EXPLORATION OF HEURISTIC RULES IN MASS HOUSING DESIGN SPACE FOR MINIMISED ENERGY CONSUMPTION AND CO_2 EMISSION

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ABSTRACT

Optimal energy sensitive design of residential buildings relies on the eclectic selection of active and passive components, where their effectiveness is supported by theoretical and simulation-based analyses. This paper presents an exploration of heuristic rules in mass housing design space for minimised energy consumption and CO_2 emission. This study is intended to encourage initiatives aimed at developing energy efficient multi-storied residential buildings in South Korea by considering relevant passive design strategies and to support architects' and engineers' judgement before zeroing down on a set of effective passive design solutions by providing ready reference of generalized test cases. Passive design of a building depends heavily on site and climatic conditions, thus the heuristics proposed in this paper is applicable primarily to residential buildings in South Korean climate.

Twelve test cases of residential building performance indicators (viz. plan proportion, building orientation, wall insulation thickness, wall insulation location, window area, window location, window construction, balcony type, balcony depth, blind angle, infiltration, natural ventilation) were selected following a literature survey based on existing and decision influencing passive design parameters. Evaluation of this analytical framework is demonstrated using simulation results generated by DesignBuilder^{TM}. The simulated energy consumption and CO_2 emission profile obtained on iterating each passive design parameter is compared against that of a base case residential unit modelled as per the local building codes in Korea. The study conclusively suggests a weighted energy efficiency per lifecycle cost method for prioritising the design strategies by including the cost factor alongside the predicted energy savings applicable to the energy sensitive design of Korean multi-family housing complexes.

INTRODUCTION

Energy security is a challenging issue for many developed and developing nations around the world. Energy efficiency in buildings is rated as the most promising alternative rather than building more power plants to meet the current energy needs (Food and Agriculture Organisation of the United Nations, Rome, 2008).

South Korea is one of the most developed Asian countries and maintains the thirteenth largest economy in the world, with a GDP of US$1.164 trillion in 2010 (Evans, 2009; U.S. Energy Information Administration, 2012; International Monetory Fund, 2012). Due to limited energy resources, South Korean Government is developing various strategies to enhance energy efficiency in building sector. However, the major challenge faced while implementing this practice is the ease of adoption by architects. Keeping this in mind, the Korean government recently made an Excel based spread sheet for the cost and energy efficiency analysis of carbon neutral energy sources applied to residential sector (MLTM, 2011). Our study follows a similar approach to provide a handy and lightweight framework for architects to eclectically choose energy sensitive residential space design solutions from a set of passive design parameters. Most of the researches in passive design evaluation of built environment are limited to a particular domain of fenestration surfaces, thermal analysis, lighting fixtures etc. (Foster, 2001; Ossen, 2005; Song, 2011; Uno, 2012). Although these provide an in depth understanding of that particular design parameter, they can seldom be compared with other available passive design options considering their lifecycle cost implications. This paper aims at presenting a holistic comparison of passive residential design variables such that the result is suited for ready reference.

Literature review

Energy optimization of built environment has been researched by the experts for the past many years. Building performance evaluation models have been developed for both quantitative as well as qualitative analysis. Qualitative tools are based on scores and criteria while quantitative tools use a physical life cycle approach with quantitative input and output data on flows of matter and energy (Forsberg, 2004). Based on the list of passive design parameters that are most frequently explored in the precedent researches plus some of our own selection, we chose twelve of them for our evaluation.

Song et.al studied the energy efficiency of internal and external insulation in apartment buildings. The results showed considerable heat loss in Interior Insulation System (IIS) due to the layers of insulation disconnected between wall-slab joints. Exterior Insulation and Finishing System (EIFS) had an advantage over IIS because of its improved performance and ease of installation using adhesives (Song, 2011). Cho et.al. studied the ventilation effectiveness by appropriate operable window opening area, partitioning and placement. They proposed optimum opening area to floor area ratios for increased natural ventilation efficiency (Cho, 2012). Uno et.al. studied the reduction in energy consumption of air conditioners in relation with air tightness and ventilation strategy in hot and humid climates. They compared the effectiveness of improvements in air tightness of air conditioned room versus the air- tightness of whole apartment and concluded that the former had a more positive influence over the energy reduction (Uno, 2012).

S.-S Kim et al. (Kim, 2005) studied the performance evaluation for multi-family residential buildings in Korea. Forty-one objectives and feasible housing performance indicators were selected and the weights of each category and indicator were calculated using the analytical hierarchy process (AHP) analysis to convert the weights into credits. The study covered a major section of residential building performance parameters ranging from housing environment, housing function, level of residential comfort and many more in addition to energy sensitive residential space design variables.

Simulation tool and hypothesis

The simulations are performed with Design Builder^{TM}. This tool is chosen over other simulation packages such as Energy Plus and TRNSYS because of the intuitive GUI of the software. Most importantly, the focus of our study is on the interpretation of simulation results and not on the method of simulation.

A typical multi-storey residential unit (100m^2 floor area) in Korea is chosen for analysis. The ceiling height for each storey is 2.4m. The balcony extension types and dimensions are specified in the test cases. To reduce the total test time, we simulated a single residential unit placed in the middle of an apartment building. Negligible heat loss through top and bottom slab of this selected unit is assumed to exclude inter-floor heat transfer. Fan coil unit is chosen over other heating systems as it closely represents radiative indoor temperature adjustment scheme in a typical Korean residential unit. Activity schedule of a working class family of four people is defined. All internal gains are set to operate with occupancy. A comfortable lighting illuminance of 150 lux is maintained throughout the space (CIBSE, 1999). Materials selected are those which are commonly used for constructing Korean multi-storied residential buildings. Details of material properties, layer arrangement and test cases is enclosed in the appendix.

The design parameters evaluated through sensitivity analysis in this study are the ones closely related to conduction (plan proportion, wall insulation thickness, wall insulation location, window area, window construction, balcony type) convection(infiltration and natural ventilation) and radiation(plan proportion, orientation, window area, window location, window construction, balcony depth, blind angle) mode of heat transfer in a typical residential space.

Each of the test case is simulated for eight cardinal orientions. However, glazing on the south showed the best energy performance and thus the graphs from Figure 1-13 are all for the glazing on the south façade.

All test cases except specifically mentioned, have interior insulation with 100m^2 floor area and default infiltration of 0.3 ACH.

Discussion about simulation outcomes

a. Plan proportion (Longer facade aligned in east-west direction)

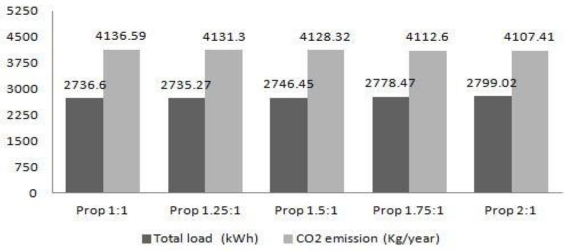

Figure 1. Plan proportion energy/ CO2 sensitivity

The total (heating + cooling) load increases by 2% on increasing the residential unit's width and length proportion ratio. This is mainly because the reduction in heating due to solar gain is offset by the increase in cooling load during summer. The heating is done by gas boiler and the appropriate source-to-site factors have been applied. This also accounts for the anomaly seen in the decrease of CO$_2$ production with the increase in total load.

b. Orientation

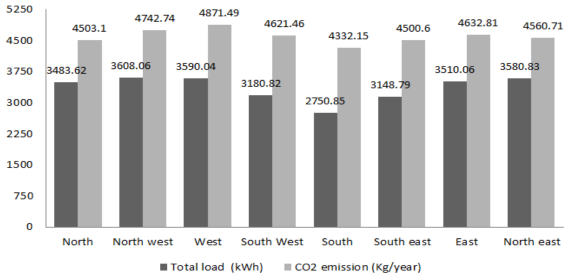

Figure 2. Orientation energy/ CO2 sensitivity

The orientation is iterated by rotating the 50% glazed facade of the building from north in anti-clockwise direction. The south faced glazing has the least energy consumption. Daejeon, the test site is located at 36°19’17’’N, 127°25’10’’ (angle based on solar geometry). Thus all the further iterations represented in the graph are for glazing on the south facade.

c. Wall insulation location

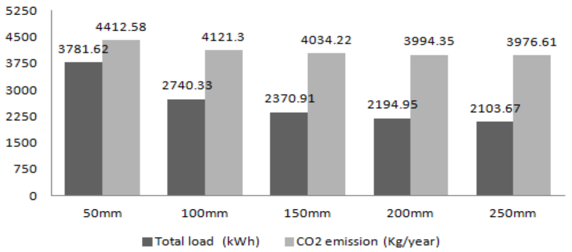

Figure 3. Wall insulation location energy/ CO2 sensitivity – Interior insulation

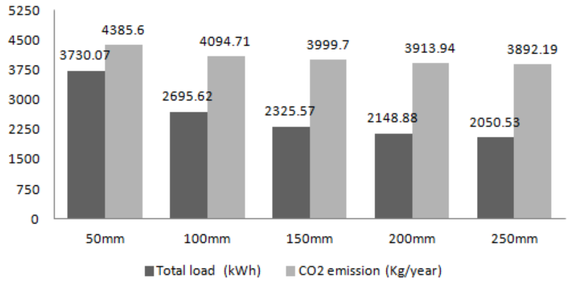

Figure 4. Wall insulation location energy/ CO2 sensitivity – Middle layer insulation

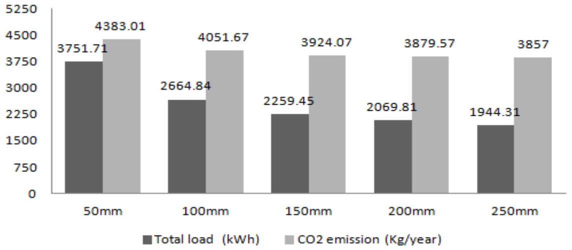

Figure 5. Wall insulation location energy/ CO2 sensitivity – Exterior insulation

In the countries where heating energy becomes dominant such as South Korea, insulation is the most important passive design parameter as evident from the energy savings accrued by changing the insulation material placement (interior, middle layer, exterior) and thickness. Amongst those three insulation locations, exterior insulation gives the best result. This observation is consistent with Song et.al who also concluded that exterior insulation type performed better than interior insulation type as it has heat loss from the disconnected wall slab joints. As expected, the energy consumption decreases on increasing the insulation thickness. However, the boundary on the increasing thickness is decided by the increase in the cost addressed in later in this paper.

d. Window area

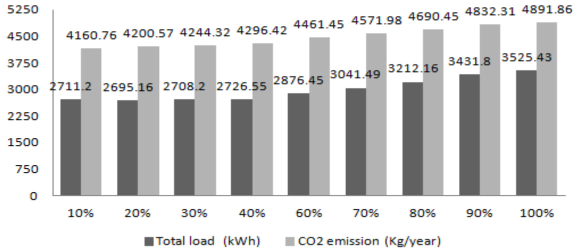

Figure 6. Window area energy/ CO2 sensitivity

Increasing the window area on the south facade increases the overall energy consumption. This is observed due to the increased cooling load by solar gain during the summer season and increased heat loss through larger window area during summer and winter since window has greater heat transfer rate compared to typical wall construction.

e. Window location

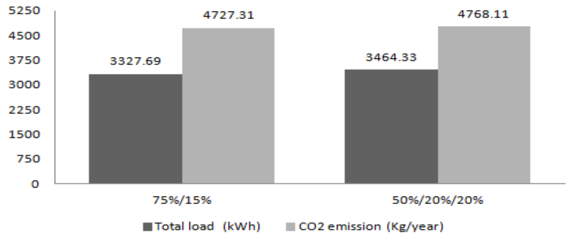

Figure 7. Window location energy/ CO_2 sensitivity

In this iteration, the window opening is made on different facades of the residential unit. The 75%/15% window installation test case has glazing on the south and north facade. The 50%/20%/20% test case has glazing on the south, east, west façade, respectively while maintaining a constant overall glazed area. It is observed that the test case with windows on south and north facades performed better than the one with glazing on south, east and west facades. The difference here is primarily ascribed to the dynamically varying amount and intensity of solar radiation depending on each orientation throughout a year.

f. Window construction

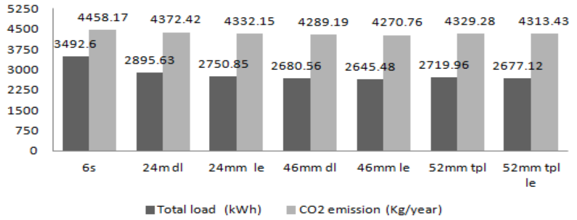

Figure 8. Window construction energy/ CO2 sensitivity

Window construction described in appendix is simulated in this set of iteration to observe the impact of the arrangement of glazing layers on energy consumption. Along with gazing thickness and cavity in fill gas type, the number of glazing layer becomes influential factor in energy conservation. The triple layer glazing can reduce the energy consumption by 23% while double layer glazing reduces it by around 20 %. However, the trade-off between the improved energy saving and cost needs to be considered.

g. Balcony type

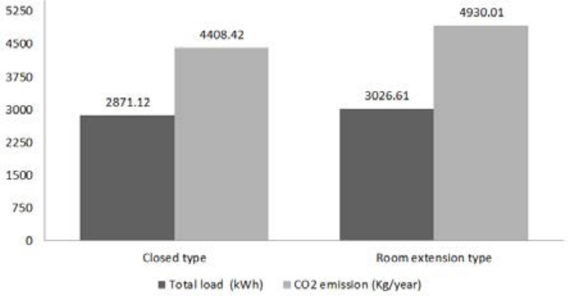

Figure 9. Balcony type energy/ CO2 sensitivity

Currently, most of Korean apartment complexes have two distinctive types of balcony design such as closed balcony type and room extension type. Closed balcony forms a separate chamber with exterior and interior glazing layers without cooling or heating whereas room extension type actually represents room space that is extended through the balcony space to secure more living area. Closed balcony type displayed better energy consumption profile over room extension type counterpart due to increased insulation and relatively less area demanding heating and cooling even though it has disadvantage of decreased solar heat gain during winter.

h. Balcony depth

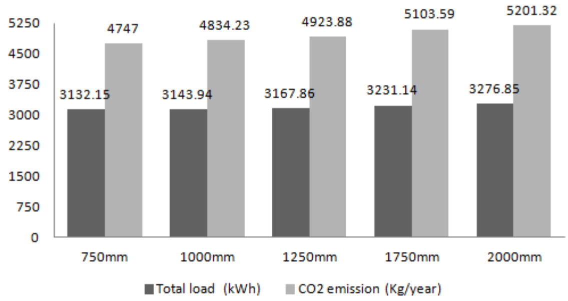

Figure 10. Balcony depth energy/ CO2 sensitivity

No significant fluctuations were observed in the energy profile by iterating balcony depths. Current regulation in Korea regarding allowable balcony depth extension limit is 1.5m and most of actual installation cases converge to this limit, therefore, this design parameter has very little room for practicing variance. Furthermore, this parameter is subject to preferences of occupants and thus is less important from energy consumption perspective.

i. Blind angle

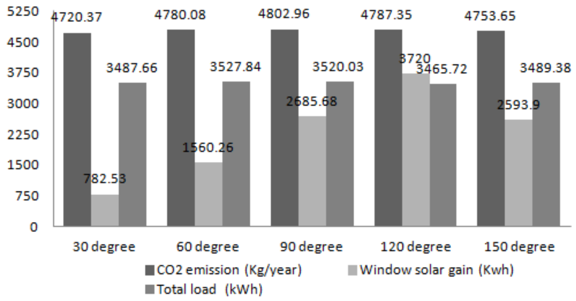

Figure 11. Blind angle energy/ CO2 sensitivity

Blind angles displayed an interesting energy profile in each test case. Obviously blind has implication on controlling solar radiation quantifiable through SC or SHGC. Cutting off solar radiation is beneficiary during summer but not desirable during winter season, therefore, the accumulative impact of fixed blind angle throughout a year could cancel out this positive and negative aspects of energy related implications. The solar heat gain was maximum for 120^{o} blind angle. This effect can be explained by referring to the sun path diagram where diffused light is made to enter the room during most of the daytime.

j. Infiltration

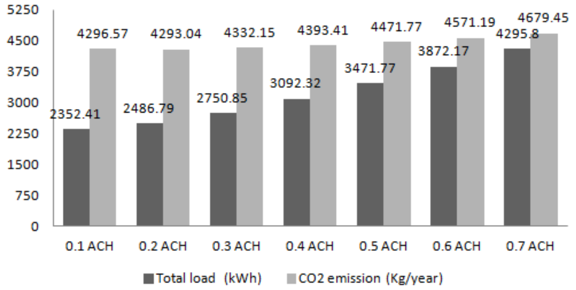

Figure 12. Infiltration energy/ CO2 sensitivity

Like other cold countries, air tightness influenced the energy consumption greatly for South Korean climate. Decreasing the air change rate to 0.1 from 0.7 decreased the energy consumption by 45%. Low infiltration rates have produced exceedingly efficient energy profiles. This effect is more prominent in cold environments owing to the increased heating load with increase in infiltration. An additional advantage of air tightness when coupled with ventilation system is prevention of mold growth. Smeds et. al. studied the high performance design in houses for cold climates and suggested the air tightness to be maintained at 0.05 ACH for best energy performance (Smeds, 2007).

k. Natural ventilation

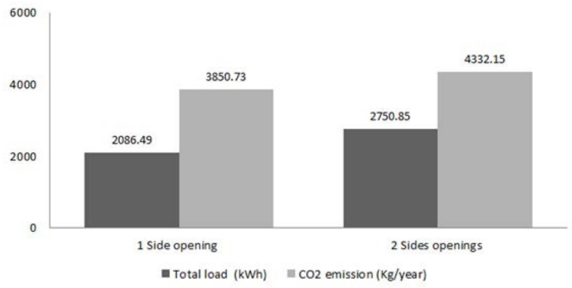

Figure 13. Natural ventilation energy/ CO2 sensitivity

Two sided natural ventilation reduced the cooling load drastically but the effect was nullified by higher heating requirements during winters. Thus natural ventilations with single opening is best suited in the given conditions.

Analysis & evaluation of the test cases

The performance of the passive design strategies evaluated by simulation tool needs to be analysed for cost effectiveness by adopting suitable ranking methodology. Methods based on multi-criteria rating like Elimination and Choice Expressing Reality (ELECTRE), Hermione or the one based on principle component analysis would have been best suited for this model (Robinson, 2011; Roulet, 2002). But keeping in mind the objective of this study i.e. easy adoption in architectural practise by designers, the test cases are prioritized based on energy consumption and cost implications using a linear energy-cost model.

$$U_e = w_e \frac{\Delta E}{\Delta C} \qquad (1)$$

$$U_{CO_2} = w_{CO_2} \frac{\Delta CO_2}{\Delta C} \qquad (2)$$

Where U_e and U_{CO2} are utility factors for each test case; $\Delta E/\Delta CO_2$ are the normalized energy and cost differences between the base case and the evaluated test case; ΔC is the difference in cost for a life expectancy of 10 years; w_e/w_{CO2} are the user defined weights such that

$$W_e + W_{co2} = 1 \qquad (3)$$

Weights are assigned by the user, or preferably by a group of people knowing the significance of each performance indicator and who agree on them.

The evaluation model suggested evaluates the variations in energy and CO_2 consumption with respect to the variations in cost and depicts an overall priority based ranking of heuristics. An illustration of a test case for increasing wall insulation thickness is summarized below.

The base case is assumed to be of 150mm insulation thickness and is compared against that of 200mm insulation thickness. The cost of XPS Polystyrene CO_2 blowing insulation in South Korea is $\$130/m^3$. Considering 70% preference for energy and 30% for the cost we have the values of U_e=1.915 x 10^{-2} $(KWh/m^2)/(\$/year)$ and U_{CO2}=1.635 x 10^{-3} $(Kg/m^2\text{-}\$)$.

Another illustration of this rating system is shown below for comparing different types of window glasses viz. 24mm dual pane, 24mm dual pane low-e, 52mm triple pane, 52mm triple pane low-e to the base case of single pane glass.

	Base Case	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Glazing	Single clear	24mm dual	24mm low-e	52mm triple	52mm triple low-e
Al frame cost $(\$/m^2)$	66	66	66	66	66
Cost $(\$/m^2)$	20	30	40	46	100
Area	12	12	12	12	12
Cooling load (KWh)	3493	2896	2751	2720	2667
CO_2 emission (Kg/year)	4458	4372	4332	4329	4313
Total Cost	306	426	546	618	1266
U_ex 10^{-2}	-	1.99	1.23	0.99	0.33
U_{CO2}x 10^{-2}	-	0.43	0.32	0.25	0.09

Higher the utility factor, better is the performance of that parameter. The utility factor can be used to decide between test cases or sub test cases on a uniform criterion.

These values can be calculated by the user by attributing suitable inputs based on the requirement and prevalent cost scenarios. These values can be plotted on a chart for different test cases and prioritized. Heuristic rules spanning through all test cases are introduced in the appendix. Above mentioned linear energy-cost model could provide user preference based prioritization among diversified multi-housing unit space design options by counting both energy conservation and cost related implications.

CONCLUSION

A set of heuristic rules is explored in this paper by systematically varying passive design parameters. For achieving high energy performances, entire building space needs to be addressed as a whole and not a particular domain. The heuristic rules described is prominently for the place of evaluation i.e. Seoul (South Korea). We further intend to target increasing mass housing in other regions and develop a ready reference of test cases for them in a similar manner. Further work needs to be done on optimization algorithms which take into consideration inter dependency of parameters and at the same time have an easy to use GUI. The main motive of taking up this research will be met if this work inspires further implementation of integrating passive design strategies in housing spaces with the help of state-of-art technology. The current stage of this project is at developing a design decision support algorithm for sustainable buildings for saving energy while not compromising on occupant comfort.

ACKNOWLEDGEMENT

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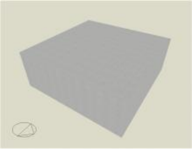
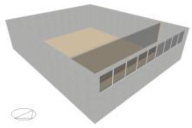
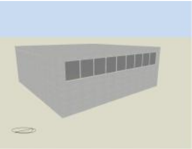
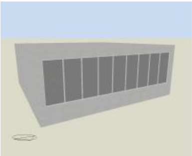
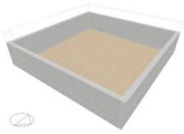
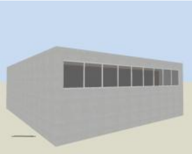
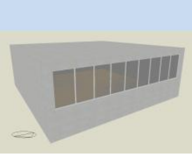
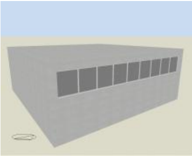
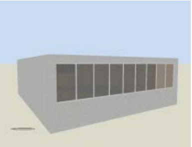
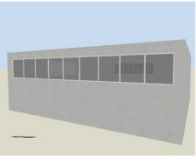
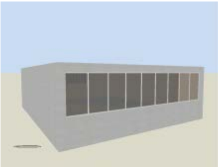
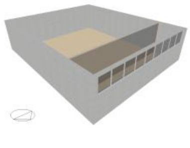
Appendix

1. Test cases and derived exemplary heuristic rules

Test Case	Derived exemplary heuristic rules based on energy consumption only
T1.Proportion	Increasing proportion ratio increases the total energy load on the building.
T2.Orientation	Orientation with glazing façade facing South direction consumes lowest energy.
T3.a)Wall Insulation location	Exterior layer wall insulation is preferable than middle layer and interior layer wall insulation.
T4.b)Wall thickness	Energy performance increases drastically with increased wall insulation.
T5.Window area	Optimum glazing area of about 50% is desirable so as to eliminate the cancelling effect of heat gain during seasonal changes in increased glazing.
T6.Window location	Windows placed on opposite sides of the wall consumes less energy as compared to the windows installed on three adjacent walls.
T7.Window construction	Multiple layered glasses for windows reduce the total energy load due to increased heat resistance.
T8.Balcony type	Room extension type balcony increases the total energy load due to increased heat loss than closed type balcony.
T9.Balcony depth	Increasing the balcony depth increases the total energy consumption.
T10.Blind angle	Energy consumption follows a sinusoidal type curve on incrementing blind angle.
T11.Infiltration	Air-tight built spaces reduce the total energy load.
T12.Natural ventilation	Natural ventilation decreases the total load on the building by assisting either heating or cooling depending on the prevalent climatic condition.

1. Test cases representing energy sensitive design parameters used in the evaluation model

Test Case	Building geometry	Subtest cases	Test Case	Building geometry	Subtest cases
T1: Proportion		T.1.1- 1:1 T.1.2- 1.25:1 T.1.3- 1.5:1 T.1.4- 1.75:1 T.1.5- 2:1	T8: Balcony depth		T.8.1- 750mm T.8.2- 1000mm T.8.3- 1250mm T.8.4- 1750mm T.8.5- 2000mm
T2: Orientation		T.2.1-North, T.2.2-Northwest T.2.3-West T.2.4-SouthWest T.2.5-South, T.2.6-South East T.2.7-East T.2.8-NorthEast	T9: Blind angle		T.9.1- 30^{o} T.9.2- 60^{o} T.9.3- 90^{o} T.9.4- 120^{o} T.9.5- 150^{o}
T3: Wall Insulation location		T.3.1-Interior insulation type T.3.2-Middle layer insulation type T.3.3-Exterior insulation type	T10: Blind Insertion point		T.10.1- 2nd side of outer window
T4: Window area		T.4.1- 10% T.4.6- 60% T.4.2- 20% T.4.7- 70% T.4.3- 30% T.4.8- 80% T.4.4- 40% T.4.9- 90% T.4.5-50% T.4.10-100%	T11: Infiltration		T.11.1- 0.1 ACH T.11.2- 0.2 ACH T.11.3- 0.3 ACH T.11.4- 0.4 ACH T.11.5- 0.5 ACH T.11.6- 0.6 ACH T.11.7- 0.7 ACH
T5: Window location		T.5.1-75%South/ 15% North T.5.2- 50%South/ 20%West/ 20%East	T12: Natural Ventilation		T.12.1-1 Side opening T.12.2-2 Sides opening
T6: Window construction		T.6.1- Sgl Blue 6 T.6.2- 6cl_12air_6cl T.6.3- 6le_12air_6cl T.6.4- 6cl_12air_6cl (outside) + (100 air) 5cl_12air_5cl(inside) T.6.5- 6cl_12air_6le (outside) + (100air) 5le_12air_5cl T.6.6- 6cl_18.5air_3cl_ 18.5air_6cl T.6.7- 6le_18.5air_3cl_ 18.5air_6le	Base Case		-Proportion 1:1 -Wall interior insulation (100mm) - Glazing 75%S/15%N -24mm dual glazing (cl) -Closed type balcony(1.5m) -90^{O} blind angle
T7: Balcony type		T.7.1- Closed type T.7.2- Room extension type			