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IMPACT OF USING DIFFERENT MODELS IN PRACTICE – A CASE STUDY WITH THE SIMPLIFIED METHODS OF ISO 13790 STANDARD AND DETAILED MODELLING PROGRAMS

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ABSTRACT

The updated ISO 13790 Standard is part of the new set of CEN Standards that supports the European Energy Performance of Buildings Directive (EPBD) requirement for a general framework for calculation of the energy consumption of buildings. The Standard sets out procedures for space heating and cooling energy calculations, allowing the use of three different methods: a simplified monthly quasi-steady state method, a simple-hourly method and detailed simulation. This paper examines the implications of allowing different methods to be used for assessing the energy usage. The research method used was to undertake a comparison of the various methods applied to a common building specification, with parametric analyses of variations in this specification. The paper discusses differences in results for heating and cooling requirements between the simplified methods and when a detailed simulation program (ESP-r) is used with constrained (according to the Standard) inputs and with a number of unconstrained inputs. The case where two different detailed simulation programs (ESP-r and EnergyPlus) are used in practice for the same building is also included and conclusions are drawn regarding the practical use of different detailed modelling programs against the simplified methods, as well as against each other.

KEYWORDS

EPBD, ISO 13790, simplified methods, detailed simulation programs.

INTRODUCTION

The European Energy Performance of Buildings Directive (EU 2003) requires that Member States should establish a common methodology at national or regional level for the calculation of the integrated energy performance of buildings based on all the areas specified in the Annex of the Directive. To address this requirement, a set of European and International Standards were prepared or updated in order to provide the methods and required material for the calculation. A summary of the most important EPBD Standards is given by Roulet and Anderson (2006). One of the main Standards in this set is the updated prEN ISO DIS 13790 (2007) which provides a framework for the calculation of energy use for space heating and cooling in buildings, mainly for annual periods. This paper focuses on the practical application of the three methods included in this Standard; a simplified monthly quasi-steady state method, a simple-hourly method and the option of using a (validated) detailed simulation program.

Numerous comparative studies between simplified and detailed methods have been done before. With particular reference to this study, Beccali et al. (2001) compared two simplified methods similar to those described in the monthly method of the 13790 Standard with TRNSYS for cooling load assessments based on three typical Italian climates. Jokisalo and Kurnitski (2007) applied the monthly method described in a previous draft of the 13790 Standard for heating load assessments based on a typical Finish climate against the results of IDA-ICE. Corrado and Fabrizio (2007), studied the dynamic parameters of the monthly method described in a previous draft of the 13790 Standard for cooling load assessments based on a typical Italian climate against the results of EnergyPlus. These three studies revealed large differences between the results of the simplified methods and the detailed programs: the calculation of the dynamic parameters was often identified as the main source of the differences. This study focuses on all the methods that are included in the latest 13790 Standard to assist EPBD implementation in the European countries. The simplified methods are fully prescribed within the 13790 Standard which also gives details for the common procedures and descriptions, boundary conditions and input data that detailed simulation programs should follow in order to ensure consistency between all the methods.

METHODOLOGY

A comparison of the various methods applied to a common building specification was undertaken in order to calculate the annual energy needs for heating and cooling. The systems used to cover these energy needs were not considered in this study. The simplified monthly and hourly methods were used according to the specifications described in the 13790 Standard. The inputs and boundary conditions of ESP-r (2006) and EnergyPlus (2006), the two detailed simulation programs used in this study, were constrained according to the Standard's instructions. A case where ESP-r is used with unconstrained inputs based on default algorithms or values, often used by building professionals in practice, is also included. Ensuring equivalency for the inputs and the boundary conditions used in all methods (apart from the unconstrained case) was considered critically important for the analysis. It should be mentioned that this study does not aim to follow any detailed validation procedures and does not intend to prove the accuracy of any of these methods. The intention is to investigate the use of all these methods in practice and the differences that might arise according to the choice of method by building professionals.

Case study and parametric analysis

The building used for this case study consists of 9 spaces with a total floor area of 336 m^2. The base case for the annual heating calculations was based on a central/northern European location (Amsterdam). The same location was used for cooling but for the reason that cooling loads are not always high for these parts of Europe, a southern European location (Athens) was used as additional base case in order to examine the sensitivity of the methods to higher cooling loads and for the different design changes described in this paper. Alternative locations were also studied for the heating and cooling calculations as part of the climate variations in the parametric study. To avoid increasing the complexity of the calculations with regards to the simplified methods, all spaces were assumed to have the same set-points for heating and cooling and also the same heating, cooling, ventilation and internal gains schedules.

The parametric studies were based on common input changes that could possibly have a significant effect on the buildings' annual heating and cooling energy requirements. Some of these changes did not affect the monthly method (e.g. changing the internal gain profiles) so they could be used to study the impact of assuming average monthly values. Results for the following different cases are presented in this paper:

- Three building locations and climates, representing a southern, a central and a northern European location.
- Five different internal heat gains schedules. The base case incorporates an hourly varied occupants and lighting schedule where the gains from occupants and lighting during the occupied hours are 12 W/m^2 and 10 W/m^2 respectively and 10% of these values for unoccupied hours and weekends. Two of the other cases use the same average monthly internal heat gains values as the base case but for one of them values are averaged hourly for every day of the week (e.g. same hourly value for 24 hours and for 7 days every week) and for the other they are averaged for every hour of the weekends and the weekdays (e.g. same hourly values for 24 hours during the weekdays and another steady hourly value for 24 hours during the weekends). One of the last two other cases uses higher internal heat gain values compared to the base case but with the same hourly patterns and similarly, the last case uses lower internal heat gain values than the base case, again with the same hourly patterns.
- Three different glazing areas, with the base case using 58.1m^2 of glazing, and two other cases using half and double this amount.
- Four different external wall constructions, representing a very lightweight, a lightweight, a heavyweight and a low insulation heavyweight wall.
- Five different ventilation schedules. The base case incorporates 0.72 ac/h for 24h every day during the year and two of the other cases use the same average monthly ventilation rates as the base case but their values vary during the day and between weekends and weekdays. One case uses higher ventilation rates (1.5 ac/h) than the base case and the other one uses lower ventilation rates (0.3 ac/h) than the base case, again for 24h every day.
- Three different building orientations. The base case was rotated 90^o and 180^o anticlockwise.
- Six different heating and cooling setpoint strategies. Three of these strategies have a steady setpoint during the year and for the other three, intermittent heating or cooling was used.

Equivalency between the different simplified methods and the different simulation programs

Equivalency between the methods for the input data and the boundary conditions had to be ensured so that an accurate evaluation of the results and their sensitivity to the design changes is possible.

For the purpose of the study, the same climate files were used for both ESP-r and EnergyPlus. These files have the widely used EnergyPlus/ESP-r format (Crawley et al. 1999). Tabulated hourly temperature data were then exported and used in the simplified methods (after averaging in the case of the monthly method). In the case of solar radiation data, the original climate files were used for the detailed simulation programs. Incident solar radiation on all surfaces was calculated with the simulation program and used as inputs for the simplified methods.

The setpoint temperatures, even in the cases of intermittency, were also the same for all methods. In ESP-r, ideal controls were used for maintaining the operative temperature in the zones to be the same as the other methods. In a similar way, an ideal system ("Purchased Air") was used in EnergyPlus for the same purpose. In the cases of intermittency, the method described in the 13790 Standard for the simple monthly method was used to determine the relevant reduction factors.

Regarding the heat transfer by transmission, the same areas, materials, layers and constructions of the building were used in all methods. Consequently, the thickness and the conductivity of every surface layer were ensured to be the same in all methods. In order to set the same surface resistances for the inside and outside face of the surfaces, the pre-defined values in prEN ISO DIS 6946 (2006), and prEN ISO DIS 10077-1 (2006) in the case of windows, have to be used. This means that for ESP-r and EnergyPlus, the inside and outside convective and radiative heat transfer coefficients must be set to fixed values through the calculation period; this was achieved by setting the emissivity of the materials that are in contact with the inside and outside environment to zero and then setting fixed convection coefficients to provide the specified surface resistance values. However, the direction of the heat flow varies over the year for roof, ceilings and floors, as do the values for the surface resistance if they are dependent on the heat flow direction as the 6946 Standard suggests (e.g. upward and downward heat flow). In the case of ESP-r, there is a facility to take the direction of the heat flow into account and apply the appropriate fixed values for the combined convection coefficients. It is also possible to use a fixed value for all surfaces without taking into account the heat flow direction over the calculation period: this approach was used for EnergyPlus and the simplified methods (e.g. always upward heat flow for roof). A comparison between the two methods that are available in ESP-r for the base case of the specific case study did not result in any significant differences in the ESP-r results. However, this might not be always the case, especially when a building with low insulation is studied under a more varied climate than the base case's climate. In these cases, the direction of the heat flow (e.g. upward or downward) could often vary and the use of the simplified methods should be considered with care.

Regarding the heat transmission to the ground, the method described in Annex D of the prEN ISO DIS 13370 (2006) was used for the detailed simulation programs to model the construction of the floor and the boundary conditions below it. This included a specific thickness of soil and a virtual layer (with specific thermophysical properties) below it. The resulting calculated monthly ground temperatures were used over the simulation period. Regarding the simplified methods, the same heat transfer coefficients were used in accordance with those specified in the 13790 and related Standards. Thermal bridges were not accounted for in any of the methods. For the foundation, a slab on the ground was assumed with 1-D thermal conduction only.

Equivalency between the input data for all methods with regards to the losses from ventilation or infiltration was ensured by using the same air flow schedules on an hourly and monthly basis. However, ventilation heat losses or gains are based on the operative temperature in the monthly simplified method and on the air temperature in the simplified hourly and the detailed simulation programs. This is not though an input or a boundary condition difference and so the equivalency between the methods is maintained. The air is assumed to be supplied from the external environment to the building spaces at the ambient temperature.

For the internal heat capacity of the building surfaces, similar considerations apply as those mentioned in the section for the heat transfer by transmission. The same areas, materials, layers and constructions of the building were used in all methods. This includes the thickness, the conductivity, the density and the specific heat of every surface layer. For the simplified monthly and hourly methods, the internal heat capacity C_m was used and calculated according to the instructions defined by the 13790 Standard.

For the solar gains calculation, the equivalency between the 13790 methods was ensured by following the same rules as those mentioned in the sections for the solar radiation data and the internal heat capacity calculations. In addition, the surface absorptivity of every external opaque surface layer was ensured to be the same in every method. Specialised programs, WIS (2004) and WINDOW5.2 (2005), were used to provide detailed optical properties for the detailed simulation programs and the solar energy transmittance (g-value) for the simplified methods**.** In this way, model equivalency was achieved for the optical properties. ESP-r can also report the standardised g-values of the windows independently according to the EN 410 Standard (1998). For the specific case study, the frames of the windows were not taken into account in any of the calculation methods used in this paper. Moreover, the viewfactor to the ground was ensured to be the same for all the surfaces in every method. Finally, no shading devices were used for the modelled building.

As previously mentioned, the external surface emissivities were set to zero in order to have a fixed surface resistance in the detailed simulation programs. This means that for purposes of equivalency between all the methods, the longwave radiation heat exchange with the sky was not taken into account. Detailed simulation programs solve the heat transfer by transmission and radiation to the sky simultaneously, so they cannot follow at the same time both of the ISO 13790 instructions for their treatment. It is not possible, in other words, to model the transmission losses assuming a fixed radiative heat transfer coefficient for the fixed surface resistance and at the same time to use a time varying external radiative heat transfer coefficient for the longwave radiation heat exchange with the sky.

The internal heat gains in the spaces were also the same for every method. The same schedules were used on an hourly or monthly basis for every method. In ESP-r and EnergyPlus, 50% convective and 50% radiative fraction was assumed in accordance with the ISO 13790 instructions.

In practice, users do not constrain the simulation programs according to the 13790 prescriptions and normally use the default algorithms provided as a more realistic representation of the built environment's dynamics. A case where ESP-r is used with the default convection coefficient algorithms and with typical material emissivity values is included. An insolation analysis that takes into account the time-dependent insolation patterns was also performed for the unconstrained cases with ESP-r.

In reality, it is also common to include time varying air flows, for example when natural ventilation is considered or when modelling the plant systems and considering their effect on the local indoor air flows and their interaction with the convection and radiation heat transfers. However, the effects of these variations were not included in this paper.

RESULTS AND DISCUSSION

The results of the different calculation methods for the building's annual heating and cooling energy requirements are shown in Tables 1 and Table 2 respectively.

Annual heating energy requirements

For the annual heating and cooling energy requirements of the specific building, the results between the four calculation methods revealed good agreement in some cases and considerable disagreements in other cases. The first section of this discussion does not include the "unconstrained" ESP-r results that are also presented in Tables 1 and 2.

In detail, the annual heating energy requirements results vary for the base case between 46.3 kWh/m^2 (ESP-r) and 61.1 kWh/m^2 (monthly 13790), a 24.2% difference with respect to the simplified monthly method's result. The results for this case between the two dynamic simulation programs were in good agreement (8.6% with respect to ESP-r's result); similarly for the results between the two simplified methods (8.2% with regards to the simplified monthly method's result). This was also the general trend noticed for most, but not all, of the results for the different cases described in this paper.

All methods have a similar sensitivity (i.e. the magnitude of the differences were similar) to the different locations and climate that were used to investigate the annual heating energy requirements.

Averaging the internal gains on a daily or weekly basis did not seem to have a significant effect on the final annual heating energy requirements apart from the case where the simplified hourly method was using the same average hourly schedules every day instead of the original hourly varying internal gain schedule. The two schedules were equal on a weekly and monthly basis but the annual heating energy requirement results for the simplified hourly method vary from 48.0 kWh/m^2 to 56.1 kWh/m^2 (14.4% difference with respect to the base case result of the simplified hourly method). The results from the two dynamic simulation programs are slightly sensitive to this change and the results from the simplified monthly method remained the same for all these cases.

Significant differences were also noticed between the annual heating energy requirement results produced from the four methods for the case that investigates their sensitivity to the high internal heat gain loads. The results vary from 31.5 kWh/m^2 (ESP-r) to 50.7 kWh/m^2 (monthly 13790), a 37.9% difference with respect to the monthly method's result. However, for the low internal heat gains case, good agreement between all methods was noticed.

The different glazing area cases again revealed differences in the results produced from the different methods. For the large glazing area case, annual heating energy requirements were within the range 56.5 kWh/m^2 (ESP-r) to 77.9 kWh/m^2 (monthly 13790), a 27.5% difference with respect to the monthly method's result. Similarly, annual heating results between the methods for the case of the low glazing area vary from 42.8 kWh/m^2 (ESP-r) to 53.8 kWh/m^2 (monthly 13790), a 19.6% difference with respect to the simplified monthly method's result.

Changing the construction of the external walls to a slightly "lighter" construction (total internal heat capacity Cm=56.9 kJ/m^{2}K) than the base case leads to similar differences in the annual heating results as those for the base case. However, when using a heavyweight wall (total internal heat capacity Cm=231.56 kJ/m^{2}K) all methods produce results that are in a very good agreement with each other.

From the annual heating results produced for the different ventilation cases it can be concluded that averaging the pre-defined air flow schedules on a daily or weekly basis did not seem to have a significant effect on the initial results of each method.

Generally good agreement between the annual heating results of all methods was noticed for the case where high ventilation air flows were used. The range of the results varied between 99.7 kWh/m^2 (ESP-r) and 113.4 kWh/m^2 (monthly 13790), a 12.1% difference with respect to the simplified monthly method's result. On the other hand, for the case where low ventilation air flows were used, the annual heating results values varied significantly between 23.8 kWh/m^2 (EnergyPlus) and 35.3 kWh/m^2 (monthly 13790), a 32.6% difference with respect to the simplified monthly method's result.

Rotating the base case had an effect on the annual heating results for all methods. The two simulation programs produced results that were more sensitive to the building's orientation changes than the two simplified methods. For example, rotating the building 90^o anticlockwise changed ESP-r's annual heating result from 46.3 kWh/m^2 to 53.0 kWh/m^2, while the simplified hourly's method result changed from 56.1 kWh/m^2 to 58.7 kWh/m^2.

In the cases where a different heating setpoint was used, all methods are similarly sensitive. Differences that were noticed for the base case can still be noticed for the different setpoints used for this study.

For the intermittent heating cases, large differences were noticed between the annual heating results of all four methods. In detail, for the case where heating was imposed during the occupied hours of the day, the simplified hourly method produces a result (9.2 kWh/m2) significantly lower than the result of the simplified monthly method (18.2 kWh/m^2) and markedly lower than the results of the two dynamic simulation programs (24.3 kWh/m^2 for ESP-r and 28.1 kWh/m^2 for EnergyPlus). Large differences can also be noticed where heating was imposed during the night (unoccupied hours). In this case, the annual heating using the monthly method remained the same as the previous case with the heating imposed during the occupied hours. The annual heating result of the simplified hourly method changed from 9.2 kWh/m^2 previously to 29.9 kWh/m^2 in this case. The annual heating results in this case of intermittent heating during the night vary between 18.2 kWh/m^2 (monthly 13790) and 38 kWh/m^2 (EnergyPlus), a 108.8% difference with respect to the simplified monthly method's result. Finally, for the last case where intermittent heating was applied during different periods of occupied hours the results show large variations but this time the simplified methods are in a good agreement with each other as are the two dynamic simulation programs.

Annual cooling energy requirements

Regarding the cooling energy requirements of this building, large differences were noticed for the results produced for the base case and the cold climate case (Aberdeen). The most significant difference was for the Aberdeen climate case where the simplified monthly method's output was 34.3 kWh/m^2 and EnergyPlus's output was 9.3 kWh/m^2. However, for the warmer climate (Athens) the annual cooling results for the base case were in better agreement. The largest difference that was noticed for this case was again between the results of EnergyPlus (98.2 kWh/m^2) and the simplified monthly method (116.3 kWh/m^2).

For the different internal gains scenarios, the range between the annual cooling results produced from all methods was similar to the results for the base case. However, good agreement was achieved between the annual cooling results of all methods for the high and low internal gains cases that were studied for a warm climate (Athens). The same conclusions were drawn for the different glazing area cases. Again, for the climate of Amsterdam the differences in the annual cooling results were considerable but for the climate of Athens the maximum differences were in the range of 15.9% with regards to the simplified monthly method's result.

As for annual heating results, the annual cooling results for the different external wall constructions were in a better agreement for all the four methods in the case of the heavyweight walls. In the case of the non-insulated heavyweight construction and the Amsterdam climate, the simplified monthly method's annual cooling output (27.3 kWh/m^2) was significantly higher than the outputs of the other three methods. It was also noticed that the simplified monthly method was not so sensitive as the other three methods for this design difference. For these two construction cases, the annual cooling decreases in the other three calculation methods. However, for the Athens climate, the simplified hourly method's annual cooling output (107.3 kWh/m^2) was considerably lower than the outputs of the other three methods. The sensitivity of the simplified hourly method to this wall construction change does not seem to agree with all the other three methods.

For the different ventilation cases, similar conclusions to those for the different glazing cases can be drawn. Annual cooling results have a large variation for the Amsterdam climate but are in closer agreement for the Athens climate.

Studying the annual cooling results under different orientations revealed differences in some cases for both of the Athens and Amsterdam climates. It was also shown that the different methods were differently sensitive to these orientation changes. For example, the annual cooling result of the simplified hourly method for the Athens climate was decreased when changing the building's orientation 90^o anticlockwise in comparison with the base case result while the annual cooling results of the other three methods increased. A similar difference was noticed for the simplified monthly method's annual cooling result when rotating the building 180^o anticlockwise while using the Athens climate. In this case, the annual cooling result of the simplified monthly method was slightly increased in comparison with the base case result but the annual cooling results of the other three methods decreased when comparing with the base case. For the Athens climate and with regards to annual cooling loads, the two dynamic simulation programs seem to be slightly more sensitive to these orientation changes than the simplified methods.

In the cases where a different cooling setpoint was used, all methods seem to be similarly sensitive. The differences that were noticed especially for the base case and the Amsterdam climate can still be noticed for the different setpoints used for this study.

For the intermittent cooling cases, large differences were noticed between the annual cooling results of all four methods. The monthly method's annual cooling result for all these three intermittent cooling cases remained the same whereas the other three methods varied significantly. Although annual cooling results for the two dynamic simulation programs were in a good agreement, differences were noticed between the results of the simulation programs and the simplified methods, as well as between the two simplified methods. This is especially obvious for the case of intermittent cooling during the night.

Results from the "unconstrained" ESP-r cases

The annual heating and cooling energy requirement results taken from the use of ESP-r with less constrained inputs cannot be directly compared with the other results of Tables 1 and 2 because they include the building surfaces' longwave radiation heat exchange with the sky. For the annual heating energy requirements, the values for all cases, apart from the intermittent heating cases, are slightly lower than the values taken when ESP-r is used according to the 13790 instructions. The opposite trends occur for the annual cooling results. The differences are not significant apart from the cases where the non-insulated heavyweight wall was used (e.g. for the Amsterdam climate, the annual cooling calculated with ESP-r varied from 13.9 kWh/m^2 initially to 22.3 kWh/m^2 for the "unconstrained" case).

Discussion

While the aim of this study is not to validate the methods used, an attempt to explain the differences and agreements on the results obtained would help to draw conclusions for the potential use of the methods described here. The outputs of the calculated gains and losses from these methods were compared for the base case building to investigate the potential differences. From this comparison, it was confirmed that while the heat gains (solar and internal) and heat losses (ventilation and transmission) were almost the same between the monthly method and the simulation programs when the instructions of the 13790 Standard were followed, the calculation of the utilisation factor used in the monthly method to take into account the dynamic effects was causing the main differences in the results. This factor takes into account a calculation of the time constant of the building together with some suggested reference numerical parameters. By ensuring that the gain/loss ratio has been calculated correctly and by assuming that the utilisation's factor formula has been previously validated or checked, it was concluded that the calculation of the building's time constant and the selection of the relevant numerical parameters had a significant impact on the results' differences.

An attempt was also made to compare the gains and losses for the base case between the simplified hourly method and the simulation programs. While the heat gains output was confirmed to be the same in all methods it was difficult to track down the heat losses output from the simplified hourly method. Early indications showed that the calculated internal temperature values with the simplified hourly method had a critical impact in the cases where differences between the results of this method and the results of the simulation programs were noticed.

CONCLUSION

All methods described within the 13790 Standard were applied to a common building specification. Equivalency between the inputs and the boundary conditions used in all the methods was ensured according to the 13790 instructions. It was concluded from the parametric studies that there were cases where the annual heating or cooling results of all methods are in a good agreement but there were also other cases were these results vary significantly. However, in almost all cases the results between ESP-r and EnergyPlus are in a good agreement. The same applies for the majority of the cases between the results of the simplified hourly and simplified monthly methods. Based on the trends of the results obtained from this study it can be seen that between the two simplified methods, the simplified hourly method produces usually results that are closer to those obtained from the simulation programs. In general, the simplified methods seem to produce results that are in better agreement with simulation programs when they are used for heating energy use calculations that involve continuous heating applications for heavyweight building constructions, for buildings with low internal gains and/or for buildings with high ventilation rates.

This study does not provide conclusions for the accuracy of these methods. While the application of the methods in practice is not simple, building professionals should carefully consider their selection in terms of their accuracy and validation history.

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Table 1. Annual heating energy requirements (kWh/m^2)

	Monthly 13790	Hourly 13790	EnergyPlus	ESP-r	ESP-r (unconstrained)
Base Case (Amsterdam – 19 ^{o}C setpoint)	61.1	56.1	50.3	46.3	45.4
Climate Aberdeen	73.7	66.5	58.2	53.8	52.8
Climate Athens	14.0	12.0	5.2	4.6	3.9
Internal Gains averaged hourly (7 days/week)	61.1	48.0	47.0	44.9	43.7
Int. Gains averaged hourly (Weekdays/Weekends)	61.1	49.2	47.9	45.8	44.6
High internal gains	50.7	44.0	35.1	31.5	31.3
Low internal gains	76.6	74.7	71.7	67.0	65.8
Glazing area: double	77.9	70.8	63.9	56.5	51.6
Glazing area: half	53.2	49.8	44.9	42.8	41.0
Construction: very lightweight	68.3	63.3	57.1	55.4	53.9
Construction: heavyweight (Cm=231.56 kJ/m^{2}K)	47.2	46.7	47.4	45.4	43.9
Construction: heavyweight, no insulation	138.0	125.0	141.8	142.0	125.1
Ventilation daily schedule	61.1	52.9	48.5	46.8	44.4
Ventilation Weekday/Weekends schedule	61.1	53.2	48.7	47.0	44.3
High ventilation rates (1.5 ach)	113.4	111.5	106.5	99.7	91.9
Low ventilation rates (0.3 ach)	35.3	29.8	23.8	23.9	22.4
Rotate 90^o anticlockwise	63.9	58.7	55.1	53.0	50.6
Rotate 180^o anticlockwise	60.8	56.1	50.6	48.8	46.0

Setpoint @ 21 °C	79.5	73.0	67.1	64.6	60.6
Setpoint @ 17 °C	45.3	42.5	35.8	34.5	32.1
Intermittent heating 7-17.00h	18.2	9.2	28.1	24.3	18.6
Intermittent heating 0-10.00h	18.2	29.9	38.0	35.6	29.5
Intermittent heating (different periods @ 19 °C)	9.1	7.3	27.5	22.6	16.1

Table 2. *Annual cooling energy requirements (kWh/m^2)*

	Monthly 13790	Hourly 13790	EnergyPlus	ESP-r	ESP-r (unconstrained)
Base Case (Amsterdam - 24 °C setpoint)	43.8	32.0	22.3	24.1	26.0
Climate Aberdeen	34.3	18.6	9.3	10.6	12.4
Climate Athens	116.3	106.1	98.2	100.2	105.2
Internal Gains averaged hourly (7 days/week)	43.8	23.5	18.6	20.0	21.8
Int. Gains averaged hourly (Weekdays/Weekends)	43.8	24.6	19.2	20.6	22.4
High Internal Gains	66.4	52.1	39.0	41.4	44.1
Low Internal Gains	23.5	16.4	9.7	10.9	12.1
Glazing area: double	75.3	58.8	42.0	40.7	43.2
Glazing area: half	29.0	19.9	13.0	14.0	15.5
Construction: very lightweight	43.9	31.8	22.1	24.0	26.5
Construction: heavyweight (Cm=231.56 kJ/m^{2}K)	27.0	20.9	20.5	22.1	24.7
Construction: heavyweight, no insulation	27.3	15.8	12.9	13.9	22.3
Ventilation daily schedule	43.8	30.0	22.4	24.1	25.9
Ventilation Weekday/Weekends schedule	43.8	29.9	26.2	23.8	25.6
High ventilation rates (1.5 ach)	35.5	22.5	13.3	14.8	16.8
Low ventilation rates (0.3 ach)	51.2	41.6	32.0	33.7	36.0
Rotate 90° anticlockwise	42.5	29.9	22.0	23.6	25.7
Rotate 180° anticlockwise	45.4	32.0	22.5	24.3	26.0
Setpoint @ 26 °C	37.8	24.2	14.3	15.9	17.8
Setpoint @ 22 °C	51.4	41.4	32.2	34.2	36.1
Intermittent heating 7-17.00h	31.3	28.3	20.7	21.7	21.8
Intermittent cooling 0-10.00h	31.3	6.1	9.1	9.4	9.3
Intermittent cooling (different periods @ 24 °C)	31.3	17.1	19.7	18.4	16.7
Base Case (Athens - 24 °C setpoint)	116.3	106.1	98.2	100.2	105.2
Internal Gains averaged hourly (7 days/week)	116.3	97.4	94.6	96.1	101.1
Int. Gains averaged hourly (Weekdays/Weekends)	116.3	98.2	94.9	96.4	101.4
High Internal Gains	148.9	137.6	129.5	132.3	138.2
Low Internal Gains	82.3	76.3	70.3	71.7	75.7
Glazing area: double	184.7	167.5	155.9	164.1	151.2
Glazing area: half	82.8	75.2	69.6	70.5	74.6
Construction: very lightweight	117.1	107.5	100.4	102.6	109.3
Construction: heavyweight (Cm=231.56 kJ/m^{2}K)	103.1	93.6	97.9	99.5	107.4
Construction: heavyweight, no insulation	134.7	107.3	120.9	123.2	148.9
Ventilation daily schedule	116.3	105.5	99.8	101.6	106.7
Ventilation Weekday/Weekends schedule	116.3	104.9	101.6	100.8	105.7
High ventilation rates (1.5 ach)	110.7	101.3	94.0	95.4	101.1
Low ventilation rates (0.3 ach)	121.5	112.3	106.1	108.1	113.1
Rotate 90° anticlockwise	117.6	104.4	101.2	102.5	107.1
Rotate 180° anticlockwise	118.8	104.0	96.4	98.4	103.0
Setpoint @ 26 °C	99.9	89.2	79.6	81.5	86.7
Setpoint @ 22 °C	133.7	125.6	119.1	121.2	125.9
Intermittent cooling 7-17.00h	99.0	80.4	84.0	84.3	83.2
Intermittent cooling 0-10.00h	99.0	33.1	60.1	59.3	56.8
Intermittent cooling (different periods @ 24 °C)	99.0	50.2	80.4	73.5	66.5