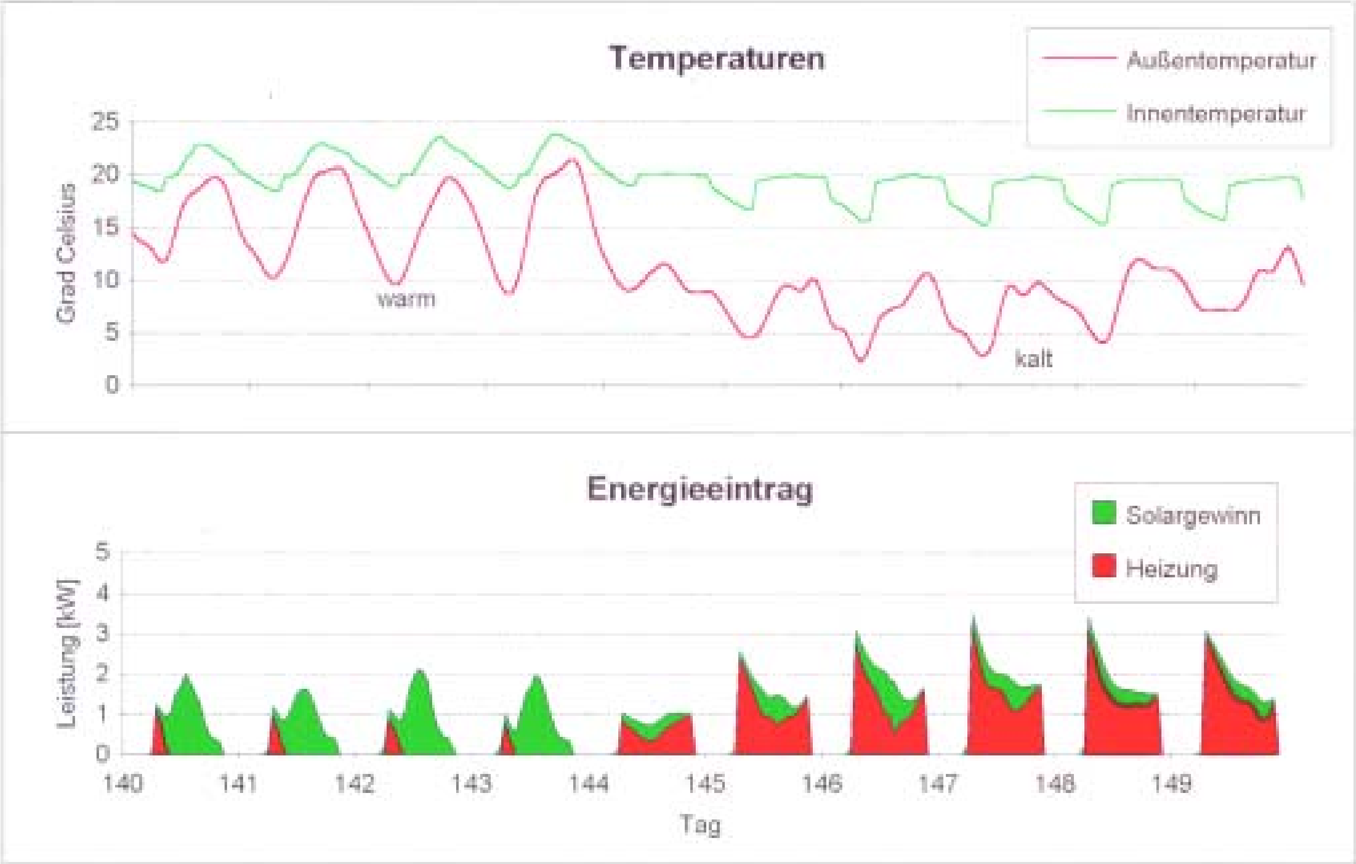


Figure 4: Detailed presentation of simulation results in the course of time for indoor temperature and heat load as functions of ambient temperature and global solar radiation.

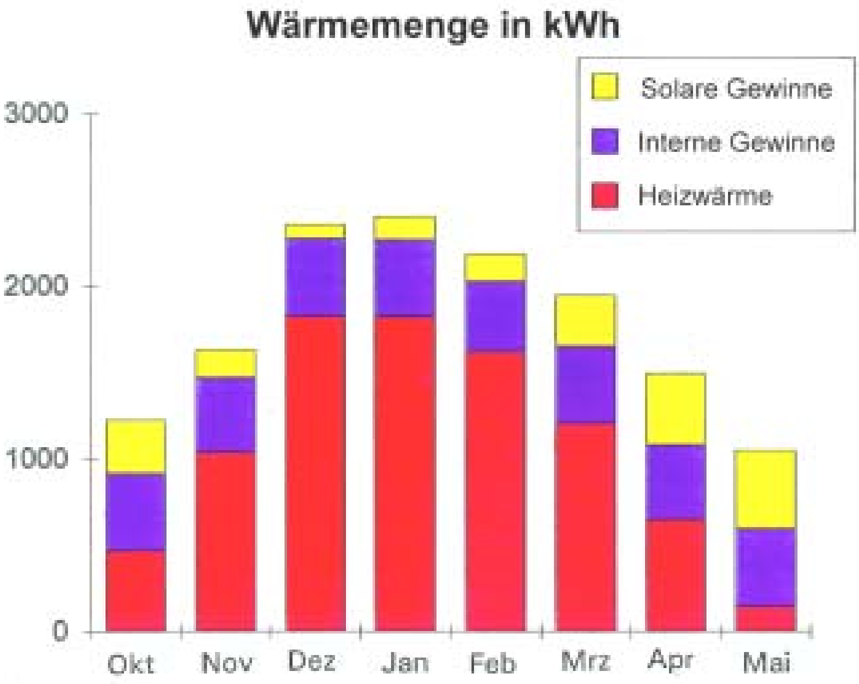
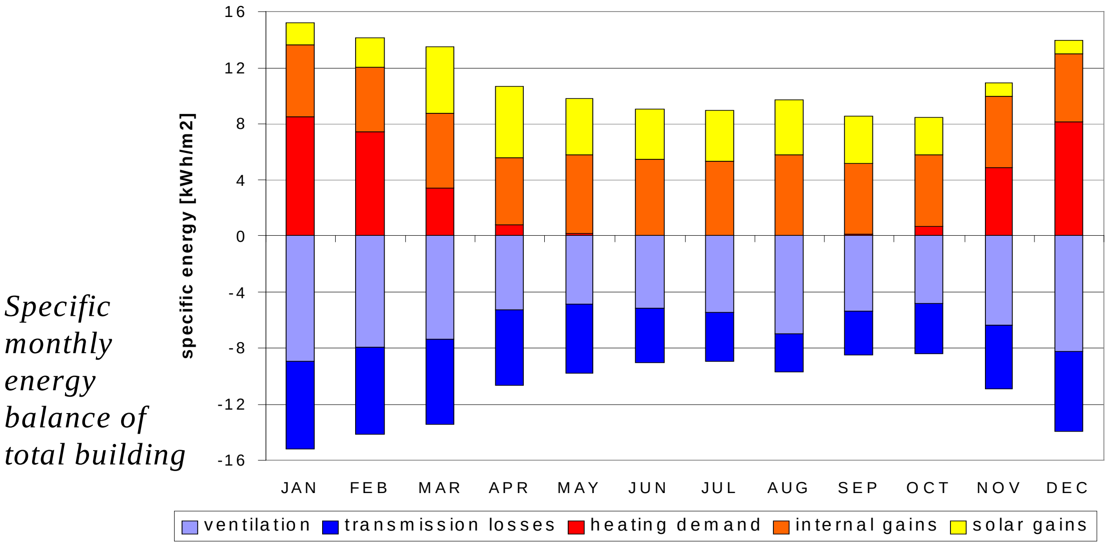


Figure 5: Monthly distribution of supply energies (useful internal, useful solar and auxiliary heating) to cover the required total energy demand of a building.



Dipl.-Phys. Oliver Kah, July 2000

Figure 6: Monthly distribution of supply energies (useful internal, useful solar and auxiliary heating) and demand energies (transmission heat losses, ventilation heat losses) to balance the total thermal energy budget of a building. Storage of heat inside the constructional mass is almost negligible.

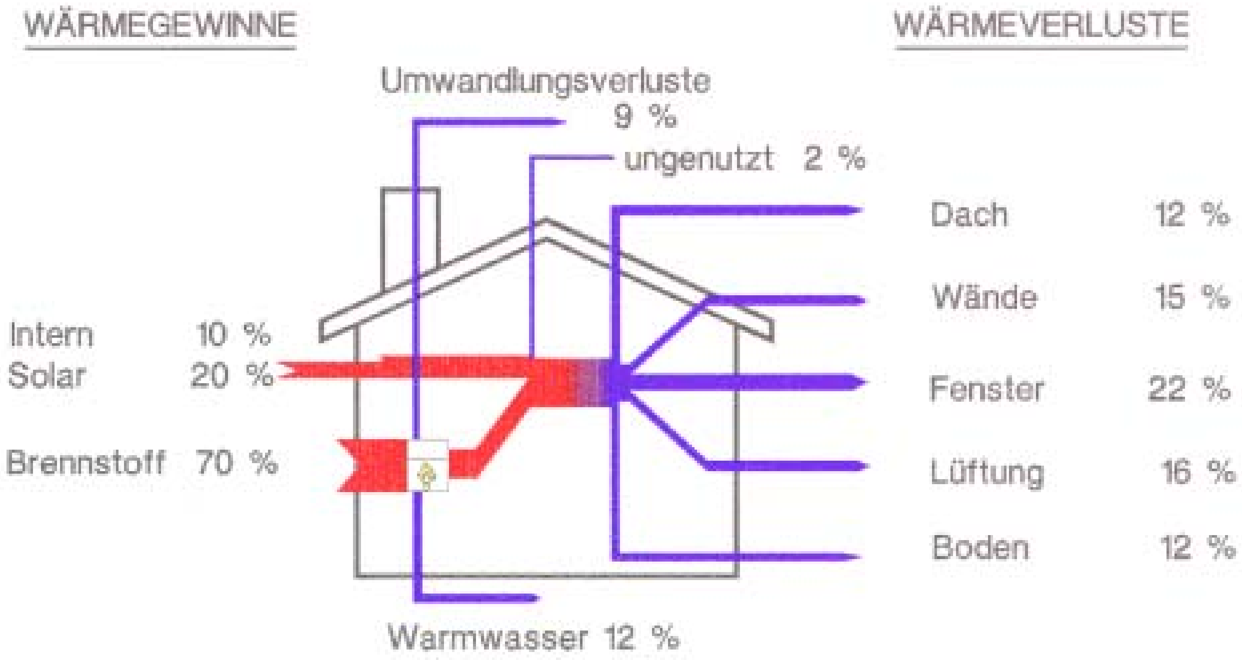
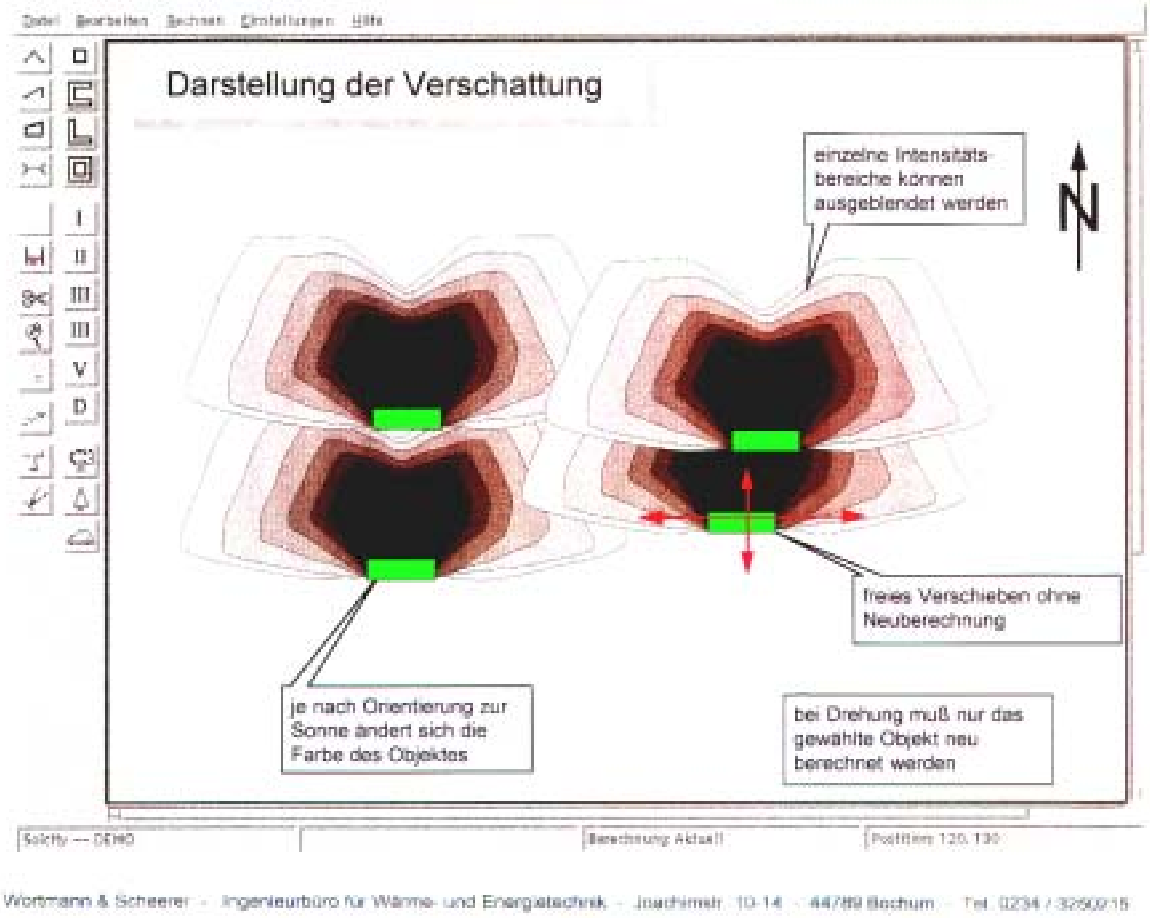


Figure 7: Seasonal balance of heat flows for energy gains from different sources and energy losses through several paths.



Darstellung der Verschattung

einzelne Intensitätsbereiche können ausgeblendet werden

freies Verschieben ohne Neuberechnung

je nach Orientierung zur Sonne ändert sich die Farbe des Objektes

bei Drehung muß nur das gewählte Objekt neu berechnet werden

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Figure 8: Energetic shading effects of individual houses within a given topography with given urban environment. Increasing dark Grey symbolizes that the potential solar gain is increasingly reduced. Therefore, positioning of buildings should be such, that dark Grey colors do not overlap.