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INTER-PROGRAM COMPARISON OF A VIRTUAL MODEL OF AN UNIVERSITY BUILDING

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ABSTRACT

This paper presents the first phase of the development of a virtual model for the new Concordia Sciences Building by using the EnergyPlus program. The size and complexity of the building makes the modeling process a challenge and, at the same time, an excellent way to compare and understand the predictions of different mathematical models. During this development, an inter-program comparison of thermal loads as predicted by EnergyPlus and EE4 programs was undertaken.

INTRODUCTION

EnergyPlus, the energy analysis program, was first released in 2001. Since its first distribution, several versions were released with new features and increased accuracy of simulation results. Several researchers have compared and evaluated particular features of the program in specific context. Winkelmann (2001) modeled different window types and configurations, and concluded that EnergyPlus allows for the analysis of windows impact on peak load, thermal comfort, condensation, natural ventilation and daylighting. Methat (2005) evaluated the natural ventilation of an office building with open atrium using the COMIS module available in EnergyPlus. Fisher and Rees (2005) presented results for simulating ground source heat pump systems. However, only a limited amount of information, related to the simulation of large buildings, has been published so far. Bellemare, Kajl and Roberge (2002) modeled an institutional building with 54 interior zones and related VAV systems. They compared results predicted by EnergyPlus with those predicted by DOE-2. Ellis and Torcellini (2005) have simulated a tall building having an overall floor area of 240,000 m^2. Their analysis was mainly focusing on stack effects and the use of floor multipliers, while HVAC systems were entered through the simple purchased air option. This approach reduces the computing time since it calculates cooling and heating loads without taking into account the performance of HVAC equipment.

Witte et al. (2001) evaluated EnergyPlus for a base case building with mechanical systems using BESTEST guidelines. HVAC BESTEST is a series of steady-state tests used to evaluate the ability of whole-building simulation programs and it consists of comparative/analytical verification of a specified mechanical system applied to a simplified near-adiabatic building envelope. Results from eight commonly used simulation programs are also included as a comparison benchmark for any new software.

The Concordia Sciences Building (CSB) has a good combination of architectural and mechanical complexity and is thus a challenging building to model. The building under study was submitted for Commercial Building Incentive Program (CBIP) application, which uses the DOE-2 program as the engine for EE4 program to estimate the annual energy cost and consumption of the proposed building versus the performance of a reference building. The files provided by the mechanical consultant were helpful to create the initial input file for the EnergyPlus program in this study. This provides a platform to compare different features and simulation results of DOE-2 and EnergyPlus programs. The current analysis is limited to the heating and cooling loads of two sections of the building, sectors B and C. As a starting point, the reader should be aware that these two programs use different approaches in the estimation of zone thermal loads. The DOE-2 program uses the weighting factors method and a constant indoor air temperature to estimate the zone thermal loads in the LOADS block. The EnergyPlus program uses the heat balance method to estimate the variation of indoor air temperature within or outside the limits imposed by the thermostat and the corresponding zone loads.

BUILDING CHARACTERISTICS

The Concordia University Science building is located on the Loyola campus in Notre-Dame-de-Grace, Montreal. The building is divided in three main sectors: A, B and C (Figure 1). Sector A is the heart of the building and mainly consists of laboratories and offices. Sector C is located on the south-west side of the building and sector B is the Bryan wing, an existing building that is integrated to the science building. The majority of the envelope infrastructure has been kept and the interior has been redesigned to accommodate the new university needs.

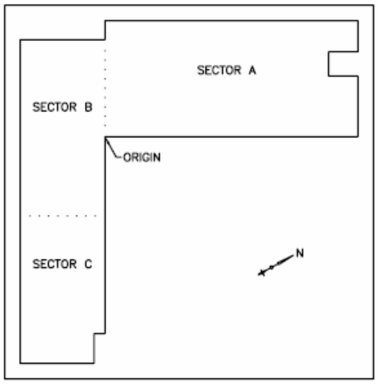

Figure 1. Building layout.

Sectors B and C, which are considered for this study, have one basement and three floors above ground, with a floor area of approximately 9,600 m^2.

MODELING ISSUES USING ENERGYPLUS

The complexity of the building has led to several modeling issues related to the estimation of thermal loads that need to be solved. Some of those issues are presented below. Given the size of the building and its vocation, there is a large number of zones and building surfaces (walls, roofs, partitions, floors) to be taken into consideration (Table 1).

Table 1
Number of zones and surfaces used in the Energy Plus program.

SECTOR	ZONES	PLENUM	SURFACES
B	18	4	286
C	21	8	333
TOTAL	39	12	619

In the EnergyPlus program, the origin of each zone must be defined in reference to the origin of the building/floor, using x, y, z-coordinates. The origin is located at the ground floor level of the bottom left corner of sector A (Figure 1).

In order to obtain more accurate results, it is recommended to include every surface within a zone. In the case of one interior partition that separates two zones, the vertices of this partition must be defined in both zones. This condition helps in obtaining the same surface area on both sides of the partition. This way, the conservation of energy principle applied to the partition is respected.

Temperature within a zone is controlled and kept close to its set point temperature, while plenum temperature is uncontrolled and fluctuates depending on heat gains and losses between the plenum and surroundings. Plenums are created for zones with return air plenum and with direct exhaust. To limit the total number of zones, all direct exhaust plenums located on the same floor and same sector are grouped together. The use of plenums has increased the complexity of the input file, but it has also simplified the definition of ceiling/floor as an internal surface. The floor layout being considerably different from one floor to another, it is a challenge to define ceilings and floors with identical superficies, in order to meet the program conservation of energy requirement. The problem is resolved by defining a plenum between the two surfaces (a ceiling and a floor). The floor of each plenum is divided in pieces to match the ceilings of the zone located below. Similarly, the ceiling of each plenum is divided in pieces to match the floor of the zones located above. In zones where there is no plenum, such as mechanical rooms, the ceiling towards adjacent spaces is left unfilled. By leaving the information blank, no heat transfer between zones is taken into consideration, however, the heat storage capacity of the object is still taken into account. The floor slab having a high thermal mass and the temperature difference between the two zones being relatively small, the amount of heat transfer between two zones located on two adjacent floors is minimal and can be neglected. This approach simplifies the model by limiting the total number of surfaces to be included in the input file.

Equipment loads and lighting loads are defined starting from data provided in the DOE-2 file, which is given in terms of installed load per zone floor area (W/m^2). However, the EnergyPlus program requires the information to be entered as the total installed lighting power (W) for each zone. Thus, the required data for EnergyPlus program were calculated using the zone area as defined through the x, y and z-coordinates and information provided in the converted file. Schedules of operation are also based on the original DOE-2 file.

Infiltration is evaluated only for above ground perimeter zones. Air tightness in large building is extremely hard to evaluate. As a guideline for model input, Kaplan & Canner (1992) recommend using 0.2 (l/s)/m^2 of gross exterior wall area, while calculations based on the Model National Energy Code for Buildings (MNECCB 1997) are based on 0.25 (l/s)/m^2. Since the latter value is also used as default in EE4/DOE-2 for CBIP applications, the same value is input in EnergyPlus. Infiltration is assumed to occur only when the HVAC systems is OFF. When the system is ON, no infiltration occur due to building pressurization.

Since the DOE-2 program does not consider the air ventilation rate in the calculations of thermal loads in the LOADS block, the EnergyPlus input file was modified to reflect the same assumption.

By incorporating all building information together, the EnergyPlus program predicts the hourly heating and cooling loads for each zone for the simulation period.

INTER-PROGRAM COMPARISON

The development of input files for EnergyPlus and EE4 programs is rather different. The EnergyPlus input file is built using the IDF editor, no interface being available at the start of this project. EE4 on the other hand has a complete interface that assists in the data entry process. The EnergyPlus input file has 51 zones and 619 surfaces. Each annual simulation of cooling and heating loads of all spaces takes 1h15 to 1h30 minutes on a laptop with Intel Pentium M of 1.4 GHz, and 512 MB of RAM, or between 88 and 106 seconds/zone. The EE4 input file has 29 zones, and each annual simulation takes about 1 minute, or 2 seconds/zone.

A number of runs were required to achieve practical results. To ease the entry process for HVAC systems in EnergyPlus, compact HVAC systems were originally used. Compact HVAC objects provide a shorthand way of describing standard HVAC system configurations. Those models include built-in default data and user input data entry for basic system options. EnergyPlus automatically sets up loops, branches and node names for the specified objects. Each object can be expanded in future runs to further detailed each component. This approach abbreviates and simplifies the initial modeling. The information about schedules and HVAC systems is based on data obtained from the original EE4/DOE file. In the EE4 program, the peak loads exclude the outside ventilation air loads and are based on constant indoor space temperature, which is set to 22°C for both the cooling and heating season. In EnergyPlus, all operating schedules were entered based on MNECB default schedules for this type of building. For example, the indoor space temperature fluctuates according to the zone temperature schedule. During the heating season, the zone temperature is set to 22°C during occupancy and 18°C at night time. During the cooling season, the zone temperature is set to 24°C during occupancy and 35°C at night time. Since no outside air ventilation is included in EE4, it is also set to zero in the EnergyPlus input file.

Results presented in Figure 2 show similar trends of variation of monthly cooling and heating loads as predicted by both programs. On the heating side, EnergyPlus gives a higher heating load, and the difference between EnergyPlus and EE4 is almost constant throughout the year. On the cooling side, EnergyPlus gives a higher cooling load during the winter and shoulder season months and lower load in the summer months.

The monthly variations of cooling and heating loads are also compared when the cooling zone temperature is set to 22°C instead of 24°C, as specified in MNECB. This reflects the conditions of the EE4 program in the LOADS block. The night time set back is still maintained at 35°C. Figure 3 shows the revised monthly variations under this new set of zone conditions. The prediction of heating and cooling loads by both program still show similar trend. The heating loads predicted by EnergyPlus are still higher throughout the year, with an annual relative difference of 21% comparatively to 34% previously. On the cooling side, only minor variations were noticed by setting the zone temperature to 22º during occupancy. The annual difference in cooling loads predicted by both programs is still within 5%. Although the annual predictions from both programs are within acceptable limits and the montly variation shows similar trends, further investigation is performed.

Although special attention was paid to input data, some architectural features and system schedules are slightly different from one program to another. Differences between surface areas of some building components and internal gains were noticed (Table 2). After several verifications, it was concluded that those differences come from different methods of defining the input data: the 3-D definition of each component is used in EnergyPlus, while the gross surface area is used in EE4. Table 2 shows, for instance, that overall windows area is 10% larger in EnergyPlus than in EE4, while the floor area is 8% larger.

Table 2
Comparison of surface areas used by both programs.

ITEM	DETAILS	RELATIVE ERROR (%)
Geometry	Floor area	8
	Wall area – excl. plenums	29
	Wall area - incl. plenums walls	10
	Window area	17
Internal Gains	Maximum Occupancy	2
	Lighting load	3
	Equipment Load	9

Both programs use the same installed lighting load, between 7 and 10 W/m^2, depending on the zone, and the same equipment load, between 2 and 10 W/m^2.

The exterior walls have the overall thermal resistance between 2.6 and 3.1 m^2·°C/W and roofs between 2.8 and 4.2 m^2·°C/W. The envelope components are defined in EE4 using the MNECB library. In EnergyPlus, each layer and window component are entered separately and then combined for each construction type. The enclosure components are first described based on the DOE-2 file data generated by EE4 and then revised using the example file provided with EnergyPlus to ensure the reliability of the entered information. Table 3 shows the relative error (R.E.) between the thermal conductance of some building components, as used by both programs.

Table 3
Comparison of thermal conductance of building components used by both programs.

ENVELOPE COMPONENT	THERMAL CONDUCTANCE [W/m²·K]		
	EnergyPlus	EE4	R. E. (%)
FLOOR-I-11	0.32	0.34	-6
WALL-0	0.33	0.36	10
WALL-5	0.46	0.39	16
WALL-8	0.45	0.40	12
WALL-12	3.09	2.21	28
WALL-13	0.41	0.35	14
WALL-14	0.41	0.34	17
WALL-15	0.33	0.36	-9
ROOF-III-6	0.25	0.24	3
ROOF-III-9	0.32	0.34	6

Two types of glazing are present: the double low-E clear with film 6mm/6mm air gap (glazing 0) and the double low-E clear 6mm/13mm air gap (glazing 1). Each glazing component is first defined in EnergyPlus and then combined to build the glazing system. In EnergyPlus, the SHGC is calculated by the program based on the fenestration assembly. In the EE4 program, the fenestration U-values and the solar heat gain coefficent (SHGC) are entered manually. Table 4 presents the glazing information used by both programs.

Table 4
Comparison of thermal properties of glazing systems used by both programs.

ITEM	DETAIL	EnergyPlus	EE4	R.E (%)
Glazing 0	U_{RSI}	2.297	2.21	4
	SHGC	0.419	0.38	9
Glazing 1*	U_{RSI}	1.772	1.73	2
	SHGC	0.563	0.38	32

In terms of thermal conductance, the values used by both programs are within 4%, however, a large difference of 32% is noticed with respect to the solar heat gain coefficient of glazing 1. This difference is expected to lead to higher cooling loads, as predicted by EnergyPlus, of all zones where this type of glazing is present.

Comparison between peak heating and cooling loads of several zones, as predicted by both programs, is presented in Table 5. For both cooling and heating, the peak load in EnergyPlus is higher than the one calculated by EE4. The night setback temperature has a major impact on the peak value. In EnergyPlus, in most zones the peak cooling load is predicted early in the morning, i.e. when the set point is set back to 24°C from 35°C. In EE4, the peak cooling loads mostly occur late in the afternoon due to thermal mass effect and constant set point temperature. The difference in solar heat gain coefficient for glazing 1 also accounts for some of the discrepancies in peak cooling load for those zones using this type of glazing, which are indicated with a star (*) in Table 5.

The cooling loads of zone no.16, a fully interior zone, are compared in Figure 4, to investigate the impact of different calculation methods in the absence of exterior surfaces. The peak load is predicted by the EnergyPlus program early in the morning, as discussed above, when the zone set point is set back for occupancy conditions. EnergyPlus prediction is about 48% higher than the peak load from EE4.

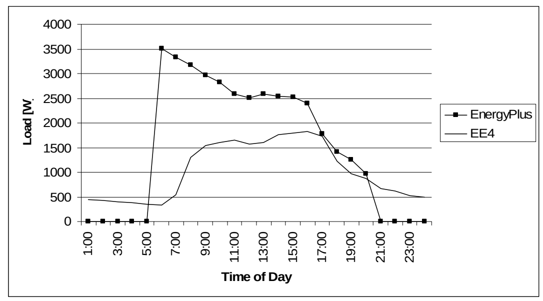

Figure 4. Cooling load of core zone no.16 using default schedules.

Schedules for zone no.16 were then modified to have a constant zone temperature set point, as used in EE4.

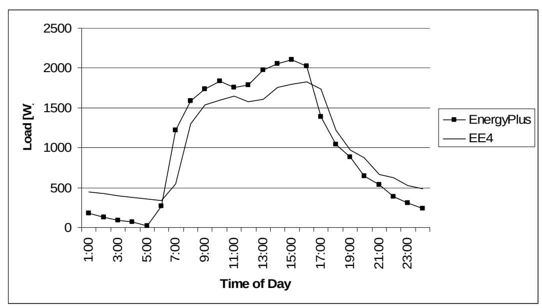

Figure 5. Cooling load of core zone no.16 using revised schedules.

Under the revised schedule, the variation of daily loads, as predicted by both programs, is similar (Figure 5). EnergyPlus prediction is about 14% higher than the peak load from EE4 comparatively to 48% previously. Since the conditions are now identical, the difference in peak loads is supposed to come from the difference in mathematical models used for cooling load calculations. The exterior environment plays no role in this difference, since zone no.16 is a core zone with no exterior surfaces. To further investigate this issue, the schedule of internal gains of zone no.16 is modified to introduce an instanteneous lighting load of 10 kW at 9:00 on the summer design day. It is assumed that 85% of load goes to the space and 15% to the plenum. Figure

6 shows the response of zone cooling load as predicted by both programs.

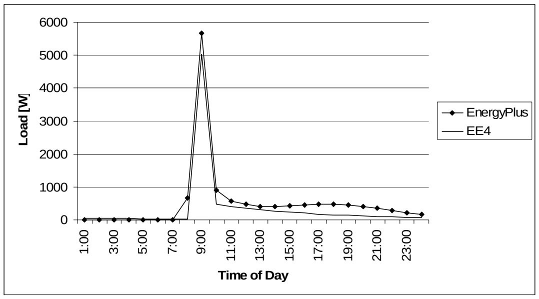

Figure 6. Instantaneous load response for zone no.16.

Since the peak load predicted by EnergyPlus is about 11% higher than in EE4, and the subsequent hourly loads are also higher, it is concluded that the difference in mathematical models, including default values, is the cause of such difference in peak cooling loads.

Based on the original set of schedules, i.e. default MNECB schedules, total zone and building loads are compared in Table 6. Most likely the difference in cooling and heating loads is due to the difference in night time setback conditions and mathematical models.

CONCLUSION

Developing a virtual model for a large scale building using EnergyPlus is a challenging process. Initially, the Concordia University Sciences building was modeled in EnergyPlus based on detailed schedules and components information. Although the annual building loads are estimated by both programs within 20% and the monthly loads have similar trends of variation, further reduction of this difference may be obtained if the EnergyPlus input file is modified using default schedules of the EE4/CBIP program. The change of input file to achieve identical operating conditions in EnergyPlus compared to EE4 is time intensive and complex.

Data comparison between EnergyPlus and EE4 were performed both on inputs and outputs. The annual total building load is lower in EnergyPlus while the peak load is higher for most zones. Futher investigation including the addition of sector A, the simulation of HVAC systems and plants, and the comparison with measured data is under way.

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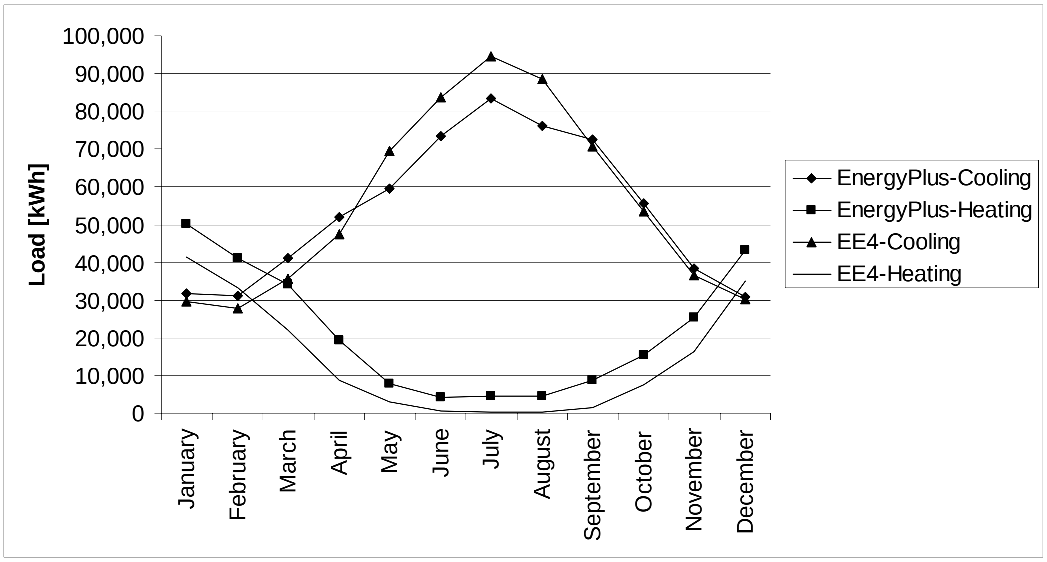

Figure 2. Monthly thermal loads of sectors B & C using default schedules.

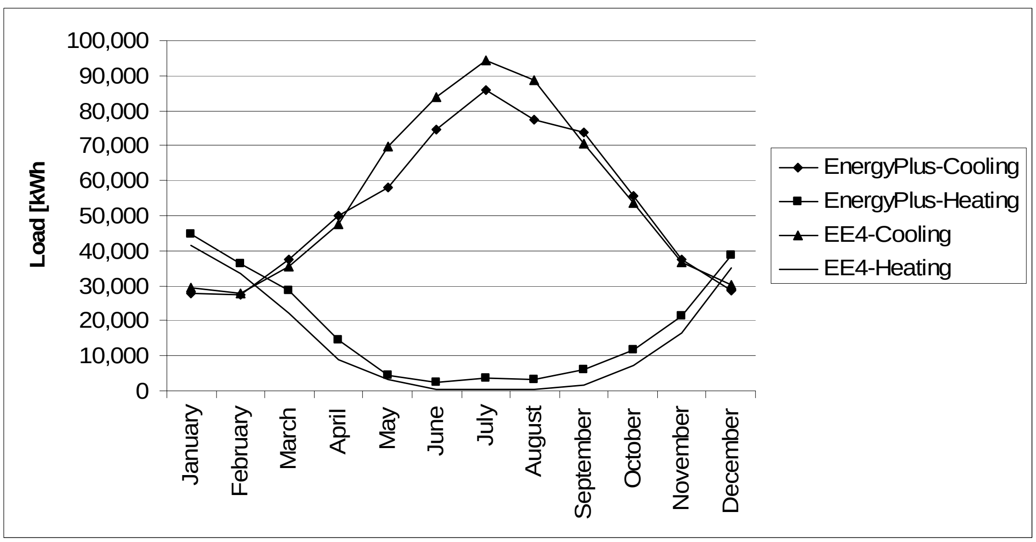

Figure 3. Monthly thermal loads of sectors B & C using a cooling set point of 22ºC.

Table 5

Comparison of peak thermal loads using default schedules.

	COOLING [KW]			HEATING [KW]		
ZONE NUMBER	**EnergyPlus**	**EE4**	**R.E. (%)**	**EnergyPlus**	**EE4**	**R.E. (%)**
Zone-1	16.3	7.3	55	14.5	8.1	44
Zone-2*	10.5	8.2	22	3.0	1.8	41
Zone-3	13.1	4.8	63	1.9	0.0	-
Zone-4	11.2	4.0	65	3.1	0.0	-
Zone-5	1.9	0.8	57	1.2	1.2	-4
Zone-6*	9.2	6.3	31	5.3	4.9	7
Zone-7*	19.6	7.8	60	5.3	0.0	-
Zone-8	4.0	1.4	66	0.6	0.0	-
Zone-9	3.3	0.7	79	2.2	2.4	-9
Zone-10*	14.8	10.7	28	3.8	3.6	4
Zone-11	43.8	26.4	40	14.6	22.5	-54
Zone-12	13.4	11.8	12	5.1	9.8	-90
Zone-13	13.9	4.7	66	1.6	0.0	-
Zone-14	1.8	0.8	58	0.5	0.0	-
Zone-15*	15.2	9.2	40	11.9	9.0	25
Zone-16	3.5	1.8	48	1.4	0.0	-
Zone-17	14.0	9.1	35	4.5	5.4	-21
Zone-18	13.3	4.3	67	1.4	0.0	-
Zone-19	12.4	7.3	41	3.3	6.1	-85
Zone-20*	36.4	11.9	67	20.4	11.2	45
Zone-21*	35.6	15.8	56	6.2	0.0	-
Zone-22	13.7	3.6	73	4.3	0.0	-
Zone-23*	18.8	11.2	40	14.3	14.0	2
Zone-24	5.2	3.9	26	3.4	1.8	45
Zone-25	10.0	4.0	60	1.3	0.0	-
Zone-26*	37.7	12.7	66	23.9	14.0	42
Zone-27	11.4	8.4	26	6.1	9.3	-53
Zone-28	13.4	4.4	67	2.1	0.0	100
Zone-29	13.1	9.1	31	5.7	5.4	5

Table 6
Annual thermal loads of all occupied zones of sectors B & C using default schedules.

	COOLING [kWh]		HEATING [kWh]	
ZONE NUMBER	**EnergyPlus**	**EE4**	**EnergyPlus**	**EE4**
Zone-1	30,503	9,440	18,021	16,004
Zone-2*	20,179	29,740	1,759	238
Zone-3	21,508	47,652	22	0
Zone-4	24,440	34,003	371	0
Zone-5	2,887	625	1,014	2,686
Zone-6*	15,759	12,316	3,319	7,165
Zone-7*	28,748	52,175	855	0
Zone-8	5,812	13,386	7	0
Zone-9	4,070	378	1,454	6,799
Zone-10*	28,748	34,745	911	896
Zone-11	62,414	54,517	15,596	28,160
Zone-12	22,568	26,579	2,561	9,912
Zone-13	18,942	46,331	25	0
Zone-14	2,763	3,259	82	0
Zone-15*	19,514	15,663	15,046	11,614
Zone-16	5,542	7,742	391	0
Zone-17	27,890	27,737	1,506	3,029
Zone-18	21,389	42,564	17	0
Zone-19	21,627	20,930	1,548	4,922
Zone-20*	42,283	18,397	20,183	16,369
Zone-21*	59,326	95,320	188	0
Zone-22	11,030	15,100	3,919	0
Zone-23*	23,602	15,781	17,379	23,232
Zone-24	4,793	9,748	5,908	1,820
Zone-25	11,769	28,384	320	0
Zone-26*	37,833	17,912	24,830	23,103
Zone-27	15,565	20,649	4,769	11,093
Zone-28	18,171	42,745	444	0
Zone-29	20,408	27,341	2,410	3,139
Total	**630,230**	**771,160**	**144,756**	**170,181**