Optimum design of low-cost housing in developing countries using nonsmooth simulation-based optimization

ANH TUAN NGUYEN[1], SIGRID REITER[1]

[1]Local Environment Management and Analysis (LEMA), Faculty of Applied Sciences, University of Liège, Belgium

ABSTRACT: An optimum design of Low-cost housing (LCH) offers low-income urban inhabitants great opportunities to obtain a shelter at affordable price and acceptable indoor thermal conditions. In the present study, the design and operation of a low cost dwelling were numerically optimized using simulation-based approach in which a dynamic building simulation program (EnergyPlus) was coupled with the optimization engine (GenOpt). Three multi-objective cost functions which include construction cost, indoor thermal comfort and 50-year operating cost were applied for naturally ventilated (NV) and air-conditioned (AC) buildings. Optimization problem which consists of 18 building parameters combined with 6 ventilation strategies was examined by two population-based optimization algorithms (Particle Swarm optimization and Hybrid algorithm) to find optimum combinations among these variables. The results show that the design requirements of NV and AC dwellings are not quite similar, and in a few categories, even contradictory. Optimum design corresponding to each cost function was outlined. Results of this paper also show great potential of optimization in comfort improvement, energy saving, life cycle cost, up to 40%.
Keywords: low-cost housing, optimization, life cycle cost, building energy simulation

INTRODUCTION

The applications of simulation based optimization have been considered since the year 80s and 90s based on the rapid growth of computational science and mathematical optimization method. A pioneer study in optimization of building engineering systems was presented in [1] by Wright in 1986 when he applied Direct Search method in optimizing HVAC system. Genetic algorithm was then introduced and applied in optimization of building envelop design, HVAC system and its control [2; 3]. In 2001, Wetter [4] first introduced optimization engine GenOpt with different optimization algorithms that significantly contributed to optimization solutions in building engineering. Other optimization engines, e.g. BEopt, TopLight… were mentioned elsewhere [5], but the application is not common because of their limited flexibilities. Since then, numerous optimization researches have been carried out, aiming to optimize building designs, passive strategies, energy consumption, HVAC controls, construction cost, life-cycle cost, environmental impacts... Nevertheless, optimization research related to low-cost housing (LCH), which is actually essential in most developing countries, has not been mentioned.

Housing demand in developing countries is still very high. In Vietnam in 2008, 72.2% of the existing housing was semi-permanent and temporary houses and 89.2% of the poor did not have a permanent shelter [6]. Therefore, LCH has recently been among the top strategies for resolving urban housing issue in developing countries, where the rural – urban migration and population booming have generated a huge pressure on urban sustainable development. Due to the cost constraints, LCH usually employs natural ventilation as the major cooling strategy and indoor air quality control. HVAC systems are rarely used, thus indoor comfort is mainly achieved by passive solutions and strategies. Also, developing countries often lie in warm and humid climate zone that significantly influences the design of LCH. Therefore, construction costs as well as thermal comfort are the matters of great concern, rather than the issue of building energy consumption.

The present paper discusses about the process by which an optimal solution of LCH in the North of Vietnam is achieved using simulation-based optimization. Optimization method and results of this study are essential references in determining the development of this housing type in developing countries.

METHODOLOGY

To optimize the cost and thermal comfort problem by simulation-based method, an appropriate dynamic thermal simulation tool, namely EnergyPlus 6.0 [7], was used in this study. EnergyPlus was coupled with an optimization engine GenOpt [8] to minimize different multi-objective functions. Fig.1, which was slightly modified from the origin in [8], shows how EnergyPlus couples with the optimization engine.

In naturally ventilated building, airflow rate has a great influence on indoor thermal environment. Sensitivity analysis on Building Energy Simulation also showed that the air flow rate is among the most sensitive parameters which have greatest effect on the output [9]. In this

study, Airflow Network model in EnergyPlus was used to predict the flow rate from the local wind regime. Further detailed description of the airflow network model can be found in Walton [10] and his related works.
The present study assumed that EnergyPlus could give reliable result without the need of user's calibration. Also, since one-year weather file of Hanoi was used, the 50-year Life cycle cost analysis assumed the climate would not change as projected by scientists.

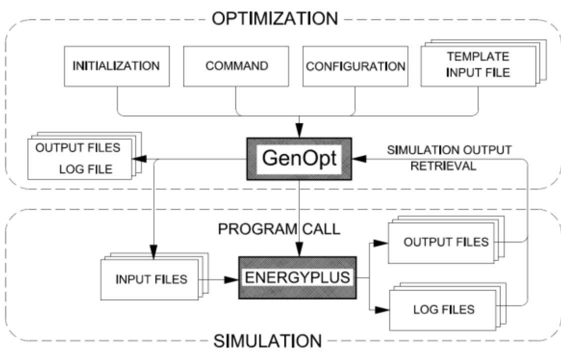

Figure 1: Coupling principle between GenOpt and EnergyPlus that evaluates the objective function

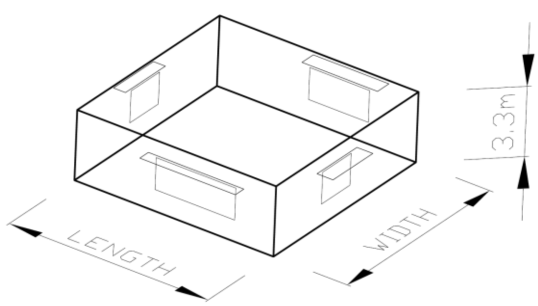

Figure 2: Building model in the optimization

BUILDING MODEL AND OPTIMIZATION PARAMETERS

A simple model of low-cost dwelling was used as shown in Fig.2. It is a rectangular parallelepiped with 4 windows on its four facades. Doors were intentionally omitted as their thermal properties were assumed similar as those of external walls. The building floor area and height are fixed at 100m^2 and 3.3m, respectively and thus only the building width and length are varied correspondingly. The house is occupied by maximum 4 people who share one gas stove (maximum heat dissipation of 250W). Maximum lighting consumption is 1 kWh. The weather file of Hanoi, representing the climate of North Vietnam, was used. It is worthy of note that optimal solution of this simple model given by optimization will indicate most appropriate design principles and parameters that can be further applied in more sophisticated buildings in the North of Vietnam.

Table 1: Numerical design options (continuous variables)

Design parameter (with unit)	Range
Building orientation (azimuth) [Degree] - x_1	-90 to 90
Building width (W) [m] - x_2	4 to 10
Building length (L) [m]	L = 100/W
South Window overhang size [m] - x_3	0.2 to 0.8
North Window overhang size [m] - x_4	0.2 to 0.8
East Window overhang size [m] - x_5	0.2 to 0.8
West Window overhang size [m] - x_6	0.2 to 0.8
South window width [m] - x_7	1 to 4
North window width [m] - x_8	1 to 4
West window width [m] - x_9	1 to 3
East window width [m] - x_{10}	1 to 3
External wall absorptance - x_{11}	0.3 to 0.9
Reference infiltration (AC case) [m^3/s] - x_{12}	0.05 to 0.15
Window infiltration (NV case) [kg/s-m] - x_{12}	0.002 to 0.006

Table 2: Non-numerical design strategies (discrete variables)

Element	Type (with 'codified name')	Cost ($/m^2)
thermal mass - x_{13}	110mm thickness (600)	20
	210mm thickness (601)	26
	410mm thickness (602)	36.5
floor type - x_{14}	Concrete Slab NO insulation (500)	34
	Concrete Slab 2cm insulation (501)	39
	Concrete Slab 4cm insulation (502)	43
Natural ventilation scheme - x_{15}	Daytime ventilation summer (401)	
	Daytime ventilation summer + mild seasons (402)	
	Night ventilation summer (403)	
	Night ventilation summer + mild seasons (404)	
	Full day ventilation summer (405)	
	Full day ventilation summer + mild seasons (406)	
roof type - x_{16}	two-side plaster 120mm heavy RC (300)	45
	two-side plaster 120mm heavy RC with 2cm insulation (301)	52
	two-side plaster 120mm heavy RC with 4cm insulation (302)	58
window type - x_{17}	Single clear glazing 6mm (200)	45
	Single clear glazing 6mm with loE film (e2=.2) (201)	70
	Double 6mm reflective glazings with 13mm Argon) (202)	220
external wall - x_{18}	110mm two-side plaster brick wall (100)	20
	290mm two-side plaster brick wall with air gap 5cm (101)	26.5
	Two-side plaster brick wall with 2cm central insulation (102)	33
	Two-side plaster brick wall with 4cm central insulation (103)	38

Two cases will be investigated. In the first case - NV case, the house is naturally ventilated (hourly air flow rates are calculated using Airflow Network model) and no HVAC system is installed. In this case, windows and other openings are controlled by the occupants using some simple ventilation strategies. Table 2 shows six possible ventilation strategies which are commonly used in hot humid climate. In the remaining case – AC case, the house is air-conditioned. It is assumed to be equipped with an Ideal Loads Air System and thermostat setpoint is fixed at 20ºC and 26ºC. These setpoints were intentionally chosen to maintain PPD index [11] of indoor environment in most cases not to exceed 20% (80% acceptability, correspondingly). Other crucial parameter that needs to be correctly set is infiltration rate. After many parametric runs, we decided to calculate air infiltration rate as the function of outdoor wind speed and temperature difference as follows:

$$Q = I_i(A*\Delta T + B*V_{outdoor}) \quad (1)$$

where:

I_i is reference infiltration flow rate (m^3/s). This value is varied during optimization process (Initial value is 0.1), ΔT (T_{zone} -T_{out}) is difference between indoor and outdoor temperature (ºC); $V_{outdoor}$ is hourly outdoor wind speed (m/s); A and B are temperature and velocity coefficient, respectively. We assumed (A, B) = (0.05,0.18) because these coefficients produce a value of 0.026 m3/s (0.75 ACH) at 2ºC ΔT and 2 m/s wind speed, which corresponds to a typical summer condition in Hanoi.

All parameters to be optimized as well as their assigned value during optimization process are listed in Table 1 and 2.

THE CHOICE OF OPTIMIZATION ALGORITHMS FOR THE PRESENT PROBLEM

The demand of a search-method that works efficiently on a specific optimization problem has led to various optimization algorithms. It is worthy to note that a certain optimization algorithm might fail to find out the global minimum of the problem if local minimum (or minima) exist. As an example, if the simulation program contains empirical assigned value (e.g. wind pressure coefficient), adaptive solvers with loose precision settings or iterative solvers that iterate until a convergence criterion is met, such as EnergyPlus, they may cause the cost function discontinuous and thus gradient based optimization algorithms (e.g. Discrete Armijo Gradient) usually fail far from the global minimum [12]. The choice of optimization algorithm for a specific problem is therefore crucial to yield greatest reduction.

In this study, the model is considered complex as it has 18 independent variables to optimize. Wetter and Wright [12] compared the performance of 9 optimization algorithms and reported that for detailed optimization problem, Hybrid algorithm (a combination of Particle Swarm Optimization and Hooke-Jeeves Algorithm) achieved the biggest cost reduction but required a little more simulations than Genetic algorithm. This is a combination of Direct search optimization family and stochastic population based optimization family. The Hybrid algorithm works more effectively since it performs a global search by the Particle Swarm Optimization (PSO) which "increases the chance to get close to the global minimum rather than only a local minimum, and the Hooke–Jeeves algorithm then refines the search locally" [12]. Furthermore, this Hybrid algorithm accepts both continuous and discrete variables which are the case in question. Therefore, Hybrid algorithm was used. PSO was also employed as a reference algorithm during optimization. Details of these algorithms can be found in GenOpt manual [8]. The settings of these algorithms were identified through small trials and were almost by default, except that we increased the number of particles per generation (to 35) to match with the large search-space. A population size of 35 strikes a balance between being large enough to allow the search to process from the first generation, without being too large to delay final convergence. The number of generation was varied depending on the optimization algorithm used, but did not exceed 500 generations.

THE ESTABLISHMENT OF OBJECTIVE FUNCTIONS

The choice of building design solution is a non-linear multi-objective optimization process, hence it always consists of a trade-off among design criteria, e.g. initial construction cost, operating cost, and occupant's thermal comfort [3]. The most simplistic approach, namely "a priori", is to assign a weight factor to each criterion, and then objective function will be simply the weighted sum of the criteria. As an example, we consider an optimization problem of a thermal zone which consists of a construction cost function $f_c(X)$ and a comfort performance function $f_p(X)$. These functions could be integrated into a single objective function by assigning two weight factors (a and b) as follows:

$$f(X) = a*f_o(X) + b*f_p(X) \quad (2)$$

Another approach does analysis on a set of trade-off solutions (Pareto set) among which a final solution from that set will be then determined. However in some case, The Pareto set may become very sophisticated (n-dimension surface) if more than two optimization criteria are applied. In the present paper, the first approach was used to combine construction cost criteria, thermal comfort criteria and operating cost criteria into one. Two objective functions for NV case and another for the AC case were established. In the NV case, operating cost is considered small, and we therefore minimize the objective function №1, which is defined as:

$$f(x) = f_c(x)\left[1 + (\overline{PPD} - 20)/100\right] \quad (3)$$

where

$f_c(x)$ is total construction cost of the house; $\overline{PPD}$ is mean PPD (Predicted Percentage of Dissatisfied) of the thermal zone in question. PPD is an environmental index proposed by Fanger [11]. For low-cost house, a PPD less than or equal to 20% (80% acceptability) is considered acceptable.

The optimization result obtained from objective function №1was then compared with the thermal comfort objective function №2 to examine the trade-off between these two criteria:

$$f(x) = \overline{PPD} \qquad (4)$$

In AC case, since indoor thermal environment in controlled by HVAC system, we therefore minimize the life-cycle cost of the house which includes initial construction cost and 50-year operating cost. Demolition cost, transportation cost and waste management cost are assumed to be similar in all solutions. Thus the objective function №3 is:

$$f(x) = f_c(x) + f_o^{50}(x) \qquad (5)$$

where

$f_c(x)$ is initial construction cost (present value); $f_o^{50}(x)$ is total 50-year operating cost (present value).

Using life-cycle costs provides an approach to combine initial construction cost and projected future costs into a single measure, called the "present value" [13]. To include this into the analysis in EnergyPlus, we assumed an inflation rate of 2,5% per year, a discount rate of 1%, an electricity price escalation rate of 0.6% (assuming that change in price for electricity and various fuels does not change at the same rate as inflation). Other annual maintenance cost, replacement cost and salvage cost are also included in the analysis (see Table 3). The current electricity price in Vietnam is 0.0728155 $/kWh [14]. Initial construction cost is calculated by EnergyPlus based on estimated component costs [15] as listed in Table 2. Other secondary construction related costs, e.g. miscellaneous cost, design and engineering fees, contractor fee, contingency, permission, bonding and insurance, commissioning fee, equipment cost, foundation cost… are included as shown in Table 3.

COMPARE THE PERFORMANCE OF HYBRID ALGORITHM AND PSO

All optimization results are presented in the Appendix. In each case, both Hybrid and PSO algorithm were employed and their performances are examined. It can be seen that Hybrid algorithm performed better than PSO in all cases with all objective functions. Moreover, Hybrid algorithm needs much less time if the same number of generation is applied. Fig.4 shows how the Hybrid algorithm worked to optimize objective function №2 and how Hooke-Jeeves algorithm effectively refined the result found by PSO. Therefore, hereafter only the results of Hybrid algorithm are examined. The results of this study also reveal that objective function played a crucial role in the final solution found. Fig.3 shows two optimum choices (1 and 2) if initial construction cost and thermal comfort is considered. These two choices are quite independent and they locate so far apart, on opposite sides of the search-space.

Table 3: Other costs and fees

Item name	Value	Frequency
Equipment cost (estimated)	1,800 $	Initial cost
Foundation cost (estimated)	2,500 $	Initial cost
Miscellaneous cost (estimated)	10 $/m2	Initial cost
Design and engineering fees	5%	Initial cost
Contractor fee	5.5%	Initial cost
Contingency fee	10%	Initial cost
Building permission, bonding and insurance	0.3%	Initial cost
Commissioning fee	0.5%	Initial cost
Maintenance cost	250 $	Every 2 years
Replacement cost	400 $	Every 10 years
Salvage cost	-50 $	Every 10 years

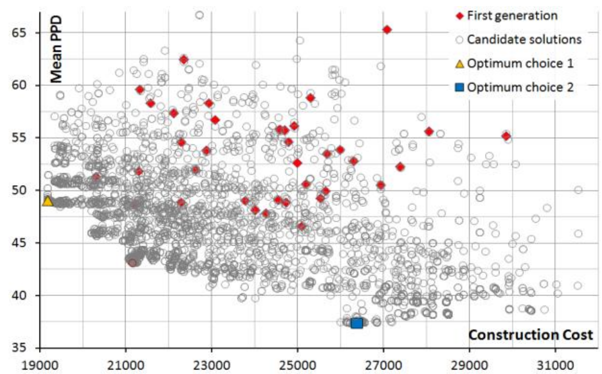

Figure 3: Candidate solutions and optimum solution found by Hybrid algorithm, objective function №1 and 2

Table 4: Effectiveness of the optimization

Objective function	Local maxima	Minima	Percentage reduction
Construction cost (objective function №1)	31528	19183	39.16%
Mean PPD	66.75	37.17	44.31%
Life cycle cost	104217	63030	39.52%

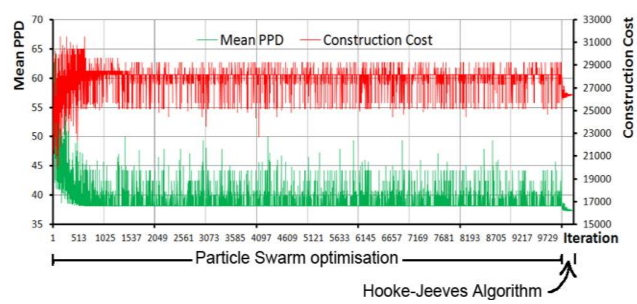

Figure 4: Optimization process of Comfort objective function №2, hybrid algorithm

EFFECTIVENESS OF THE OPTIMIZATION - COMPARISON BETWEEN THE BEST AND THE WORST CASE

In this study, the reference case does not exist. Hence the optimal solution will be compared with the worst one found during optimization process as shown in Table 4. It is obvious that the worst case herein is possibly not the global worst since optimization did not aim to look for the global worst. So the reduction reported in Table 4 maybe even greater. The analysis in Table 4 indicates that optimizations were extremely effective diagnostic tools which support designer in preliminary design stage. Optimization approach might reduce objective cost, possibly up to 40%, and ensures the selected solution to get close the optimum (or at least, near the optimum). Currently the simulation-based optimization process seems rather sophisticated as it requires coupling of the optimization engine and the building simulation tool (about 8 hours for optimization settings and coupling, in this study). However, we believe this difficulty will be resolved soon as optimization engines would be integrated into building simulation tool.

ANALYSIS OF THE NATURE OF THE OPTIMUM SOLUTION IN RELATION TO THE CLIMATE

In the objective function №1, although the comfort constraint was set (see equation 3), the solution found reached the simplest and smallest building composition, showing that comfort constraint was not strong enough. However, for the objective function №2, the optimum solution found was more balance. This solution requires maximum shading, maximum thermal resistance of external walls, roof, fenestrations, and thick thermal mass combined with full day ventilation in summer and mild season (see Table 5). The azimuth angle found (-7.5º) is not a very good solar orientation, but this orientation may enhance natural ventilation which strongly improves indoor thermal environment because Airflow network model was used in the simulations. It is a little surprising that optimum building shape was not 4m x 25m as recommended for hot humid climate, but 7.875m x 12.698m. It can be explained that long building might enhance cross ventilation, but solar heat gain augments simultaneously as building surface area increases. In hot humid climate, long building is thermally effective only if its surfaces are well shaded.

Fig. 5 shows the optimization results of AC case under objective function №3. As solar heat gain must be minimized, optimum building required good solar orientation, insulation and shading, small windows, low internal thermal mass and low infiltration (see Table 5). From Table 5, it can be seen that the differences between optimum NV case and AC case are not many. Internal thermal mass is only required in NV case, maybe for night pre-cooling when night ventilation is applied. Also, optimum building shape and building orientation were slightly different. Finally, NV case requires larger South window to enhance South East cool wind in Hanoi whereas AC case needs smallest window size to minimize heat loss and solar heat gain. In all case, a low external wall absorptance is ideal.

Table 5: Recommended design by optimization results

Parameters	NV case	AC case
Building dimension	7.9 x 12.7	9.4 x 10.7
Azimuth angle	-7.5	-1.875
South overhang	max	max
North overhang	max	max
East overhang	max	max
West overhang	max	max
South window width	3.5	min
North window width	min	min
West window width	min	min
East window width	min	min
Solar absorptance	min	min
Window crack (NV case)	min	-
Infiltration rate (AC case)	-	min
Indoor thermal mass	max	min
Floor thermal insulation	min	min
Ventilation strategy (NV case)	Full day ventilation summer and mild seasons	
Roof thermal insulation	max	max
Window type (U-value)	minimum	minimum
Wall thermal insulation	max	max

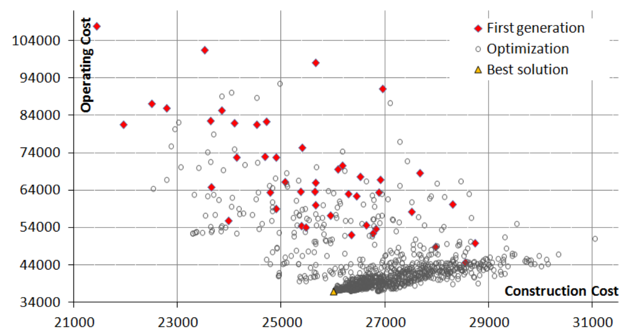

Figure 5: Candidate solutions and Optimum solution found by Hybrid algorithm, objective function №3

It is worthy to note that the objective function values found by different algorithm were very similar, but the solutions found have to some extent diverged from the optimum. In a very large search-space, no optimization algorithm could entirely ensure global optimum to be found. Therefore the selection and settings of optimization engine should be made with care and user has to ensure that some subsequence of iterations converges to a stationary point. In some cases, running many optimizations with various starting point would ameliorate the strength of the search-algorithm and help the solution found to get close to the global optimum.

CONCLUSION

This paper reports a whole process of optimizing LCH design in Vietnam. The characteristics of a low-cost dwelling and its operation were accurately modelled in detail so as to ensure the reliability of the optimization results. Optimization results show that the design requirements of naturally ventilated house and air conditioned one are not quite similar, and even in a few categories, contradictory. Comfort-optimal NV house requires good orientation dominated by dominant cool wind and appropriate ventilation scheme whereas LCC-optimal AC house needs appropriate solar orientation and strong thermal insulation or thermal resistance. Therefore, designer should take building environmental control method into account to propose an adequate design in the early stage of the project.

The study also shows the great potential of optimization in energy saving, life cycle cost and comfort improvement. The effect of optimization achieved through simulation-based optimization is actually remarkable while the computational cost and time are gradually decreased. Since the work to couple EnergyPlus - GenOpt and then to define the optimization problems takes only a few hours, optimization method shows a very promising applicability and can yield considerable economic gains.

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APPENDIX: *Optimization result (for details of the variables, refer to Table 1 and 2)*

Objective function, Algorithm, time	f(x)	$f_c(x)$	$\overline{PPD}$	$f_o^{50}(x)$	Optimum combination (variable order: x_1_ x_2_ x_3_ x_4_ x_5_ x_6_ x_7_ x_8_ x_9_ x_{10}_ x_{11}_ x_{12}_ x_{13}_ x_{14}_ x_{15}_ x_{16}_ x_{17}_ x_{18})
№1, Hybrid, 5h26’	24715	19182	48.8		3.8_9.6_0.2_0.2_0.23_0.2_1_1_1_1_0.3_0.002_600_500_406_300 _200_100
№1, PSO, 12h36’	24778	19211	49.0		-65.1_9.64_0.20_0.62_0.46_0.2_1_1_1.02_1.08_0.30_0.0025_600 _500_406_300_200_100
№2, Hybrid, 5h01’	37.17		37.2		-7.5_7.88_0.8_0.8_0.8_0.8_3.5_1_1_1_0.3_0.002_602_500_406 _302 _202_103
№2, PSO, 8h50’	37.39		37.4		70.0_9.82_0.79_0.80_0.77_0.80_3.29_1.01_1_1_0.30_0.002_602 _500_406_302_202_103
№3, Hybrid, 5h49’	63030	26011		37019	-1.9_9.38_0.8_0.8_0.8_0.8_1_1_1_1_0.3_0.05_600_500_*Not available in AC case*_302_202 _103
№3, PSO, 5h18’	63250	26043		37207	-87.0_9.97_0.20_0.79_0.46_0.57_1_1.01_1.01_1.01_0.30_0.05_600 _500_*Not available in AC case* _302_202_103