Clima #13

Dynamic Plant Simulator for HVAC Systems

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Abstract

The detailed dynamic sirnulation of coupled units in HVAC-systems and buildings is gaining increasing importance as strong tool in HVAC~engiiieering and operation. This investigation deals with the basics in the development of **an** universally applicable dynamic simulator. General fundamentals are formulated some moduls are outlined. Shnulation of a heated 4-room-residence, a solar system and a storage tank as applications demonstrate the mode of functioning and the potential of the simulator.

1. Introduction

In order to analyse energy consumption of HVAC systems in buildings, the dynamic behaviour **in** the time dornaine of thermal components and HVAC equipment, operating in buildings has to be investigated. Thermal characteristics of all cornpoilents, including the building have to be related to the physical conditions Imposed by the surroundings.
As usefull **in** large systems a universally applicable dynamic simulation model has been conceived and for application to HVAC systeins in buildings developed.
In this modular approach the complete system is considered to be a collection of integrated subsystems, each as niodul having identifiable physical characteristics and beeing modelled as precisely as desirable.
Translating physical equipment and systems to a mathematical form, that can be attached by the mathematics of control systems, results in a mathematical description of dynamic simulation which is that of one single equation of state for the total systein, a matrix-equation as function of state and disturbance, implicitly to be solved, [11, [21.
Compared with the explicit Euler-algoritlim of first order the here presented implicl it state-space representation is superior with regard to programm ng, processingspeed, accuracy and stability of numerical solution.
The components of an HVAC system, energy-generation or ~transformation, storage and -distribution, interrelated with the random conditions ,weather" and ,eiiergy~sotirces" and the building operation, may be modelled independently from each other as subroutine moduls.
This simulation system applies universally as every component of the HVAC sy.stein or of the building can be modelled in analogous way. The dynamic plant simulator is **an** important tool in HVAC engineering and operation., efficiency analysis, comparison, optimization and optimal design, studies **on** energy cons111111)tiOn, emission, **Costs** and new technologies of different HVAC systems **may be** performed.

Dynamic Plant Simulator for HVAC Systems

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Abstract

The detailed dynamic simulation of coupled units in HVAC-systems and buildings is gaining increasing importance as strong tool in HVAC-engineering and operation. This investigation deals with the basics in the development of an universally applicable dynamic simulator. General fundamentals are formulated some moduls are outlined. Simulation of a heated 4-room-residence, a solar system and a storage tank as applications demonstrate the mode of functioning and the potential of the simulator.

1. Introduction

In order to analyse energy consumption of HVAC systems in buildings, the dynamic behaviour in the time domaine of thermal components and HVAC equipment, operating in buildings has to be investigated. Thermal characteristics of all components, including the building have to be related to the physical conditions imposed by the surroundings.

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Compared with the explicit Euler-algorithm of first order the here presented implicit state-space representation is superior with regard to programming, processing-speed, accuracy and stability of numerical solution.

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This simulation system applies universally as every component of the HVAC system or of the building can be modelled in analogous way. The dynamic plant simulator is an important tool in HVAC engineering and operation; efficiency analysis, comparison, optimization and optimal design, studies on energy consumption, emission, costs and new technologies of different HVAC systems may be performed.

2. Dynamic Simulation

2.1 Model and Method

A dynanilc HVAC simulation model for thermal processes is consisting of four Components:

clinialological data or model, a. physical model of the HVAC, system(s), a. physical model of the building and a physical model of the operation.
Chinatological data, are given by the TRY-data. which are provided by the national weather services in kind of data. files.
First step of model development is the translation of the physical equipment and its processes 'in the tinie doinaine by help of the equations of energy balance. As usual ill antoinatic-control the functional relationships and interactions of the component models have been established and representated by the block diagram of the total system - building plus HVAC ~ in fig. 1.
The blocks represent transfer functions of the components, for example the boiler, the collector of a solar system, the storage tank and the walls of the building. The lines represent the energy flows resp. inforniation-flows between the components. The proceeding when simulating thernialsystenis at transient state must take in~ to account the tinie function of the loads, the transient energy flows in the walls and the dynamic energy exchange between the components of the system and e.g. a, room as 1 illustrated in fig. 2. The application of the principles of dynamics to the physical components had to be translated into the model.

2.2 Mathematical Formulation and Solution of the System Equations

The described method results ill a, system of differential equations which has to be solved numerically. In contradiction to a tistial modular approach and serial solving of the differential e(jualions, a state matrix formulation was introduced. The principle of the procedure will be demonstrated as follows:

The energy balances of the mass inside a, room (air, furniture; index 1) may be

'tten 'n the form

wri 1

di) l

WAll,' + QI,F + QIJIV + QI,H + Qit + QL dt

The tinie derivative of the indoor teinperalure dj , the state variable, can then be expressed as a, function (stun) of the state variables (other temperatures) and the disturbance variables, the outdoor temperature I)A, and the internal energies (for example the heat produced by persons; Qi,,t); additional introduction of the equation., for heat flow gives

di) l i), + al,Alt,'' ?)All,',, + (IIJIV ' gllVo + (II,H ' 9H + bi,A - 9A + bi,i,@t , Oint dt

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2.2 Mathematical Formulation and Solution of the System Equations

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The energy balances of the mass inside a room (air, furniture; index I) may be written in the form

$$m_I \cdot c_I \cdot \frac{d\vartheta_I}{dt} = \dot{Q}_{I,AW} + \dot{Q}_{I,F} + \dot{Q}_{I,IW} + \dot{Q}_{I,H} + \dot{Q}_{int} + \dot{Q}_L \qquad (1)$$

The time derivative of the indoor temperature ϑ_I , the state variable, can then be expressed as a function (sum) of the state variables (other temperatures) and the disturbance variables, the outdoor temperature ϑ_A, and the internal energies (for example the heat produced by persons; $\dot{Q}_{int}$); additional introduction of the equations for heat flow gives

$$\frac{d\vartheta_I}{dt} = a_{I,I} \cdot \vartheta_I + a_{I,AW} \cdot \vartheta_{AW_o} + a_{I,IW} \cdot \vartheta_{IW_o} + a_{I,H} \cdot \vartheta_H + b_{I,A} \cdot \vartheta_A + b_{I,int} \cdot \dot{Q}_{int}$$

,dj

(aj,j al,All,, aj,Jjj, aj,j-j) 9A[V0 dIWO 1) H + (bl,A l)l,i,,t) @A (2) Qlnl

This equation can be translated into a vector equation (matrix representation)

d0l / dt 4jj . Oj + Bi,j . sj (3)

with

Aj,j matrix of state
Oj vector of state variables

matrix of disturbance

si vector of disturbance varibles

The coefficients ai,,i and bj,j of the inafluence coefficients of matrix Alj and Bili result from the heat transfer coefficie and heat capacities, for example

al,Ali, - ak , AA1V (4)

77Il - CJ

The partial differential equation of the transient heat transfer in the walls (Fourier's law) is

di) 62g

= a - - (5)

dt 6,r2

Discrete representation of the local differential coefficient of the temperature, as~ sunied to be the variable of state the wa.11, regarding a. wa.11 with ii lavers and

1

replacing the derivatives (difrerciitia,ls) by finite difference approximations, e. g. for layer 1, yields

a

(,di-l - 2di + 9j+1 (6)

dt)2

n

and provides a reduction of the partia.1 differential equations to a. set of ordilial, Y differential equations for the i layers, which may be written identically to equation (3).
The disturbance variables of the walls are the temperatures of the neighbour room and, for example the solar radia to the walls. They are notified lii the equations for the outer laver of the walls.

Since mathematical description of the state equations of all components of the systein may be handled identically, t inatrix equallons of each physical coni~ Ponent can be combined in one matrix equation of the tota,l system,' which a,

3

$$= (a_{I,I}\, a_{I,AW}\, a_{I,IW}\, a_{I,H}) \cdot \begin{bmatrix} \vartheta_I \\ \vartheta_{AWo} \\ \vartheta_{IWo} \\ \vartheta_H \end{bmatrix} + (b_{I,A}\, b_{I,int}) \cdot \begin{bmatrix} \vartheta_A \\ \dot{Q}_{int} \end{bmatrix} \quad (2)$$

This equation can be translated into a vector equation (matrix representation)

$$\frac{d\Theta_I}{dt} = A_{I,j} \cdot \Theta_j + B_{I,j} \cdot s_j \quad (3)$$

with

$A_{I,j}$ matrix of state
Θ_j vector of state variables
$B_{I,j}$ matrix of disturbance
s_j vector of disturbance varibles
The coefficients $a_{I,j}$ and $b_{I,j}$ of the inafluence coefficients of matrix $A_{I,j}$ and $B_{I,j}$ result from the heat transfer coefficients and heat capacities, for example

$$a_{I,AW} = \frac{a_k \cdot A_{AW}}{m_I \cdot c_I} \quad (4)$$

The partial differential equation of the transient heat transfer in the walls (Fourier's law) is

$$\frac{d\vartheta}{dt} = a \cdot \frac{\delta^2 \vartheta}{\delta x^2} \quad (5)$$

Discrete representation of the local differential coefficient of the temperature, assumed to be the variable of state of the wall, regarding a wall with n layers and replacing the derivatives (differentials) by finite difference approximations, e.g. for layer i, yields

$$\frac{d\vartheta_i}{dt} = \frac{a}{(\frac{s}{n})^2} \cdot (\vartheta_{i-1} - 2\vartheta_i + \vartheta_{i+1}) \quad (6)$$

and provides a reduction of the partial differential equations to a set of ordinary differential equations for the i layers, which may be written identically to equation (3).
The disturbance variables of the walls are the temperatures of the neighbour room and, for example the solar radiaton to the walls. They are notified in the equations for the outer layer of the walls.
Since mathematical description of the state equations of all components of the system may be handled identically, the matrix equations of each physical component can be combined in one matrix equation of the total system, which is a

set of coupled ordinary differential equations for the state variables of the total systeni, the state inalrix equation,

$$\frac{dOi}{dt} \quad li,j\ ,\ E)j + Aj\ ,\ sj \qquad (7)$$

wi 'th

,1, 1 j . = 1 . . . ...?I

The tline derivation of the state variables is a. function of the state variables Oj and the disturbance variables *sj.*
The state vector 0. contains the temperatures of the system components and the interference vector s contains the climatological data. respectively the temperatures of the neighbour roonis, which are not simulated.
Aily other component k of the total systen-1 inay be considered by determining the cocfficicIAS % and bkj (see equ. 2 and 3) and combining thein to the niatrix equation of the total system (see equ. 7).
The governing system of coupled ordinary differential equation,-, can be solved (11rectly, without iteration, tising highly stable implicit integration schemes with automatic tinie step control, generated by the margin of error estiinate, for example senibiniplicit Rxinge-Klutta, methods, Gear' .9 method, or orthogonal collocallon method, yielding accurate and fast results.

3. HVAC System Simulation

3.1 Building Simulation

Base for simulation was a 4-rooiii-residence-niodel, fig. 3, consisting of 4 rooms, each with 2 outer walls, 2 inner walls and 2 windows. The residence is embedded in the middle of a multistorey building, where is assumed to have no heat transmission to neighbour residences. Ceiling and floor are combined to one inass and are described by one differential equation in discrete representation.
The components are: Inner masses, heating, windows, walls.
Inner inasses are the air and ftirniture as one inass with homogenous teinpera~ ture, which iiia.v absorb up to 15 Wo of the solar radiation; heat transfer occurs by confection, taking into account variable heat transfer coefficients.
Heating conditions are equal for each room. The radiator performance corre~ sponds to standard heat requirement calculation. Control is according to indoor temperature as result of confection and radiation. Time constants of the rooms are between 70 h an(l 140 li.
,Solar wiii(lows" are regarded massless and therefore not represented in a. diffe~ rential equation; they operate as aperture for direct and diffusive solar radiation. Area, of win(lows is varied froin 0 - *40 %* of total outer area. of residence.
"balls are inade from same material with same thickness. Solar radiation coming in is assumed to fall possibly on the walls. Outer and inner walls are discretely represented in 3 or 5 layers.

set of coupled ordinary differential equations for the state variables of the total system, the state matrix equation,

$$\frac{d\Theta_i}{dt} = A_{i,j} \cdot \Theta_j + B_{i,j} \cdot s_j \tag{7}$$

with

$i, j = 1 \ldots\ldots n$

The time derivation of the state variables is a function of the state variables Θ_j and the disturbance variables s_j.
The state vector Θ_j contains the temperatures of the system components and the interference vector s_j contains the climatological data respectively the temperatures of the neighbour rooms, which are not simulated.
Any other component k of the total system may be considered by determining the coefficients a_{kj} and b_{kj} (see equ. 2 and 3) and combining them to the matrix equation of the total system (see equ. 7).
The governing system of coupled ordinary differential equations can be solved directly, without iteration, using highly stable implicit integration schemes with automatic time step control, generated by the margin of error estimate, for example semi-implicit Runge-Kutta methods, Gear' s method, or orthogonal collocation method, yielding accurate and fast results.

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The components are: Inner masses, heating, windows, walls.
Inner masses are the air and furniture as one mass with homogenous temperature, which may absorb up to 15 % of the solar radiation; heat transfer occurs by convection, taking into account variable heat transfer coefficients.
Heating conditions are equal for each room. The radiator performance corresponds to standard heat requirement calculation. Control is according to indoor temperature as result of convection and radiation. Time constants of the rooms are between 70 h and 140 h.
„Solar windows" are regarded massless and therefore not represented in a differential equation; they operate as aperture for direct and diffusive solar radiation. Area of windows is varied from 0 - 40 % of total outer area of residence.
Walls are made from same material with same thickness. Solar radiation coming in is assumed to fall possibly on the walls. Outer and inner walls are discretely represented in 3 or 5 layers.

Celling and floor are not discretely representa.ted; heat is transferred only by con~ duction to neighbour residences. Heat is transferred at the surface by radiation alid convection.
Interna,l heat sources are combined with the inner masses.
Heal transfer between components occurs by convection, radiation and conduction. Calculation of infraxed-radiation regards all reflexions at the internal stirfa,~ ces respecting the Actual coefficients of emission conforming to the net-radiationmethod. Temperature control at day or night may be changed. The integration cyclus are 10 min. or 1 li, after each of which lleat transfer coefficients are recalculated. Air flow between rooms and outside may be controlled.
The program package balances energy for the reference model durlilg the whole simulation tinie of a bleating period, fig. 4.
The WSVO-model of the residence corresponds to building requirements a,ccor~ ding to WVO-law [31.
Improvement of insulation of outer walls from k = *0, 91*VlnI'K to *k = 0, 41Vlin'K* has been rea.lized.
Error balances were calculated for error tolerances 0.001, 0.01 and 0.1. Setting of program for simulation wa.s: 0.1 / 5 layers / 10 **iiiiii.** Several physical and numerical tests lia.d **])cell** passed with good results. Results have been gained for sin-itilalion periods of lIl, 1 (lay, 1 week, 1 month and the whole heating period; energy amounts are shown in fig. 4. Different measures for energy sa.ving had been taken into account: orientation and area, of windows, variable volume of rooms, standard insulation, translucent llistilalion, temporarily activated insulation of windows (TWS), triple-glass-wiiidows, temperature drop at night individually for each room, air exchange between tile rooms (constant or controlled). Free choice of material and windows is possible by introducing specific material consta:nts. Different fixed space-teniperaflire and simultaneously active heal sources simulate different usage of each room. Total energy consumption in function of different measures for heat-flow reduction is shown in fig. 5.
Highest reductions call be realized by increasing standard-Insula.tion and by translucent insulation.
Different size of rooms makes little difference.
Combination of different measures in function of share of window-area is given ill fig. 5.

Different methods of construction, e.g. weights, from lightweight to very heavyweight, influence energy consumption a.s shown **ill** figs. 6 and 7.
Exploitation of solar radiation:
Ill case of solar radiation overheating of rooms by too much energy input inight occur. The extent of exploitation is given in fig. 8 **ill** function of the Share of window-area. Comparing energy consumption for a, model with translucent insulation results ill nearly equabzed energy balances between input a,iid output.
Further results are published in [41, [5], [61.

Ceiling and floor are not discretely representated; heat is transferred only by conduction to neighbour residences. Heat is transferred at the surface by radiation and convection.

Internal heat sources are combined with the inner masses.

Heat transfer between components occurs by convection, radiation and conduction. Calculation of infrared-radiation regards all reflexions at the internal surfaces respecting the actual coefficients of emission conforming to the net-radiation-method. Temperature control at day or night may be changed. The integration cyclus are 10 min. or 1 h, after each of which heat transfer coefficients are recalculated. Air flow between rooms and outside may be controlled.

The program package balances energy for the reference model during the whole simulation time of a heating period, fig. 4.

The WSVO-model of the residence corresponds to building requirements according to WVO-law [3].

Improvement of insulation of outer walls from $k = 0,9W/m^2K$ to $k = 0,4W/m^2K$ has been realized.

Error balances were calculated for error tolerances 0.001, 0.01 and 0.1.

Setting of program for simulation was: 0.1 / 5 layers / 10 min.

Several physical and numerical tests had been passed with good results.

Results have been gained for simulation periods of 1h, 1 day, 1 week, 1 month and the whole heating period; energy amounts are shown in fig. 4.

Different measures for energy saving had been taken into account: orientation and area of windows, variable volume of rooms, standard insulation, translucent insulation, temporarily activated insulation of windows (TWS), triple-glass-windows, temperature drop at night individually for each room, air exchange between the rooms (constant or controlled). Free choice of material and windows is possible by introducing specific material constants. Different fixed space-temperature and simultaneously active heat sources simulate different usage of each room.

Total energy consumption in function of different measures for heat-flow reduction is shown in fig. 5.

Highest reductions can be realized by increasing standard-insulation and by translucent insulation.

Different size of rooms makes little difference.

Combination of different measures in function of share of window-area is given in fig. 5.

Different methods of construction, e.g. weights, from lightweight to very heavyweight, influence energy consumption as shown in figs. 6 and 7.

Exploitation of solar radiation:

In case of solar radiation overheating of rooms by too much energy input might occur. The extent of exploitation is given in fig. 8 in function of the share of window-area.

Comparing energy consumption for a model with translucent insulation results in nearly equalized energy balances between input and output.

Further results are published in [4], [5], [6].

3.2 Plant Simulation

3.2.1 Active and Passive Solar System

For a, passive solar system, wliere heat capacity of the component glass can bC neglected, the tlier balancing provides an algebraic equation

Opass = 190 ' AF - (Tft),r,,f f - kF - AF - Wl - 9A) (8)

wlilcli lias to bc merged into the **main** matrix of the tota.1 system and solved simultaneously. ValRlation by measurements for an active and a passive system is shown in fig. 9. Furtlier results publislied **in** [7].

3.2.2 Thermal Storage System

3.2.2.1 Physical Model

The considered tliermal storage (resign, fig. 10, is to be a. thermally stratified upstreani charge stor tank, equipped with constant Heater performance.
Natural **and** force(l convection of storage **me(liuni** water are simulated by an a(lditional equivalent li coii(ltictioii coefficient

A, qu (t, Z) = l@cond (l @ Z) + 1\coytk@ (1 (9)

Base(l on one-diniensional heat conduction and convection only the energy conservation balance bia be regarded. Consequently the modelling results **in** the following scheme, fig. 10, with tbree level stratification: inlet, central, outlet level, wliich can be lleated or not.

3.2.2.2 Mathematical formulation

Analogue to chapter 2.2 first of all the differential equation has to be establishe(l by setting up the en balance of the mass wltiilii the storage tank.
The control volume represented **in** layers, yields the following equation

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bT q-+Az
,0 - c - - - + q'i (10)
61 A -- A

wlilcli gives with AZ -@ 0 the differential equation of the storage system.

. c
6T 6 6
c. -(T) + q'i (11)
bt 6Z A 6

Intro(lucing Fourler's law of lieat flow

6T

$$q \tag{12}$$

6

3.2 Plant Simulation

3.2.1 Active and Passive Solar System

For a passive solar system, where heat capacity of the component glass can be neglected, the thermal balancing provides an algebraic equation

$$\dot{Q}_{pass} = I_{90} \cdot A_F \cdot (\tau\alpha)_{F,eff} - k_F \cdot A_F \cdot (\vartheta_I - \vartheta_A) \tag{8}$$

which has to be merged into the main matrix of the total system and solved simultaneously.
Validation by measurements for an active and a passive system is shown in fig. 9. Further results are published in [7].

3.2.2 Thermal Storage System

3.2.2.1 Physical Model

The considered thermal storage design, fig. 10, is to be a thermally stratified upstream charge storage tank, equipped with constant heater performance.
Natural and forced convection of storage medium water are simulated by an additional equivalent heat-conduction coefficient

$$\lambda_{equ}(t,z) = \lambda_{cond}(t,z) + \lambda_{conv}(t,z) \tag{9}$$

Based on one-dimensional heat conduction and convection only the energy conservation balance has to be regarded. Consequently the modelling results in the following scheme, fig. 10, with three levels of stratification: inlet, central, outlet level, which can be heated or not.

3.2.2.2 Mathematical formulation

Analogue to chapter 2.2 first of all the differential equation has to be established by setting up the energy balance of the mass within the storage tank.
The control volume represented in layers, yields the following equation

$$\varrho \cdot c \cdot \frac{\delta T}{\delta t} = -\frac{\dot{q}_{z+\Delta z} - \dot{q}_z}{\Delta z} - \frac{\dot{m} \cdot c}{A} \cdot \frac{T_{z+\Delta z} - T_z}{\Delta z} + \dot{q}_i \tag{10}$$

which gives with $\Delta z \rightarrow 0$ the differential equation of the storage system.

$$\varrho \cdot c \cdot \frac{\delta T}{\delta t} = -\frac{\delta}{\delta z}(\dot{q}) - \frac{\dot{m} \cdot c}{A} \cdot \frac{\delta}{\delta z}(T) + \dot{q}_i \tag{11}$$

Introducing Fourier's law of heat flow

$$\dot{q} = -\lambda \cdot \frac{\delta T}{\delta z} \tag{12}$$

is leading to the basis equation for simulation

6T 6 6T 6

,O.C.- = _-(-A - _) - - (T) + q'i (13)

61 6 Z 6Z A 6 -

The solution of this parabolic differential equation needs two physical random **and** one tline dependent i conditions.

Randoin conditions: The charging energy flow at the first layer of the storage tank is equal to the energy rate at entrance of the tank and consists of a convective and diffusive sliaxe, and teniperature i),, = di,,, . The temper gradient at the outlet niust he equal to zero.

Initial condition: Initial temperature (~distribution) of the storage inedittin nitist be given, e.g. as constant temperatur over the volume of the tank.

3.2.2.2 Numerical Solution

Reduction of the given partial differential equation of ljigher order for each point of definition to an ordinary differe equation of first order is aiialogue to 2.9 achieved by replacing the local difrerentials by quotients of differeces, for point. The quotients of differences are determined front the teniperatures of the discrete points of local coordinate. State space representation gives a reduction of the basis equation; introduction of the above mentioned quotien differences leads to the desired and froin 2.2 well known inatrix representation. Thus the niatrix of state for a the storage tank with variable nuinher of layers is containing only the temperatures of the layers as state variables an temperatures of cold water inlet and healer perforinance as interference variables.

Conforining to the development of a general prograiii niodul in 2.2 the restruc-

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niatrix representation which inay bc solved as stand alone prograni or nierged into the inain niatrix of state equatio the total systeni together with the other components and the building.

dO,

- = Ai,j , Oj + Bi,j , sj (14)

dl

3.2.2.3 Results

Nunierical results have been validated by coniparing thein with analytically deduced solutions.

Verification by lielp of experiments is shown **in** figs. 11 and 12.

Future works will concentrate on enlarging the niodel libraries and on increasing the efficiency **and** ease of use to i the demands of HVAC application.

is leading to the basis equation for simulation

$$\varrho \cdot c \cdot \frac{\delta T}{\delta t} = -\frac{\delta}{\delta z}(-\lambda \cdot \frac{\delta T}{\delta z}) - \frac{\dot{m} \cdot c}{A} \cdot \frac{\delta}{\delta z}(T) + \dot{q}_i \tag{13}$$

The solution of this parabolic differential equation needs two physical random and one time dependent initial conditions.

<u>Random conditions:</u> The charging energy flow at the first layer of the storage tank is equal to the energy rate at the entrance of the tank and consists of a convective and diffusive share, and temperature $\vartheta_\infty = \vartheta_{inl}$. The temperature gradient at the outlet must be equal to zero.

<u>Initial condition:</u> Initial temperature (-distribution) of the storage medium must be given, e.g. as constant temperature all over the volume of the tank.

3.2.2.2 Numerical Solution

Reduction of the given partial differential equation of higher order for each point of definition to an ordinary differential equation of first order is analogue to 2.2 achieved by replacing the local differentials by quotients of differeces for each point. The quotients of differences are determined from the temperatures of the discrete points of local coordinate.

State space representation gives a reduction of the basis equation; introduction of the above mentioned quotients of differences leads to the desired and from 2.2 well known matrix representation. Thus the matrix of state for a thermal storage tank with variable number of layers is containing only the temperatures of the layers as state variables and the temperatures of cold water inlet and heater performance as interference variables.

Conforming to the development of a general program modul in 2.2 the restructuring of the ordinary differential equation of first order allows the very clear matrix representation which may be solved as stand alone program or merged into the main matrix of state equations of the total system together with the other components and the building.

$$\frac{d\Theta_i}{dt} = A_{i,j} \cdot \Theta_j + B_{i,j} \cdot s_j \tag{14}$$

3.2.2.3 Results

Numerical results have been validated by comparing them with analytically deduced solutions.

Verification by help of experiments is shown in figs. 11 and 12.

Future works will concentrate on enlarging the model libraries and on increasing the efficiency and ease of use to meet the demands of HVAC application.

4. Literature

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[31 *Biitidesi.cpttbllk* Dcutschland: W5rniesclititzverordiiiiiig, Bonn (1994), Staatsa.nzeiger
[41 *Kast, W; Ottun, W.:* Heizeiiergiestr6iiie dynan-lisch slinuliert, HM, 38 (1987) Nr. 6, p. 300/305
[5] *Kast, IE; Oitcii, W.:* Sinitilation maclit instation5re HeizvorgSnge berechenbar, 11L11 39 (1988) Nr. 12, p. 558/561
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[7] *Kast, 1,E; Man, IL:* Mess- **tail** Siiiitila,tioiisergel)iiisse einer tellsolar belielzteii Fabrikhalle, I-ILH, 36 (1985) Nr. 12, p. 602/606

5. Nomenclature:

Indices:

A	outdoor, outside
akt	active
A 11'	otiter wall
B	floor
F	wallow
H	heating system, radiator
1,1 j	rminhig index of variables of stale and disturbance
I111	inner wall
L	air
771(13,	MaXI11111111
NR	neighbour room

·	surface
pass	passive
801	solar
1,11	flow (pipe)
R	rettirn (pipc)

4. Literature

[1] *Föllinger, O.:* Einführung in die Zustandsbeschreibung dynamischer Systeme, Regelungstechnik, 28 (1980) Nr. 4, p. A1 f.

[2] *Gilles E. D. et al:* Dynamische Simulation komplexer chemischer Prozesse, Chem.-Ing.-Tech, 58 (1986) Nr. 4, p. 268/278

[3] *Bundesrepublik Deutschland:* Wärmeschutzverordnung, Bonn (1994), Staatsanzeiger

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[5] *Kast, W.; Otten, W.*: Simulation macht instationäre Heizvorgänge berechenbar, HLH 39 (1988) Nr. 12, p. 558/561

[6] *Kast, W.; Klan, H.*: Simulation des Heizenergieverbrauchs von Wohnhäusern, HLH, 44 (1993) Nr. 10, p. 613/616

[7] *Kast, W.; Klan, H.*: Mess- und Simulationsergebnisse einer teilsolar beheizten Fabrikhalle, HLH, 36 (1985) Nr. 12, p. 602/606

5. Nomenclature:

Indices:

A	outdoor, outside
akt	active
AW	outer wall
B	floor
F	window
H	heating system, radiator
i, j	running index of variables of state and disturbance
IW	inner wall
L	air
max	maximum
NR	neighbour room
o	surface
$pass$	passive
sol	solar
V	flow (pipe)
R	return (pipe)

Formulary

a	7711'Is	thermal diffusivity
ai,j	Ils	coefficients of inatrix Ai,j
AF	771 2	area, of window
Ai,j	-	matrix of state vector
bi,j	Ils	coefficients of niatrix Bi,j
Bi,j		matrix of disturbance vector
c	J1kgE	heat capacity
CpL	J1kgK	lleat capacity of air at constant pressure
,go	R'/in'	solar radiation to a vertical surface
k	IT'im'K	heat transmission coefficient
777	kg	inass
1P I	kg	**inner** masses
71		**number** of discrete wall layers,
		number of **systeni-components**

A. TV heat flow

Q	A. IV h	energy
Qakt	4.11'h	energy of active solar system
Qges	A.IVh	total energy loss (energy supply
QII	A.Wh	Heating energy of Heating system
Qint	k 1V h	energy of internal sources
0Norm	OV	standard heat requirement
QSol	017h	solar radiation into rooin
Iq	771	thickness of wall
t	8	**time**
	771	local coordinate
.r		
(v	TV/in'K	factor of absorption
Cyk	IT'lin'K	convective licat transfer coefficient
Q,	W1777'K	heat transfer coefficient of radiation
T		coefficient of transmission
		coefficient of solar capacity of energy
71	-	efficiency
9	0 (1,	temperature
g	O C	indoor temperature
1) A	OC	outdoor temperature
01		parameter of control

Formulary

a	m^2/s	thermal diffusivity
$a_{i,j}$	$1/s$	coefficients of matrix $A_{i,j}$
A_F	m^2	area of window
$A_{i,j}$	$-$	matrix of state vector
$b_{i,j}$	$1/s$	coefficients of matrix $B_{i,j}$
$B_{i,j}$	$-$	matrix of disturbance vector
c	J/kgK	heat capacity
c_{pL}	J/kgK	heat capacity of air at constant pressure
I_{90}	W/m^2	solar radiation to a vertical surface
k	W/m^2K	heat transmission coefficient
m	kg	mass
m_I	kg	inner masses
n	$-$	number of discrete wall layers, number of system-components
$\dot{Q}$	kW	heat flow
Q	kWh	energy
Q_{akt}	kWh	energy of active solar system
Q_{ges}	kWh	total energy loss (energy supply)
Q_H	kWh	heating energy of heating system
Q_{int}	kWh	energy of internal sources
$\dot{Q}_{Norm}$	kW	standard heat requirement
Q_{sol}	kWh	solar radiation into room
s	m	thickness of wall
t	s	time
x	m	local coordinate
α	W/m^2K	factor of absorption
α_k	W/m^2K	convective heat transfer coefficient
α_s	W/m^2K	heat transfer coefficient of radiation
τ	$-$	coefficient of transmission
ϵ	$-$	coefficient of solar capacity of energy
η	$-$	efficiency
ϑ	oC	temperature
ϑ_I	oC	indoor temperature
ϑ_A	oC	outdoor temperature
σ	$-$	parameter of control

HVAC-system

time, -J Int. licat sources

air Heading system

1F-

j solar system

a
I

CD
rnass

storage -SY-S-te-M

U
Or

>

(D QPa4S **F'**

J passive system

floor
building

d **wail** **delay.**
floor

Fig. 1 Control system chart

AW, A GIWAW

wal
l

dl,AW

internal mass

L

outdoor

GM, F -01M

window
indoor

F, A So[

C-
'de wall 0 H,1

outsi

radiator

lant -------- 'Jeso It

radiation

c
o
n
v
e
c
t
i

o

n

FiR. 2 Enemv finw **chart**

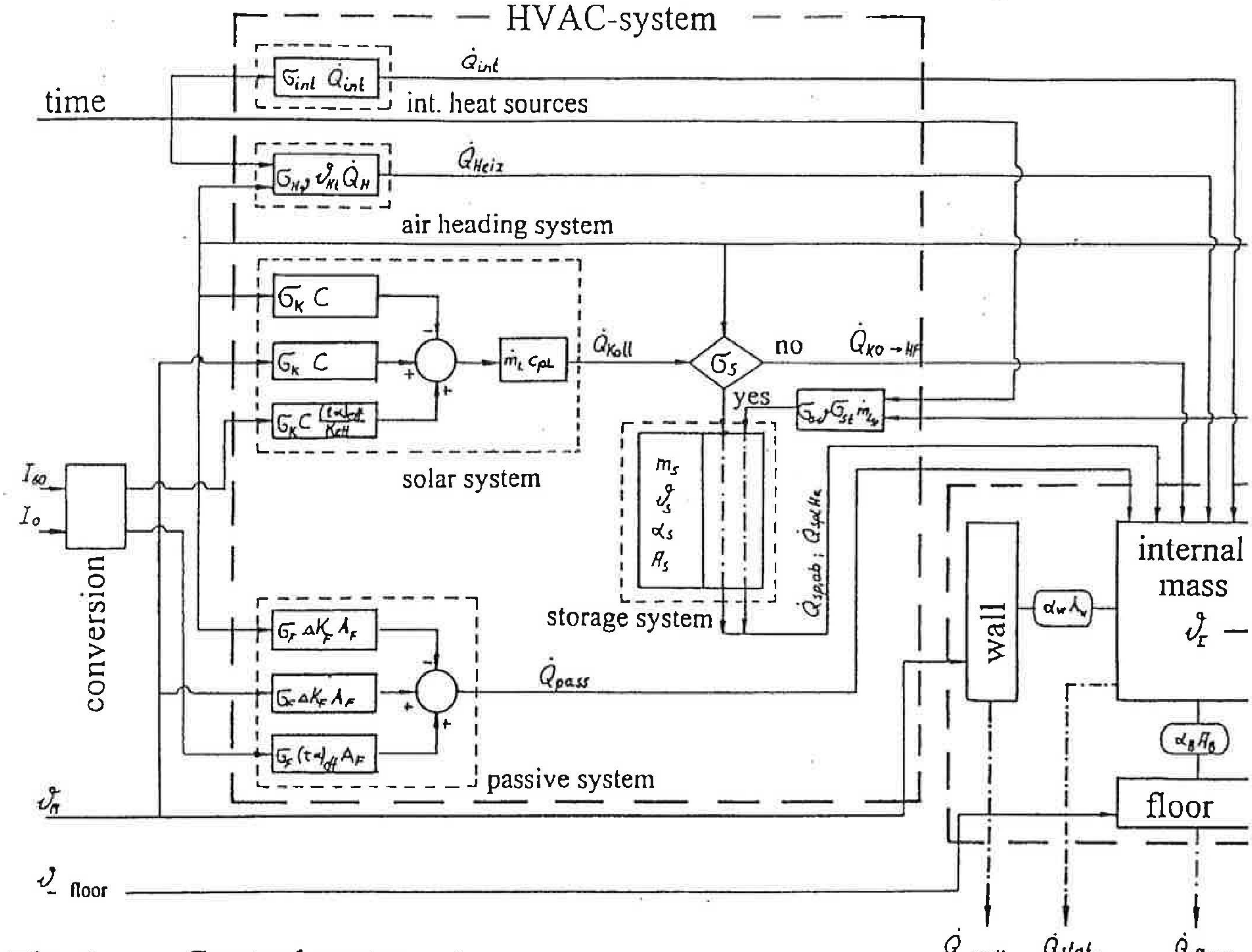
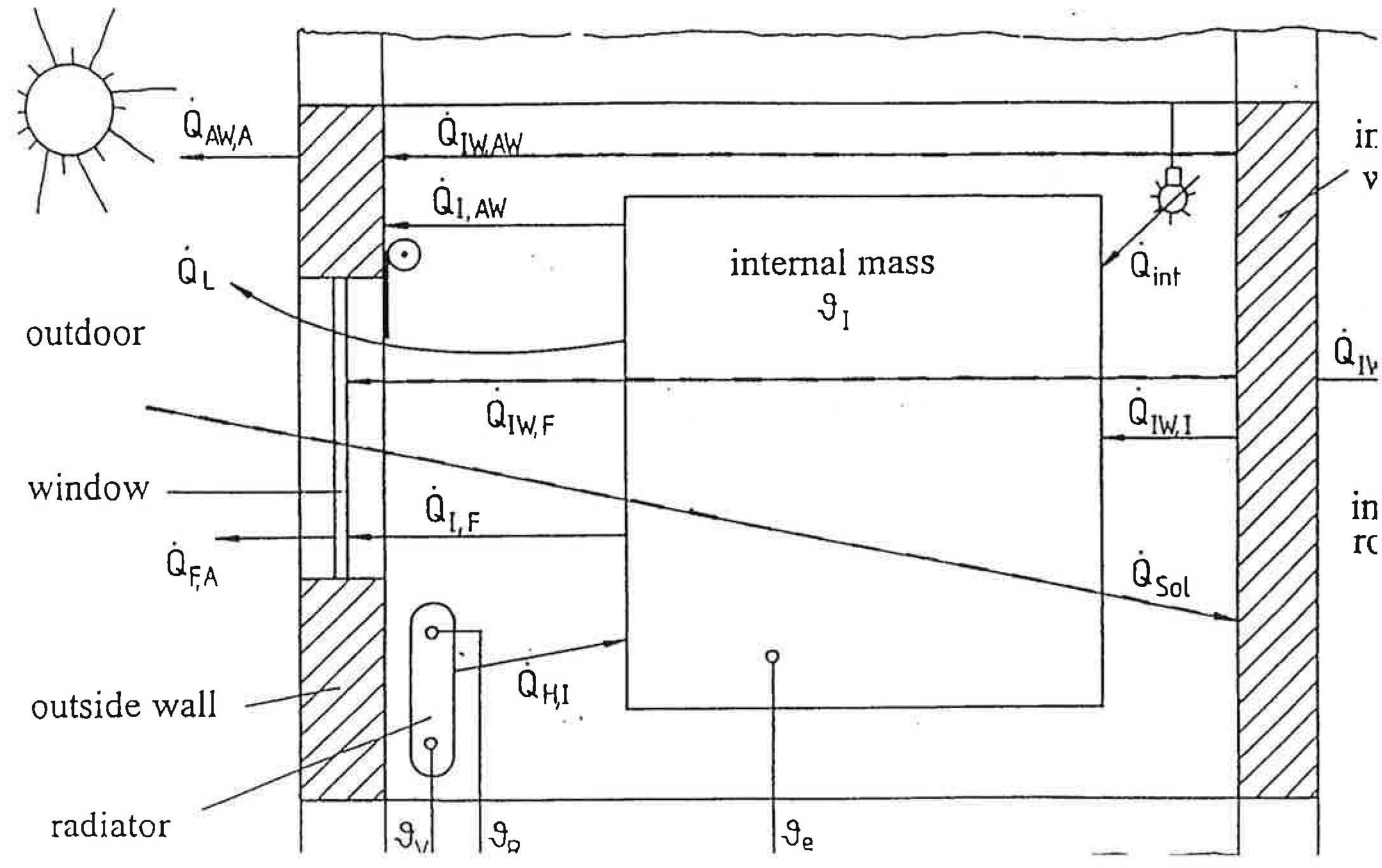


Fig. 1 Control system chart



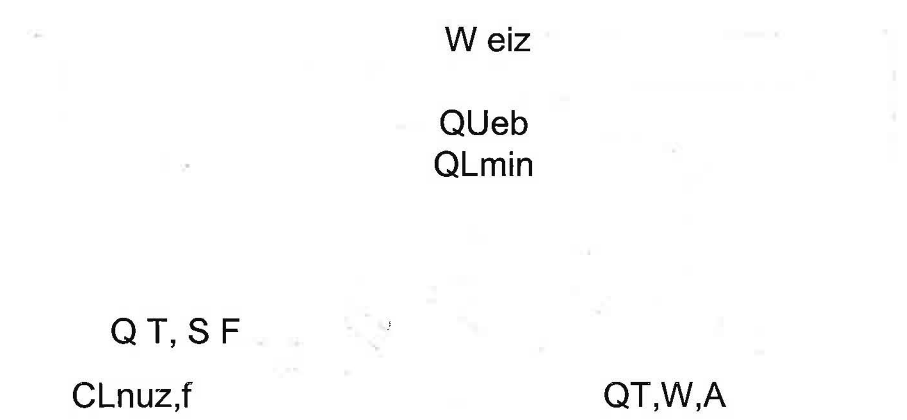
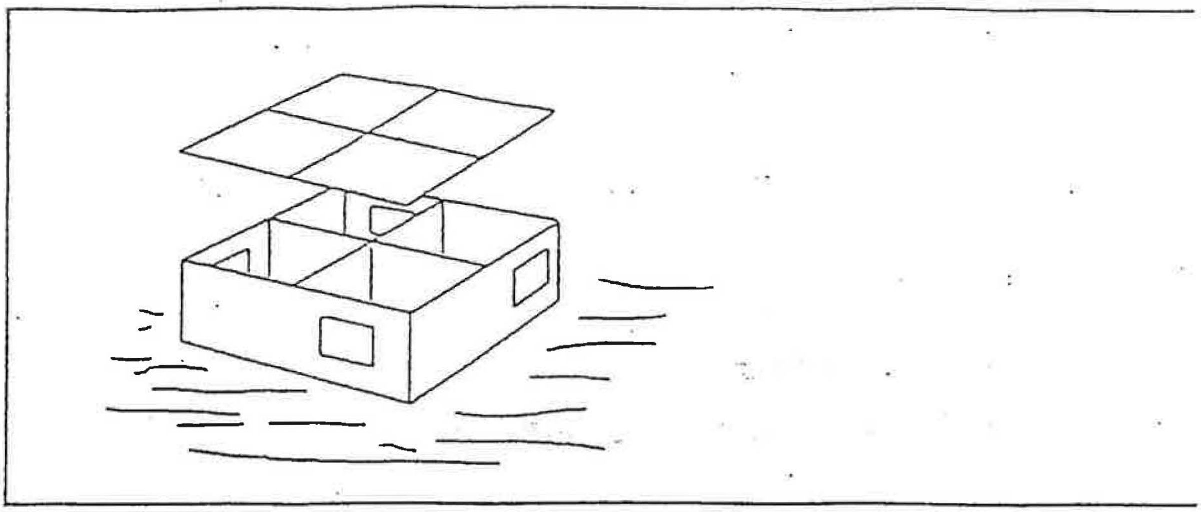
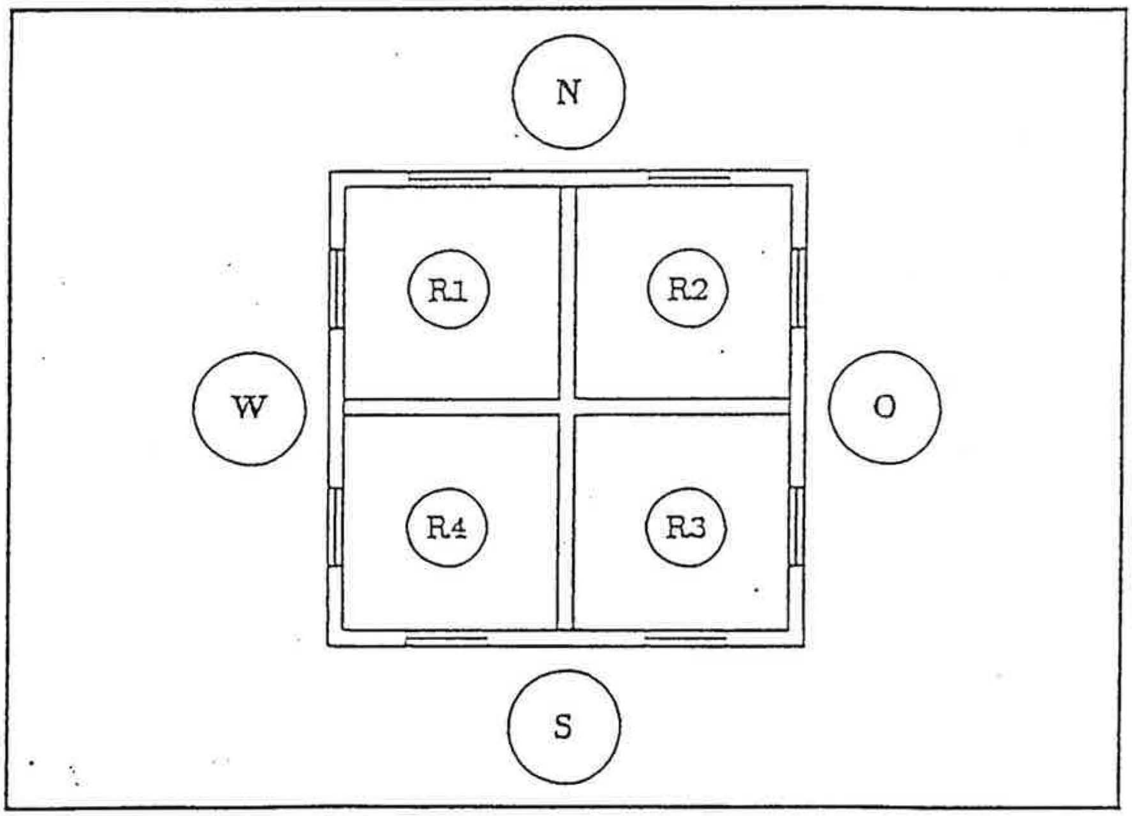
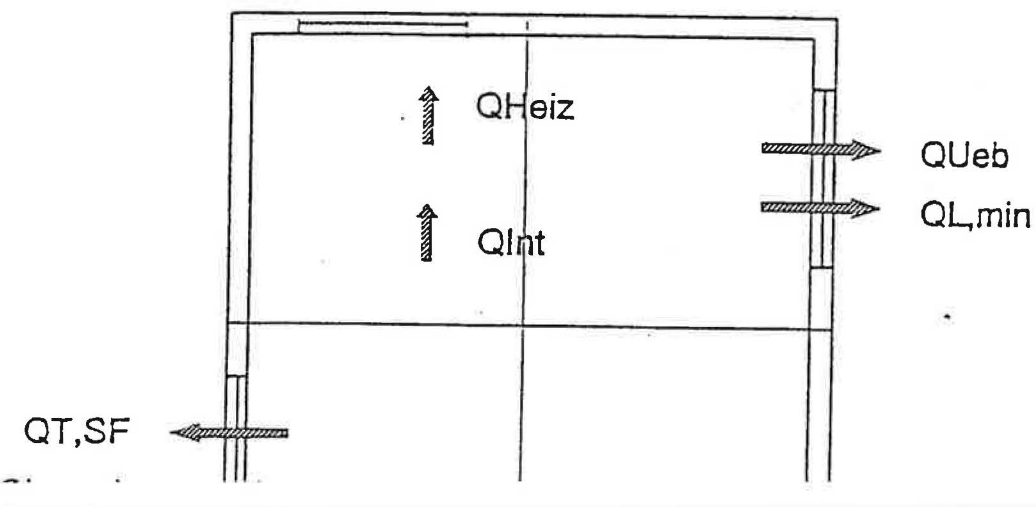


Fig. 3 Building: 4-room-model




N
R1
R2
W
O
R4
R3
S


QHeiz
QUeb
QL,min
QInt
QT,SF

Reference model: energy saving

WWO S TWS

insulation triple-glas'

Q fkWhl

12000 -

10000

8000 4-

6000

4000

2000

0

Heiz Ant Inuzi TSF *Lmin* Ueb

Reference model: heating energy

QK [kWhl

14000

13000

U"

C2 Cl)

12000 - ZE

C)

11000

10000

gooo

8000

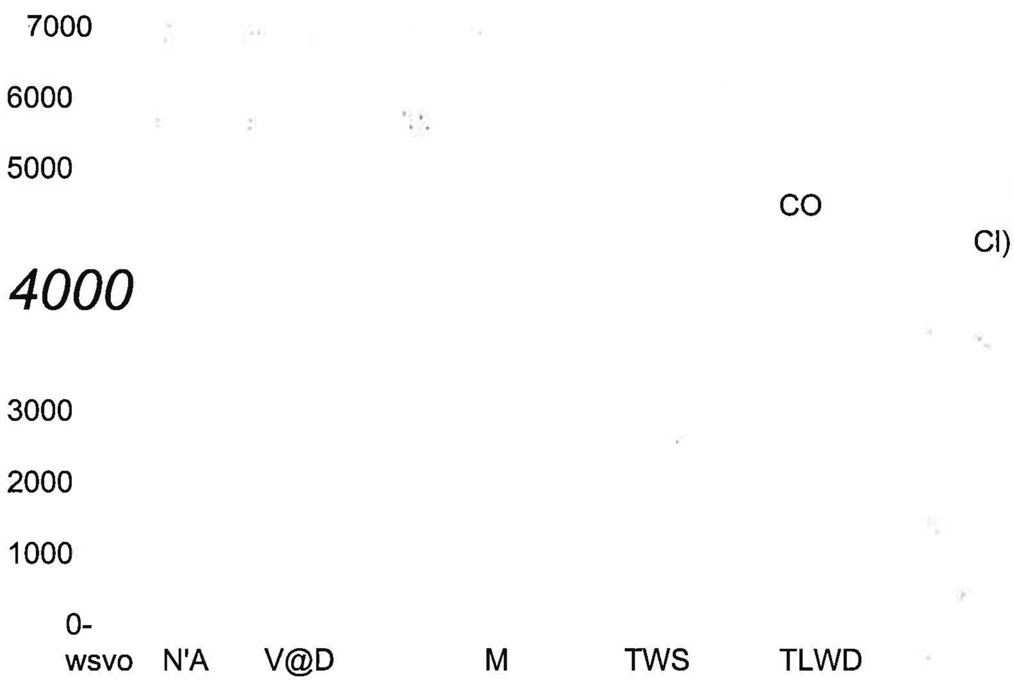
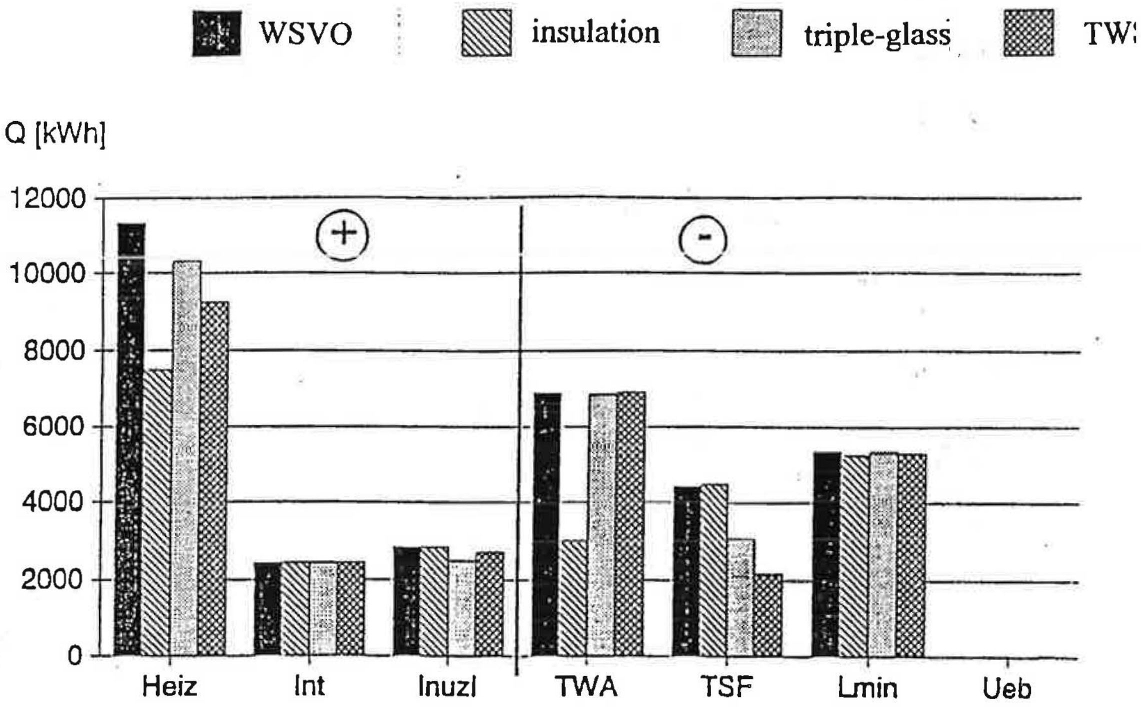
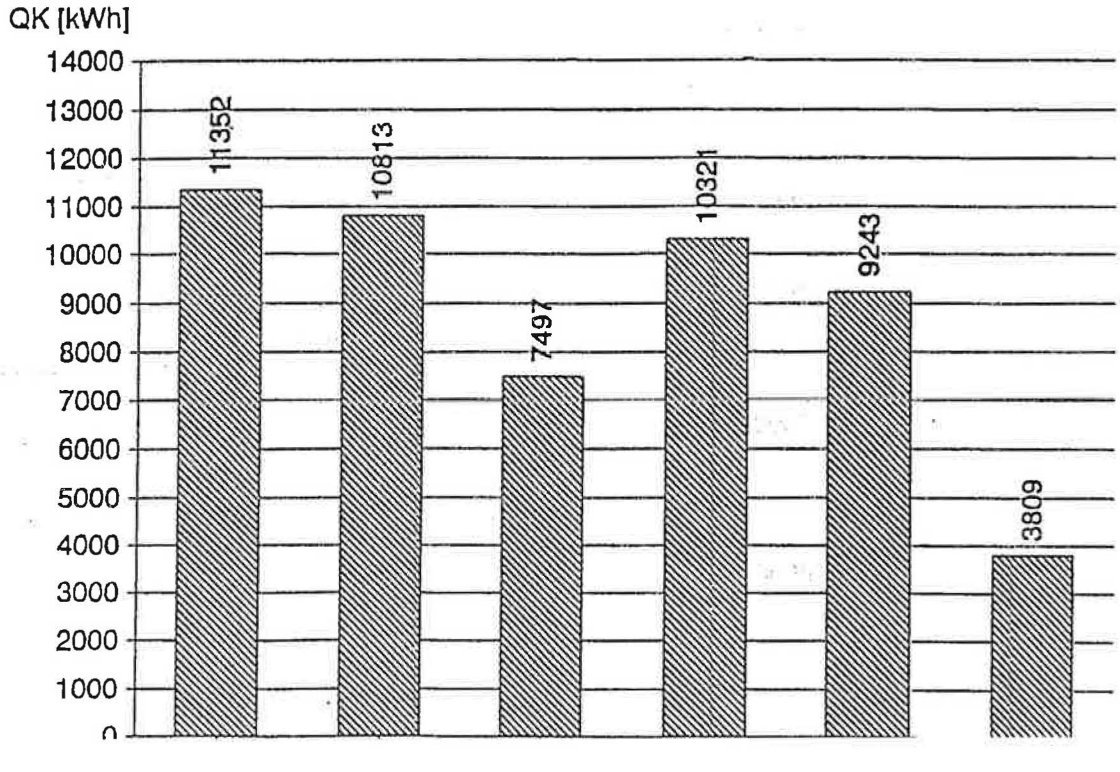


Fig. 4

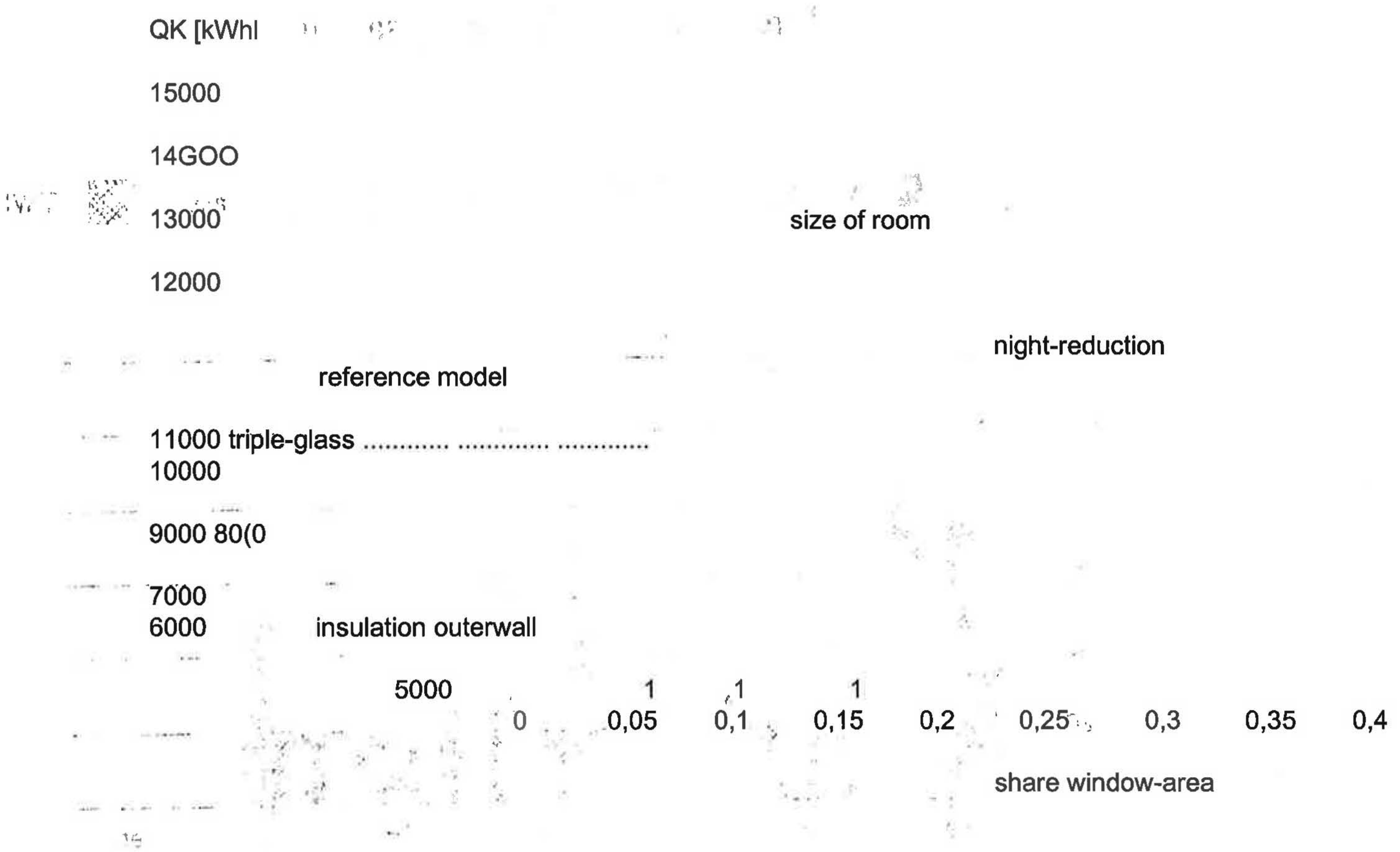
Reference model: energy saving



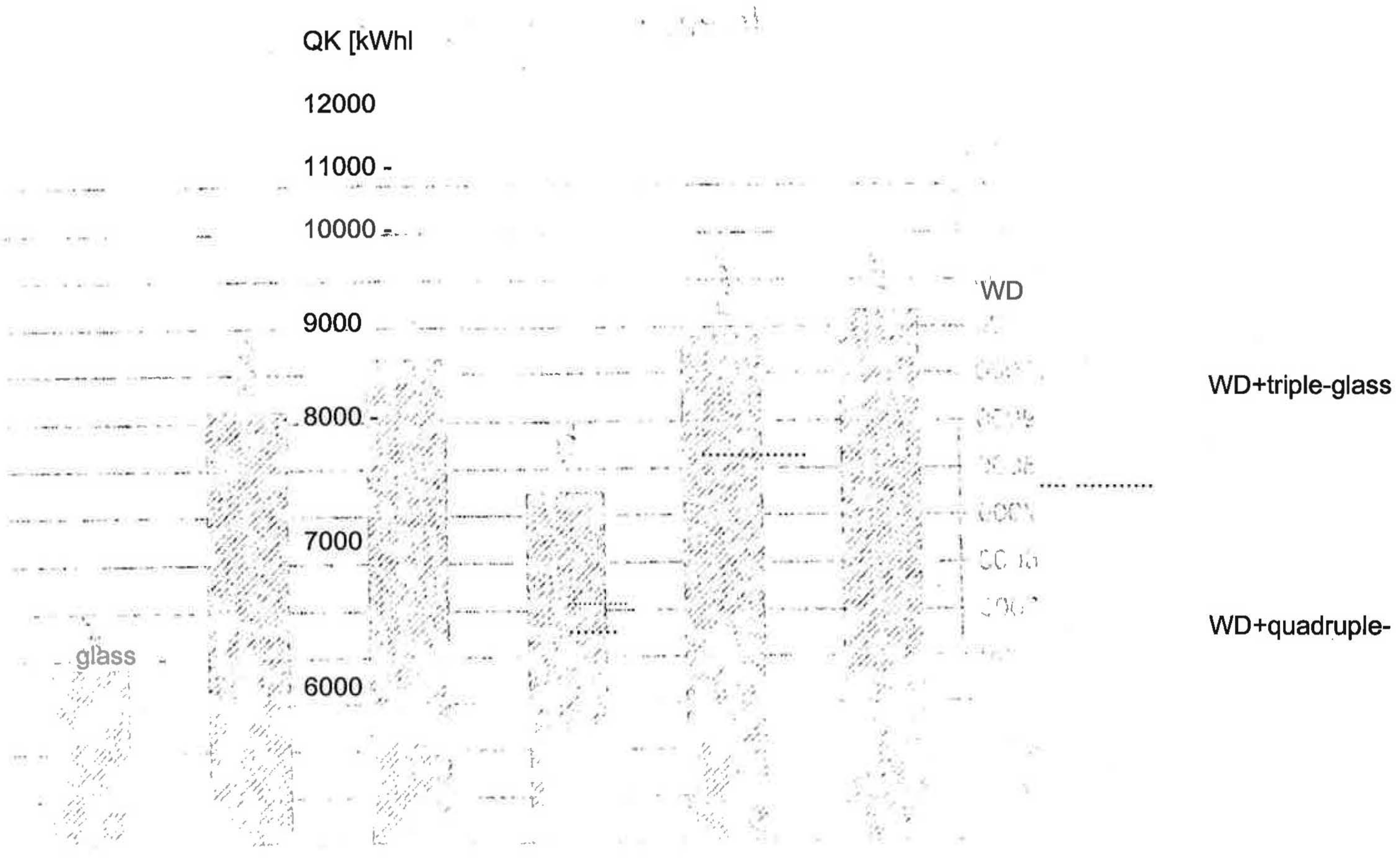
Reference model: heating energy



Energy saving, separate



Energy saving, combined



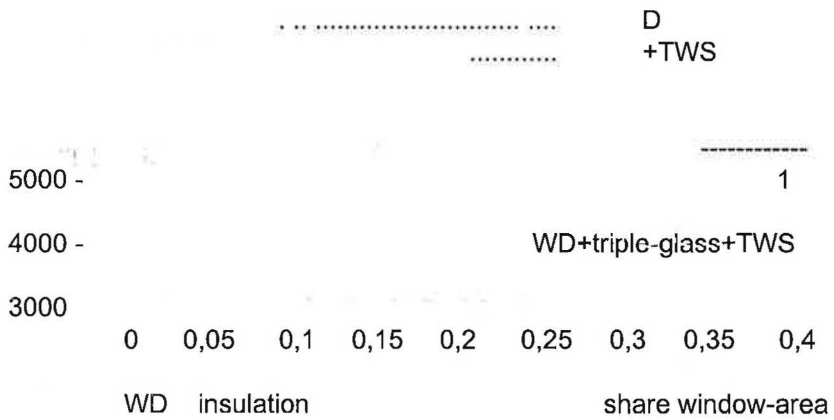
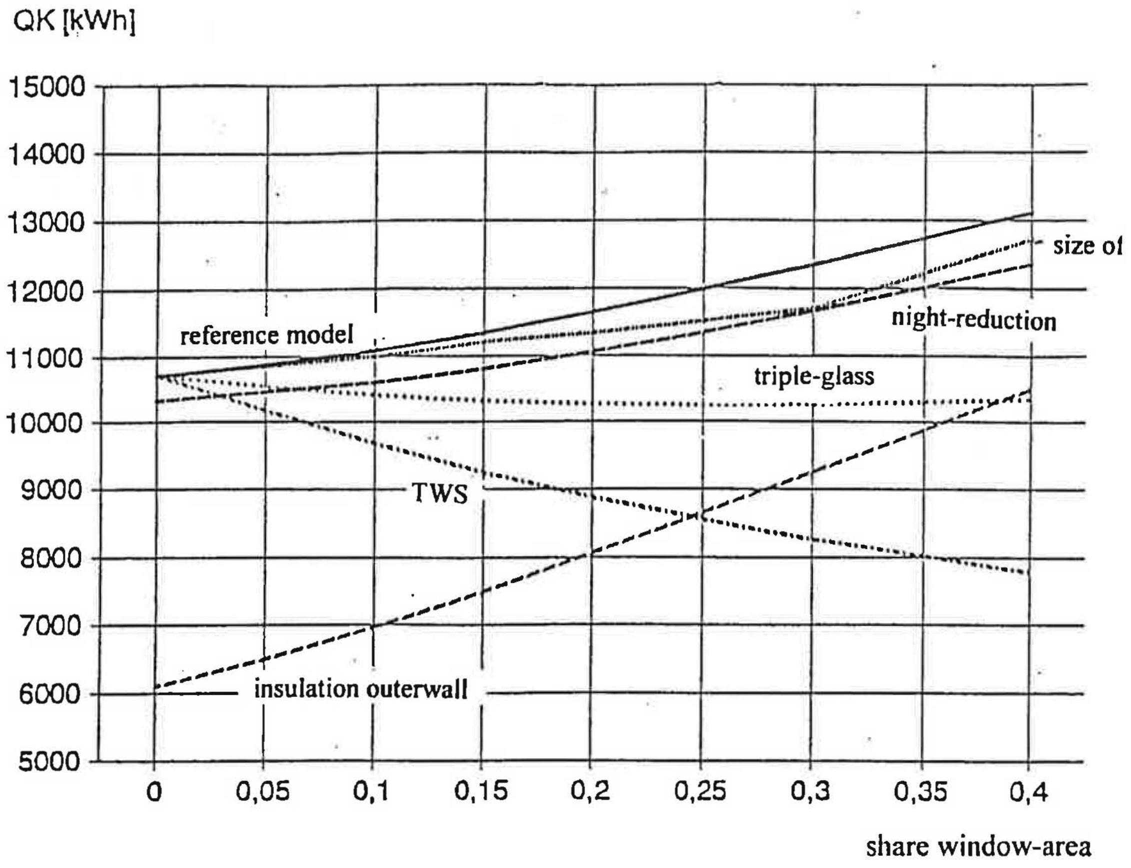
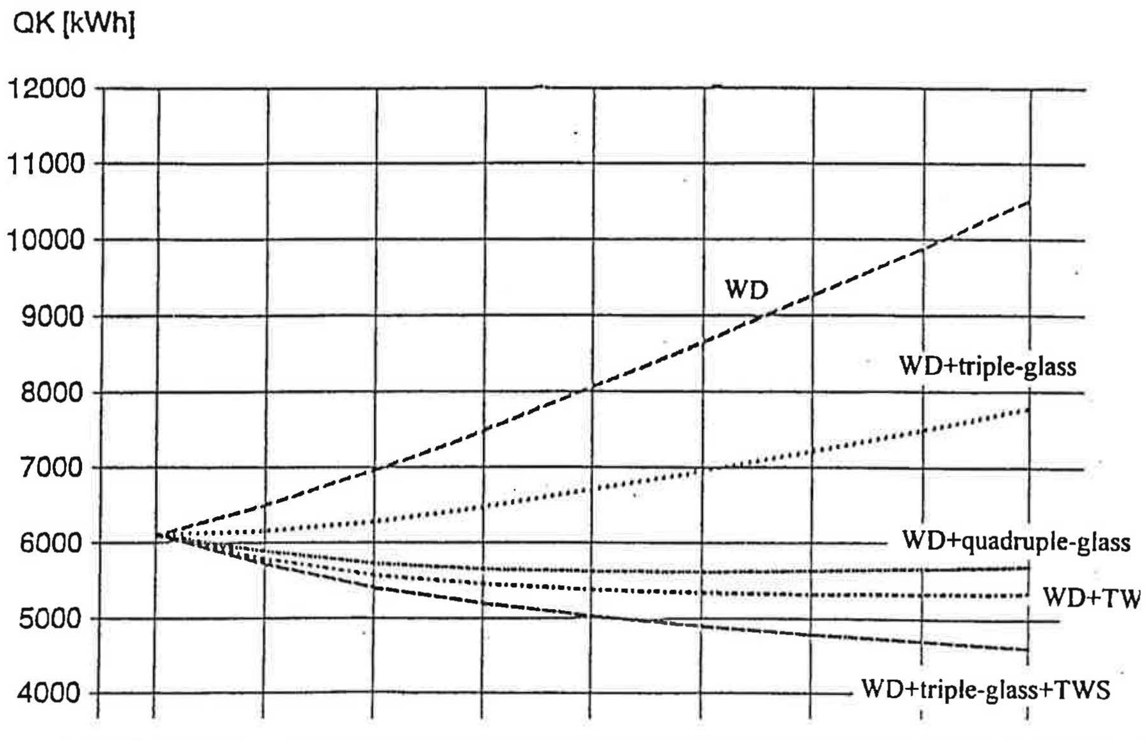

D
+TWS
5000 -
1
4000 -
WD+triple-glass+TWS
3000
0
0,05
0,1
0,15
0,2
0,25
0,3
0,35
0,4
WD
insulation
share window-area

Fig. 5

Energy saving, separate



Energy saving, combined



Construction: heat capacity
MRK)share of window area 0, *15*

outer wall
inner wall
ceiling /floor
innermass

W1K
160
140
120
100
80
60
40
20
(-I-LM0

light-
weight
middle-
heavy-
very heavy-

Construction: comparison

QK [kWhl

110(0
10500 -

light wei
middle
weight

very hea

weight

100(0 -
9500 -
9000 -
85(0
80(0
75-00
7DOO
6500
6000 light weight+TWS

5500 =...... =@---...........
5000 - very heavy weight+TWS

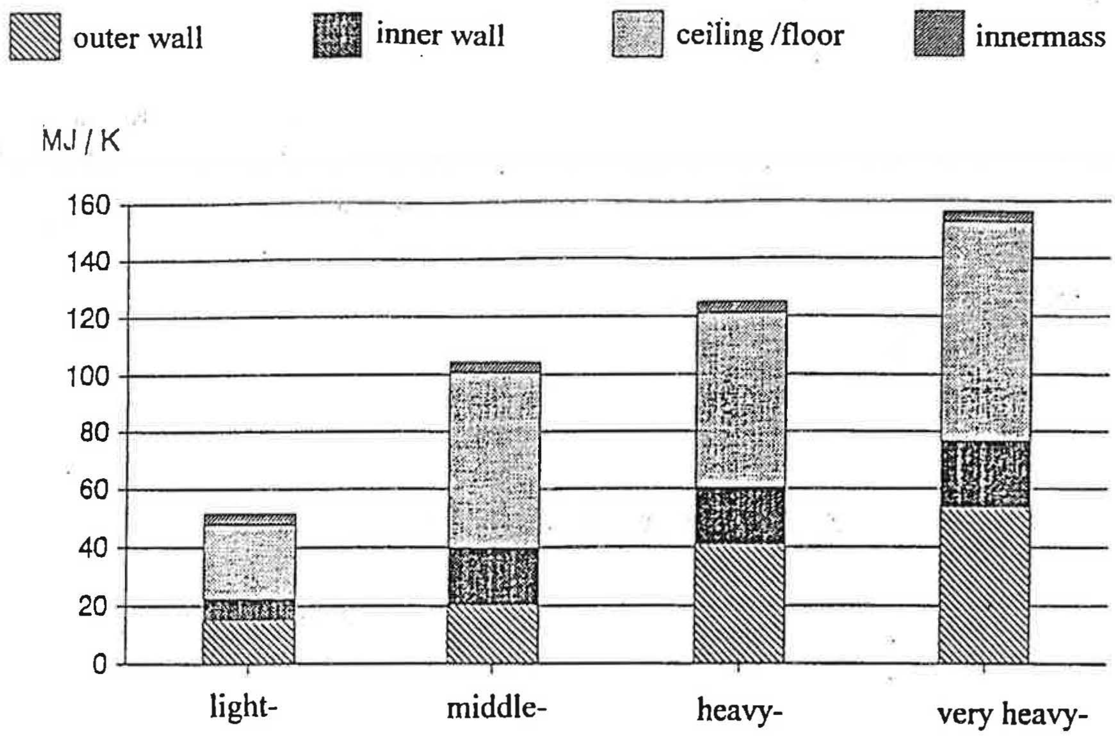
4500

0 0,05 0,1 0,15 0,2 0,25 0,3 0,35 0,4

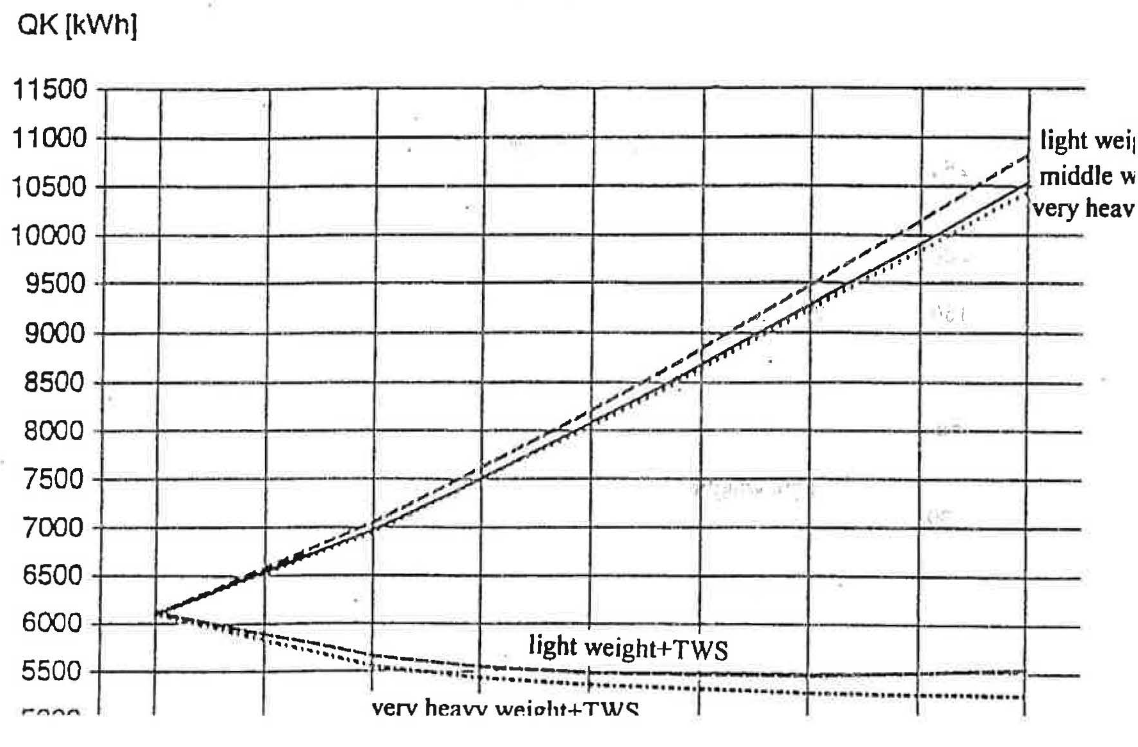
share of window area

Fig. 6

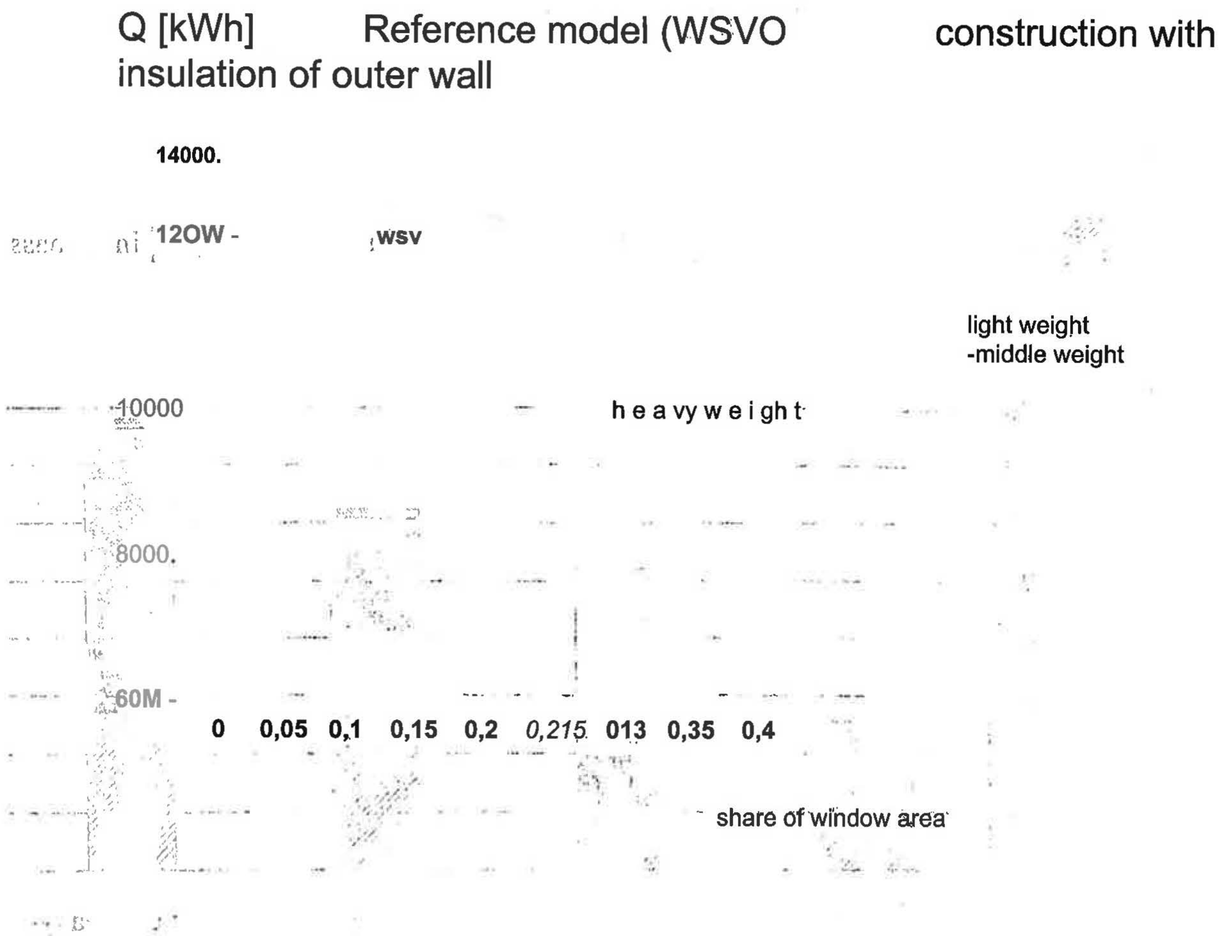
Construction: heat capacity
(MJ/K) share of window area 0,15



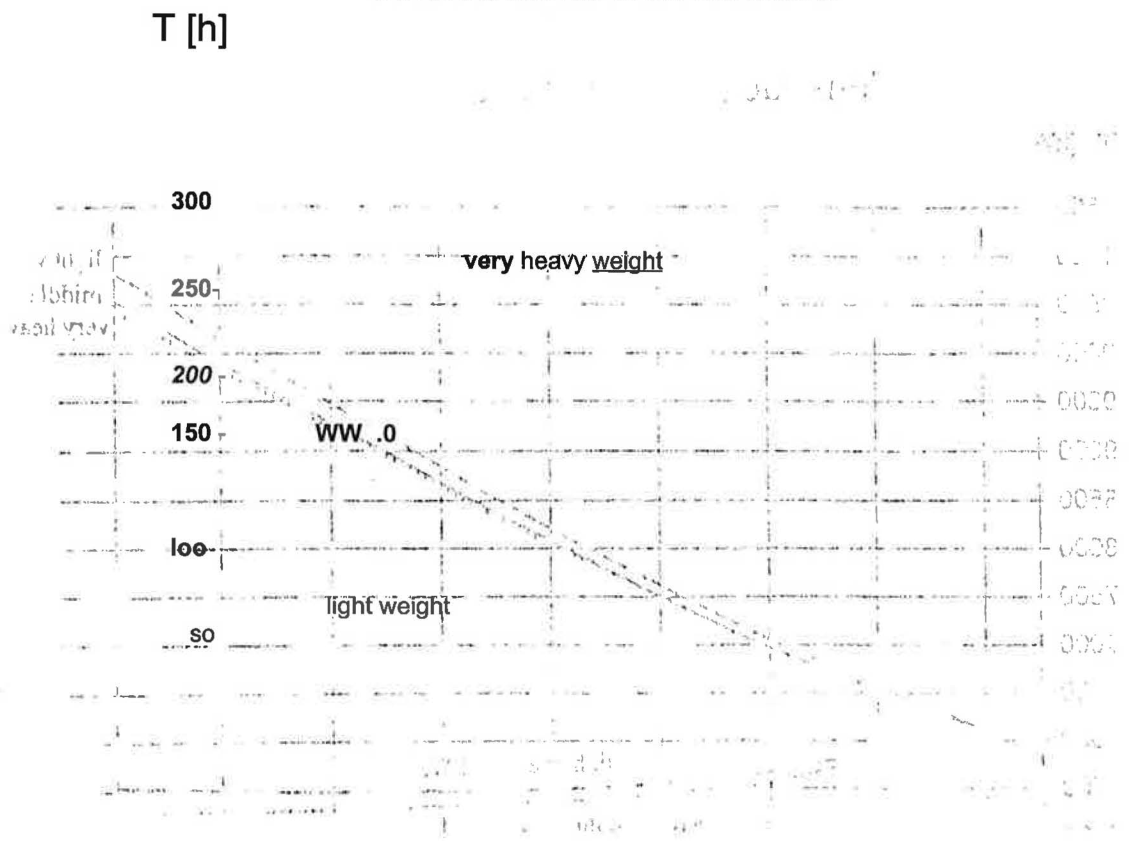
Construction: comparison



Construction: heating energy



Construction:. time constant



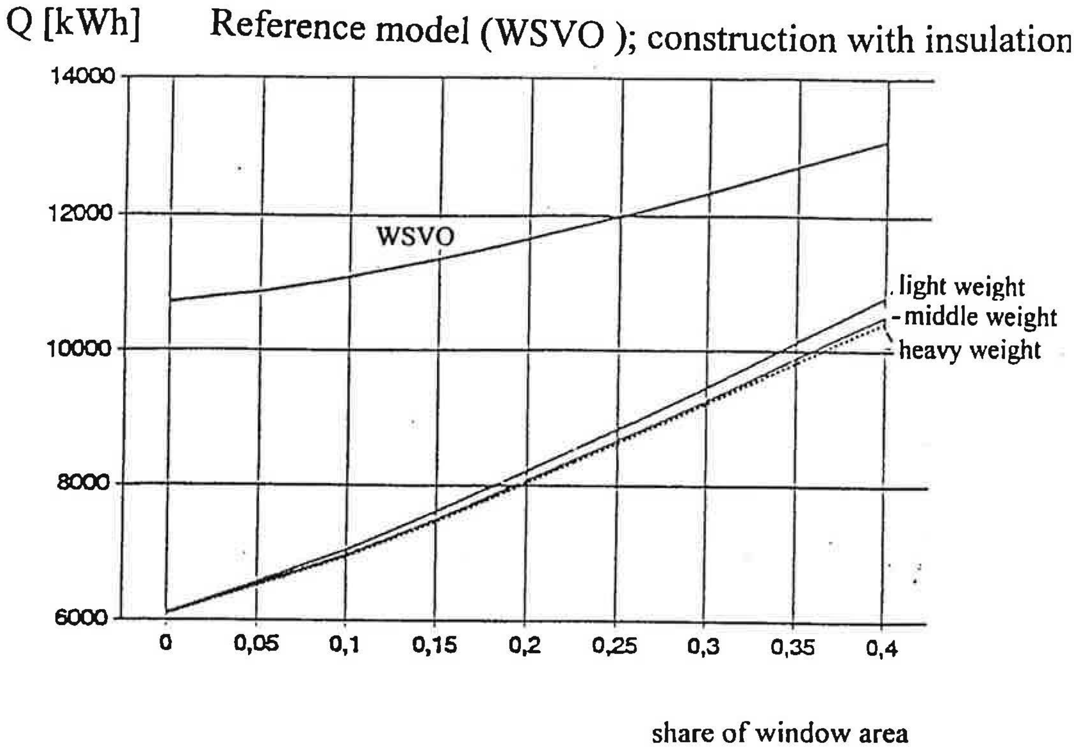
0

0 0,05 0,1 0,15 0,2 0,25 **0,3** 0,35 0,4

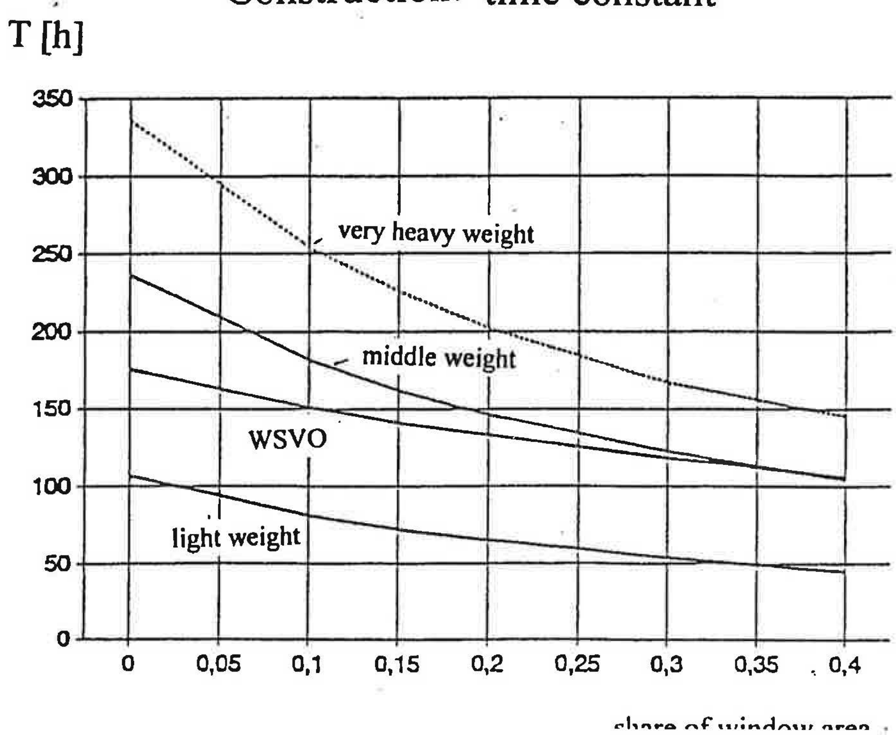
share of window area

Fig. 7

Construction: heating energy



Construction: time constant



share of window area

Solar energy: surplus

Q[kWh] Ref model (WSVO); construction with insulation of outer wall

bt weight

llig700.

600

middleweight

Wo

very heavy

weight

400

WO

1300

WI

200 - -

100-

00,05 0,1 0,15 0,2 0,25 0,3 0,35 0,4

share of window area

Solar energy: exploitation effectiveness

0,96

0,95

WWO

0,94-

very heavy weight

0,93

0,92

0,91

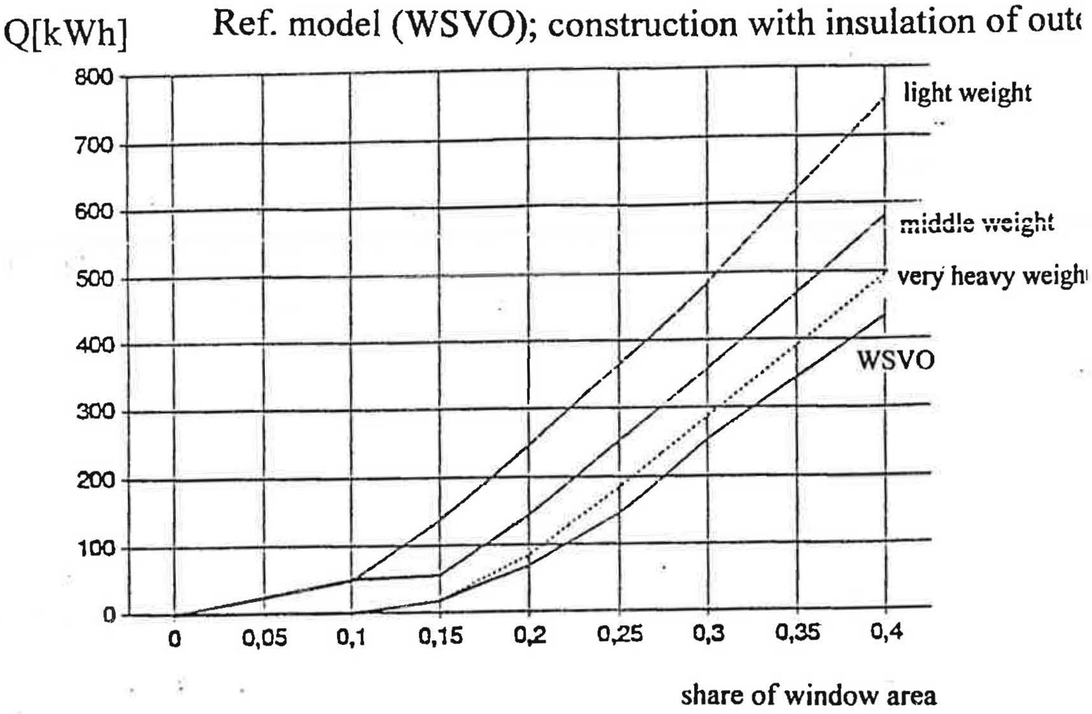
0,9

t weight

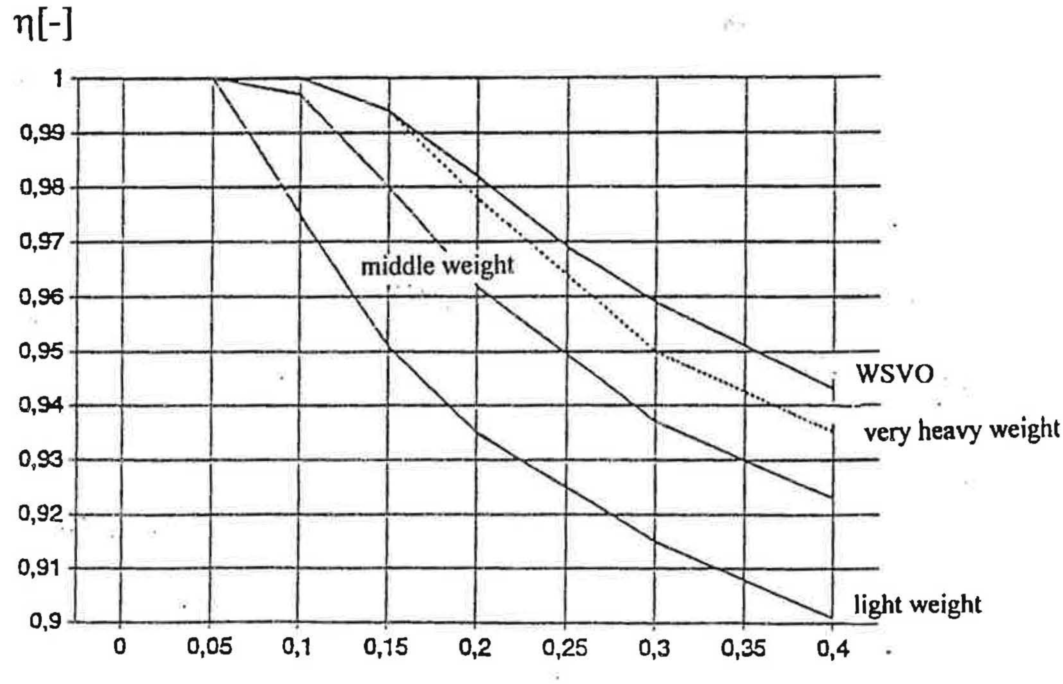
0 0,05 0,1 0,15 0,2 0,25 0,3 0,35 0,4

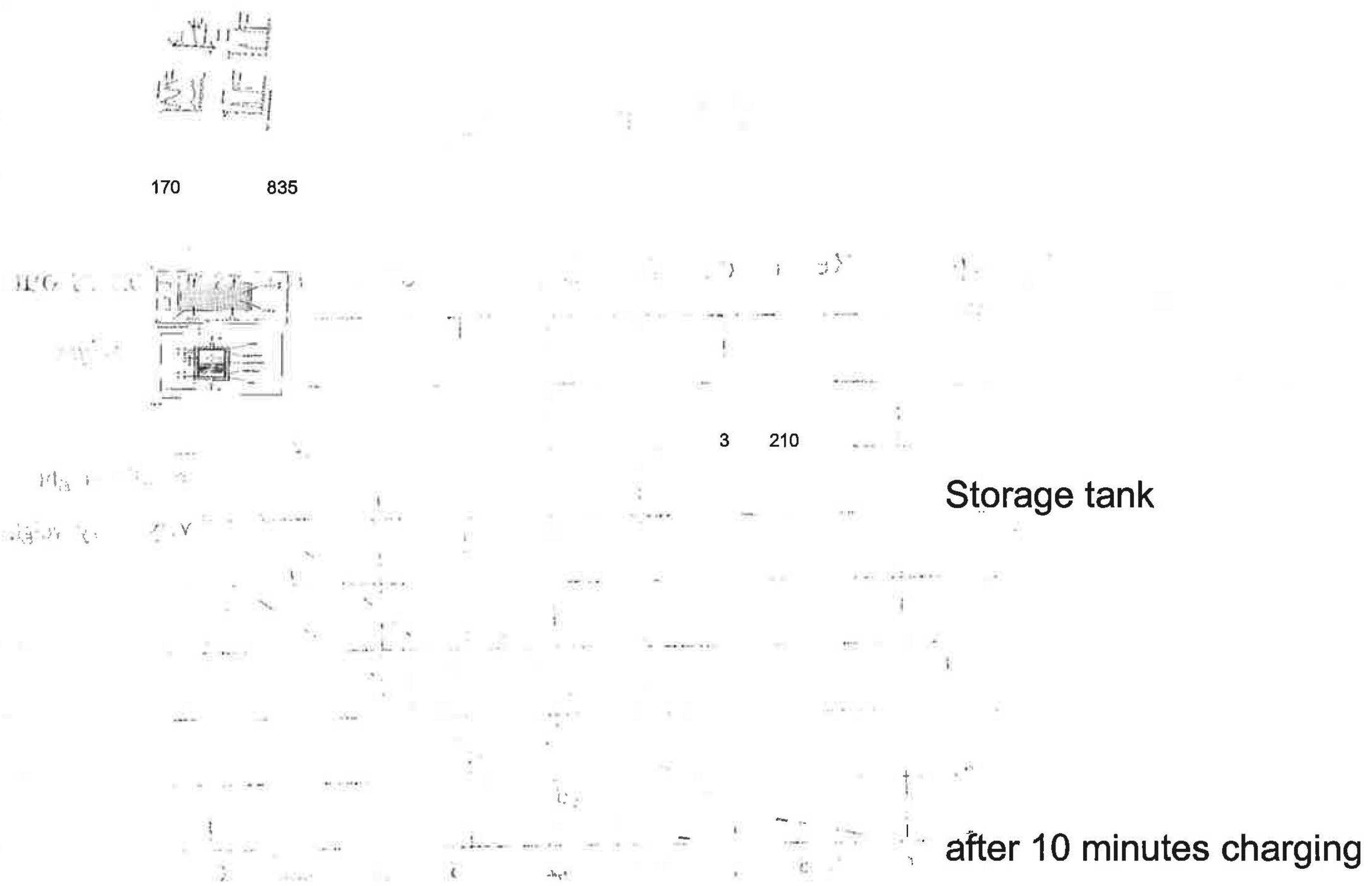
Fie. R

Solar energy: surplus

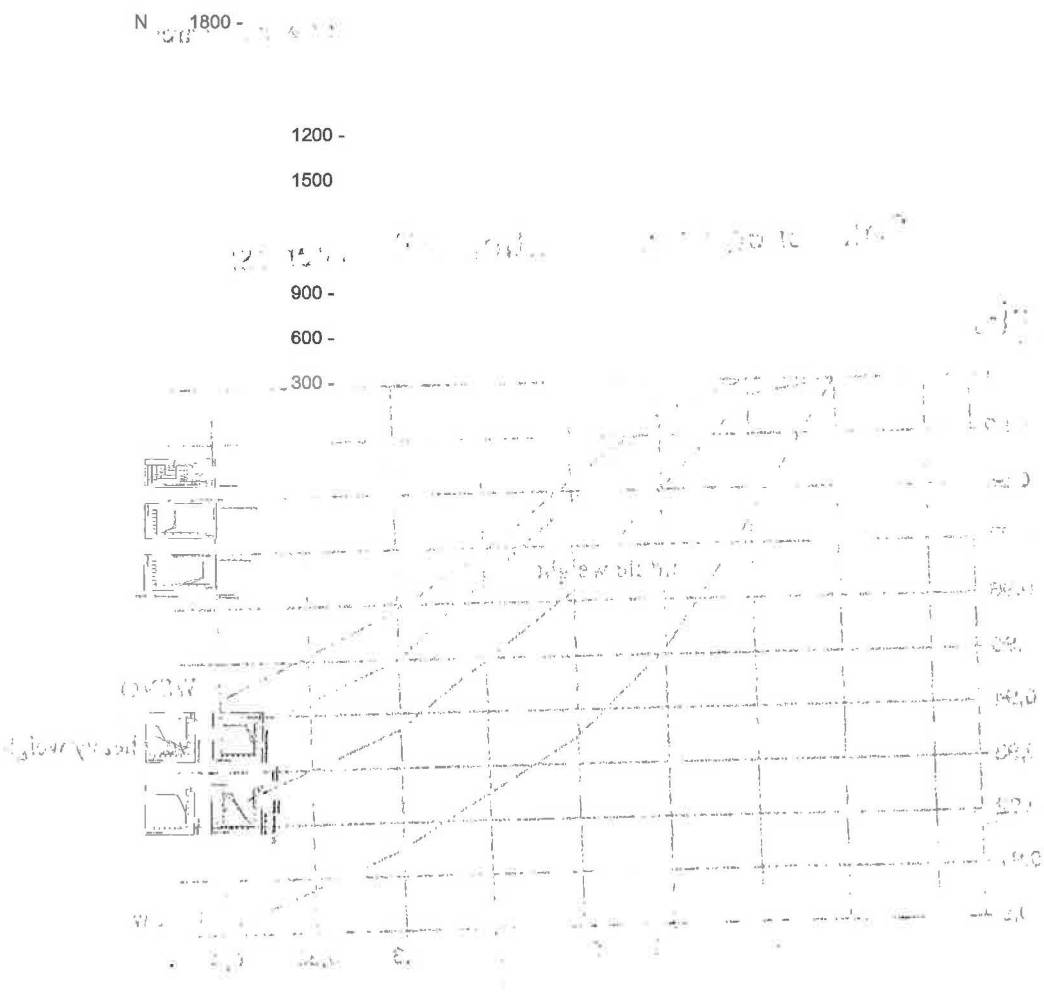


Solar energy: exploitation effectiveness





170
835
3
210
Storage tank
after 10 minutes charging



N
1800 -
1500
1200 -
900 -
600 -
300 -