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Research Paper

Optimum Building Geometric Properties Based on Solar Energy Receiving by Vertical Surfaces in the Cold Climate of Iran

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Abstract
The physical-geometric characteristics of buildings have a very important role in the regulation of microclimate conditions and the thermal situation of interior and exterior spaces of buildings. This research aims to investigate the amount of received direct radiation energy of vertical surfaces in buildings and determine the appropriate form, aspect ratio, and orientation of buildings in the cities of Ardabil, Tabriz, Sanandaj, and Hamedan in the Northwest of Iran with cold climate. For this purpose, six polygonal forms (with the same floor area and height) including square, rectangle, hexagon, octagon, hexadecagon (16-sided), and triacontadigon (32-sided) were selected to be examined. Afterward, the specified optimal form(rectangle) was surveyed with the aspect ratios of 1:1.2, 1:1.4, 1:1.6, 1:1.8, 1:2 and in the orientations of 180º, 165º, 150º, 135º, 120º, 105º SE and SW. Using the "Law of Cosines" computational method, the amount of received direct energy on vertical surfaces has been calculated and processed, for different months and during the cold and hot periods of the year. The results of the research show that the appropriate form of the buildings in the studied cities is a rectangle with an east-west orientation. The most suitable aspect ratio for the rectangular form with east-west orientation in the cities of Ardabil, Tabriz, Sanandaj, and Hamedan is 1:1.2. The appropriate orientation for the determined aspect ratio in the studied cities is 165° Southeast.

Keywords: *Optimal form, Aspect ratio, Building orientation, Cold climate, Solar energy.*

1. INTRODUCTION

The design of climate-compatible architectural and urban spaces to benefit from clean and renewable energy (including solar energy), causes to reduce the demand and consumption of fossil fuels and their environmental pollutants. Nowadays, by properly design of the form and orientation of urban buildings and spaces, the required energy for providing heat, cooling, and lighting, could be reduced. The best form of the building is a form that loses the least amount of heat in winter, and also receives the least amount of heat from the sun and surrounding areas in summer. In the cold climate, the maximum use of solar radiation is considered, and buildings in this climate should be oriented in such a way to receive maximum solar energy throughout the year. Furthermore, contacting the outer surfaces of the building with the prevailing wind in cold periods should be minimized.

Most of the studies about the relationship between building form and energy, emphasize energy consumption and management control and reducing fossil fuels demands. The studies conducted on the relationship between building form and energy consumption can be categorized into two types of research: One is to compare the influences of different building forms on energy use, whereas the other is to develop simple models for estimating the energy use of various building forms (Wei et al., 2016). Since the development of energy simulation tools, the effect of the shape and form of the building on energy performance has been widely studied. Several studies

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have shown that there is a correlation between compression (the ratio of the area of the external envelope to the volume) of the building and its energy consumption, and the forms with high compression rates have lower energy consumption, especially in a cold and hot climate (AlAnzi et al., 2009; Ourghi et al., 2007). Building shape also has a significant impact on energy costs (Mingfang, 2002; Ourghi et al., 2007; Pacheco et al., 2012). AlAnzi et al. (2009) used compression as an index in assessing the effect of shape on the energy performance of a building. The research of Depecker et al. (2001) aimed at relating the heating consumption of the buildings with their shape. Their research results showed that energy consumption is inversely proportional to the compactness (weak shape coefficient) in case of cold severe and scarcely sunny winters.

The form and external envelope of the building are the most important effective parameters on internal climate (Hemsath & Alagheband Bandhosseini, 2015; Oral & Yilmaz, 2003) and the size and orientation of the external envelope have a direct effect on the thermal performance of the building. Determining the form, orientation and proper structure of the external envelope can reduce the building energy consumption by 40% (Wang et al., 2006). In examining the impact of the aspect ratio on energy efficiency in multi-story residential buildings in Canada, the results showed that the aspect ratio and orientation have a major impact on energy efficiency. The best aspect ratios in the studied cities were the ratio of 1:1.3 and 1:1.5 with east-west orientation (McKeen & Fung, 2014). Koranteng & Abaitey, (2010), indicated that for energy performance of residential buildings the square form is the most energy-efficient whiles elongated forms used much energy; The forms started to warm up when they were oriented towards the east and west. Hachem et al. (2011), in the assessment of the geometric form effect on the solar potential of housing units, stated that the number of shading facades in self-shading geometries and their relative dimensions are the major parameters affecting solar incident and transmitted radiation. They showed that the ratio of shading to shaded facade lengths and the angle between these two facades affect the solar radiation incident on facades and roofs.

Saylan et al. (2002) in an investigation on solar energy potential in big cities of Turkey, concluded that during summer, the monthly mean solar energy potential on vertical surfaces comes from the east and west more than in other orientations in all the cities. However, during winter, it comes from the south, and the highest solar energy is received in Izmir, where the average annual global radiation attains its maximum. Additionally, north-oriented surfaces receive between 65% and 75% lower total solar energy than other orientations in all the studied cities. Teoman Aksoy & Inalli, (2006), investigated the building passive design parameters in a cold region. They concluded that for heating demand, buildings with a square shape have more advantages, and the most suitable orientation angles are 0°C and 80°C for the buildings having shape factors (the ratio of building length to depth) 2/1 and 1/2, respectively. Tokbolat et al. (2013), showed that the orientation of a building can significantly affect the energy usage rate. The south and north-facing directions are found to be the most energy efficient (initial orientation is 35º toward the northeast). Depecker et al. (2001) and also Albatici & Passerini, (2011), indicated that more compactness does not necessarily lead to less heating energy demand in a warm climate. The research of Ling et al. (2007), in a hot-humid climate, revealed that the circular form with a width/length ratio (W/L: 1:1) is the most optimum in minimizing total solar insolation. The square form with a W/L ratio of 1:1 in a north-south orientation receives the lowest annual total solar insolation compared to the other square forms. This optimum form (a circular form with a W/L ratio of 1:1 (CC 1:1)) receives the highest amount of solar insolation on the east-oriented wall, followed by the south, west, and north-orientated walls respectively. Zerefos et al. (2012), examined the behavior in energy consumption of buildings that have polygonal and prismatic envelopes in Mediterranean climates. Their research revealed that the prismatic-formed building has lower solar gains compared to its orthogonal counterpart and consumes less energy in an annual cycle. Also, the results showed a mean annual energy consumption difference of 7.88% in favor of the prismatic building envelope. Furthermore, depending on the orientation, the difference in annual energy needs has a range between 2.51% and 16.01%. The optimal building orientation is essential for determining optimal façades for the strategic placement of both complex and simple designs.

The seasons of the year are different in terms of radiation angle due to the change in the rotation of the Earth around the sun, therefore, the amount of received solar energy varies throughout the year; In this way, according to the orientation of the building, the amount of solar energy radiated to its walls changes during the year and at different times of the day. The sun's radiation before reaching the earth is exposed to absorption, reflection, and passing through the atmosphere (Gueymard, 2000). To calculate the received solar energy by the angular surfaces exposed to sunlit, it is necessary to recognize the components of direct and scattered beams. However, because most meteorological stations only measure the total radiation on horizontal surfaces, the distribution of radiation on horizontal surfaces and the total radiation on angled surfaces are not available in almost all parts of the world and it is necessary to use theoretical models to estimate it (Mondol et al., 2008). In various computational models, one or a set of the following factors has been used to estimate the intensity of solar radiation at a point on the earth's surface: sun exposure rate (Angstrom, 1924; Duffie & Beckman, 2006; Prescott, 1940), sunshine hours, maximum temperature, and relative humidity (Sabbagh et al., 1977), altitude angle and sun exposure rate (Coppolino, 1990), altitude above sea level (Samimi, 1994), Sun exposure rate, latitude, relative humidity and temperature (Neuwirth, 1980), cloud factor and zenith angle (Paltridge & Proctor, 1976), latitude, altitude, sunshine hours and average temperature (Sozen et al., 2004), sunshine hours, precipitation, dew point temperature, relative humidity, temperature, and air pressure (Kadir, 2009; Maghrabi, 2009; Wu et al., 2007).

Based on the research background, the most important parameters required to calculate the amount of direct energy received by surfaces include the latitude, azimuth angle, altitude angle, zenith angle, declination angle, solar hour angle, day length, and sunshine hours. Since these parameters are different in each latitude and climate, therefore it is necessary to study the amount of radiant energy received by vertical surfaces in most cities in Iran, especially in cities with special geographical and climatic conditions such as Ardabil, Tabriz, Sanandaj, and Hamedan.

The present study is conducted to answer this question: what are the optimal form, aspect ratios, and directions of building construction based on solar radiation in cold-climate cities? This study aims to determine the optimal form, aspect ratios, and orientation of building in accordance with the cold climate by surveying the amount of radiation energy received by vertical surfaces of buildings in the cities of Ardabil, Tabriz, Sanandaj, and Hamadan in Northwest Iran. Hereof, it seemed reasonable to hypothesize that in the cold climate of northwestern cities, to receive optimal solar energy, a rectangular shape with a lower W/L ratio, and an east-west orientation, is efficient.

2. MATERIALS AND METHODS

The optimal form, aspect ratio, and orientation of the buildings are determined, based on the maximum amount of differences between received energy, in cold and hot periods of the year or the maximum amount of sunlight energy in the cold period.

The steps taken in this study to achieve the research goal are as follows:

1. Calculating the received energy of six different forms including square, rectangle, hexagon, octagon, hexadecagon (16-sided), and triacontadigon (32-sided), and then finding the optimal form in the studied cities.
2. Calculating the energy received by the optimal form(rectangular) with different aspect ratios of width to length, including 1: 1.2, 1: 1.4, 1: 1.6, 1: 1.8, and 1: 2, and detecting the optimal ratio of W/L.
3. Calculating the received energy by the optimal form and aspect ratio, in different orientations including 180º, 165º, 150º, 135º, 120º, 105º SE, and SW, and determining the optimal orientation.

To determine the optimal form, aspect ratio, and orientation of the building in terms of receiving the sun's radiation, the hour angle, the declination angle, the azimuth angle, and the altitude angle were calculated at different hours of the day in the cities studied. The amount of received direct radiation energy on vertical surfaces has been calculated and processed through theoretical and actual calculation, using the "Law of Cosines" computational method for different months, in terms of the cold and hot periods of the year.

2.1. Study Area

Based on the Koppen-Geiger climate classification system, the cities of Ardabil, Tabriz, Sanandaj, and Hamedan have located in cold (Dfb) climates. These cities have a cold - dry climate, with cold winters and hot and dry summers. In these cities, fluctuations and temperature differences between day and night are high, the humidity is low and they have heavy snowfall (Ganji, 1954).

Using hourly changes of temperature every month and thermal comfort zones for humans, the months when a person needs heat or cold were determined. Based on the Olgyay bioclimatic chart, the "shading line" is set at 21°C. In this study, the temperature of 21 degrees has been determined as the base temperature to specify the hot period (when shading is required) and cold period (when radiation is required). Therefore, in Ardabil, Tabriz, Sanandaj, and Hamedan respectively during 65%, 68%, 61%, and 68% of the year sun radiation is required, and for 35%, 32%, 39%, and 32% of the year the shading is needed. Considering that the duration of cold months in the studied cities is more than the hot months, determining the optimum form, aspect ratio, and building orientation, is based on receiving maximum solar energy in the cold duration of the year.

2.2. Method of Calculating Radiation Energy

The amount and intensity of the beam or wave that reached a surface are equal to the multiplication of the amount and intensity of the beam in a perpendicular position by the cosine of the angle between the normal direction (the line perpendicular to the surface) and the stretch of the radiated beam. This equation is known as the 'Law of Cosines' (Watson & Labs, 1983). The amount of direct solar radiation reaching a surface on earth is calculated according to the following equations (Table 3).

Table 1. The Ratio of the External Envelope Area in the Studied Forms

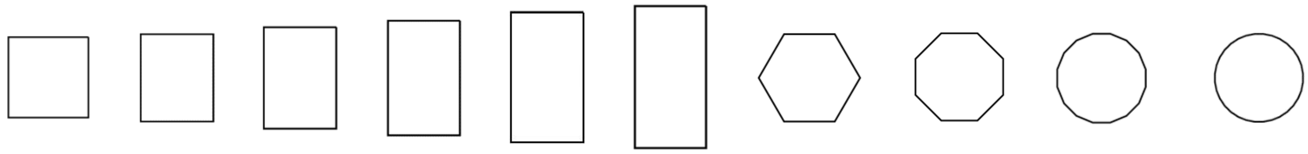
Square	Rectangle (NS & EW Orientation)					Hexa	Octa	Hexadeca	Triaconta
	1:1.2	1:1.4	1:1.6	1:1.8	1:2				
									
1.00	1.004	1.014	1.027	1.043	1.06	0.93	0.91	0.892	0.888

Table 2. Geographical-Climatic Characteristics of the Studied Cities (IRIMO, 2018)

	Latitude	Longitude	Elevation (m)	Annual Temp.(°C)			Ave. RH (%)
				Max.	Min.	Ave.	
Ardabil	38° 15´ N	48° 17´ E	1332	15.3	2.8	9.05	71
Tabriz	38° 5´ N	46° 17´ E	1361	18	6.9	12.45	54
Sanandaj	35° 20´ N	47° 0´ E	1373	21.4	5.5	13.45	47
Hamedan	35° 12´ N	48° 43´ E	1679	19.2	2.9	11.05	53

Table 3. The Equations of Calculating Direct Solar Radiation Energy

1	$I_S=I_N\times Cos\theta$	I_S, is the intensity of the radiation on the surface (BTU/H/FT2); I_N, is the intensity of the sun's radiation on the perpendicular surface to the sun's ray (BTU/H/FT2); and also θ is the angle between the sun's ray and the perpendicular line to the surface. the value of I_N is calculated by equation 2 (Ashrae, 1995).
2	$I_{DN}=I^\circ \exp(-\alpha /Sinh)$	I_{DN}, is the heat produced by direct and perpendicular sunlight; I°, is the solar constant; α, is the extinction coefficient (Ashrae, 1995) and h, is the angle of the sun's radiation.
3	$Cos\theta=Cosh\times Cos(Z-N)$	θ, is the angle of intersection between the sun and the line perpendicular to a vertical surface (wall), which is determined by the spherical cosine formula (Watson & Labs, 1983). h, is the altitude angle of the sun's radiation; Z, is the azimuth angle and N, is the direction angle to the wall, which is in the clockwise direction from the North and is measured in degrees. To determine the azimuth angle and the radiation angle of the sun at each hour of the day in equations 2 and 3, at first, it is necessary to calculate the solar hour angle and declination angle during the day.
4	$\omega=15\times(12-T)$	ω, is the solar hour angle; T, is the desired time. The beginning point of the hour angle measurement is solar noon. The measure of the angle varies from +180º to -180º. The measure of the hour angle in the northern hemisphere is positive in the morning and negative in the afternoon. Considering that the Earth rotates around its axis every 24 hours, an angle passes 15 degrees longitude per hour.
5	$\delta=23.45\times Sin[360((364+n)/365)]$	δ, is the declination angle during the day. The declination is the angular position of the solar noon concerning to the plane of the equator, and its measure varies between +23.45º and -23.45º. n, is the number of days from the beginning of the solar year.
6	$T_d=2/15ArcCos(-tan\delta\times tan\text{Ø})$	T_d, is the day length, which is symmetric to the solar noon, and the Earth moves around its own axis 15º per hour. δ, is the declination angle, and Ø, is the latitude in degrees.
7	$Sinh=(Cos\text{Ø}\times Cos\delta\times Cos\omega)+(Sin\text{Ø}\times Sin\delta)$	h, is the altitude angle of the sun's radiation. The altitude angle is the vertical angle between the horizon and the line connecting to the sun; Its measure varies from zero to 90º.
8	$SinZ=(Cos\delta\times Sin\text{Ø})/cosh$	Z, is the azimuth angle. The solar azimuth angle is the angular displacement from the South of the beam radiation projection on the horizontal plane; Its measure varies from +180º to -180º. This angle is negative from the South to the east, and positive to the West.

3. RESULTS AND DISCUSSION

Using the “Law of Cosines” computational method, firstly, the amount of direct energy received on the vertical surfaces was calculated theoretically in each hour of the day and 32 geographical directions for the studied cities, then the amount of actual direct energy received on vertical surfaces is obtained from the multiplication of theoretical received energy by the percentage of sunshine hours in different months. Finally, based on the comfort temperature (21ºC), the amount of received energy was calculated separately for hot and cold periods. Table 4 shows the average day length and percentage of sunshine hours in the studied cities.

In Tables 5 and 6, the total (annual) energy received by vertical surfaces is calculated and actualized by the percentage of sunshine hours percentage. Also in these tables, the amount of energy received by the vertical walls in cold and hot periods and the differences between them are calculated.

According to the results of Tables 5 and 6, the highest amount of annual received energy in Ardabil is at 168.75° SE and SW and in the cities of Tabriz, Sanandaj and Hamedan are at 157.5° SE and SW. The lowest amount of annual received energy in all the cities is at the north and 15° NE and NW. The highest amount of energy received in the cold period, in Ardabil (77.2%) is at 168.75° SE, in the cities of Tabriz (76.1%) and Hamedan (78.9%) are at 157.5° SE and in Sanandaj (73.2%) is at 135° SE. Also, the highest amount of differences between received energy in cold and hot periods of the years in Ardabil is at 168.75° SE and in the cities of Tabriz, Sanandaj and Hamedan are at 157.5° SE. The amount of energy received by the vertical surfaces of polygonal forms is calculated in terms of cold and hot periods and presented in Tables 7 and 8. Based on the maximum amount of received energy in the cold period, the optimal forms which are compatible with the climate of the region, are determined.

Table 4. The Percentage of Sunshine Hours in Studied Cities (IRIMO, 2018)

		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Ardabil	Ave. day length*	9.8	10.9	12.1	13.3	14.3	14.7	14.2	13.3	11.6	10.8	9.8	9.3
	Ave. sunshine hours	4.9	5.3	5.5	6	7.9	9.5	9.8	8.8	7.3	6.2	5.1	4.7
	sunshine hours (%)	49.6	48.5	45.5	44.8	55.5	64.6	68.6	66.8	63	57.3	52.4	50.4
Tabriz	Ave. day length*	9.8	10.9	12.1	13.3	14.3	14.7	14.3	13.3	11.6	10.8	9.7	9.3
	Ave. sunshine hours	4.2	5	5.8	6.5	8.7	10.8	11.4	10.9	9.7	7.7	6	4.6
	sunshine hours (%)	42.8	46.2	48	48.6	60.6	73.4	79.7	82.2	83.6	71.6	61.7	49
Sanandaj	Ave. day length*	10	11	12.1	13.2	14	14.4	14	13.1	11.6	10.9	10	9.6
	Ave. sunshine hours	5.7	6.3	6.7	7.4	9.2	10.9	10.9	10.9	9.8	8.7	6.8	5.6
	sunshine hours (%)	57	57.1	55.8	56	65.4	75.7	77.9	82.9	84.6	79.6	67.6	58.7
Hamedan	Ave. day length*	10.1	11	12.1	13.2	14	14.4	14	13.1	11.6	10.9	10	9.6
	Ave. sunshine hours	4.4	5.2	6	6.6	8.5	10.9	11	10.6	9.7	8.1	6	4.4
	sunshine hours (%)	44	47.4	49.7	50.1	60.9	76	78.5	80.7	83.3	74.1	60.3	46.2

*The day length is calculated by the writers.

Table 5. The Amount of Energy Received by Vertical Surfaces in Ardabil and Tabriz (BTU/H/FT2)

Orientation	Ardabil						Tabriz					
	Total	period				Dif.	Total	period				Dif.
		Cold	%	Hot	%			Cold	%	Hot	%	
North	310.8	162.4	52.2	148.4	47.8	14	350.6	207.1	59.1	143.5	40.9	63.7
11.25	448.1	251.6	56.1	196.5	43.9	55.1	508.2	324.2	63.8	184.0	36.2	140.2
22.5	815.3	466.3	57.2	349	42.8	117.2	928	596.1	64.2	331.8	35.8	264.3
33.75	1319.5	798.7	60.5	520.8	39.5	277.9	1508.2	1015.6	67.3	492.6	32.7	522.9
45	1922.8	1163.9	60.5	758.9	39.5	405	2198.7	1491	67.8	707.8	32.2	783.2
56.25	2618.9	1631.3	62.3	987.5	37.7	643.8	2986.6	1984.8	66.5	1001.8	33.5	983.1
67.5	3356.7	2141	63.8	1215.7	36.2	925.3	3816.9	2551.3	66.8	1265.6	33.2	1285.8
78.75	4086.7	2711.2	66.3	1375.4	33.7	1335.8	4635.3	3197	69	1438.3	31	1758.8
East	4716.3	3142	66.6	1574.3	33.4	1567.7	5335.2	3634.3	68.1	1700.9	31.9	1933.4
101.25	5373.8	3706.1	69	1667.7	31	2038.4	6062.4	4253	70.2	1809.4	29.8	2443.6
112.5	5881.5	4184.5	71.1	1697	28.9	2487.5	6616.3	4767.9	72.1	1848.4	27.9	2919.5
123.75	6284.3	4575.3	72.8	1709	27.2	2866.3	7050.8	5159.7	73.2	1891.1	26.8	3268.6
135	6588	4859.5	73.8	1728.5	26.2	3131.1	7371.7	5457.9	74	1913.8	26	3544
146.25	6805.2	5149	75.7	1656.2	24.3	3492.7	7591.2	5757.1	75.8	1834.2	24.2	3922.9
157.5	6910.7	5276.1	76.3	1634.5	23.7	3641.6	7687.2	5847	76.1	1840.2	23.9	4006.8

Orientation	Ardabil						Tabriz					
	Total	period				Dif.	Total	period				Dif.
		Cold	%	Hot	%			Cold	%	Hot	%	
168.75	6918.9	5344	77.2	1574.9	22.8	3769	7683.8	5833.8	75.9	1850	24.1	3983.8
South	6908.4	5204.7	75.3	1703.7	24.7	3501	7666.9	5608.1	73.1	2058.8	26.9	3549.3
-168.75	6918.9	5087	73.5	1831.9	26.5	3255.1	7683.8	5486.1	71.4	2197.7	28.6	3288.4
-157.5	6910.7	4844.8	70.1	2065.9	29.9	2778.8	7687.2	5227.4	68	2459.8	32	2767.7
-146.25	6805.2	4537.8	66.7	2267.4	33.3	2270.4	7591.2	4908.5	64.7	2682.8	35.3	2225.7
-135	6588	4162.5	63.2	2425.5	36.8	1737	7371.7	4525.5	61.4	2846.2	38.6	1679.3
-123.75	6284.3	3725.5	59.3	2558.8	40.7	1166.7	7050.8	4087	58	2963.8	42	1123.1
-112.5	5881.5	3281.6	55.8	2599.9	44.2	681.7	6616.3	3624.6	54.8	2991.7	45.2	632.9
-101.25	5373.8	2811.3	52.3	2562.6	47.7	248.7	6062.4	3128.7	51.6	2933.7	48.4	195
West	4716.3	2289.6	48.5	2426.7	51.5	-137.1	5335.2	2572.3	48.2	2762.9	51.8	-190.6
-78.75	4086.7	1792.1	43.9	2294.6	56.1	-502.6	4635.3	2057.7	44.4	2577.5	55.6	-519.8
-67.5	3356.7	1321.3	39.4	2035.4	60.6	-714	3816.9	1545.1	40.5	2271.8	59.5	-726.8
-56.25	2618.9	899.5	34.3	1719.3	65.7	-819.8	2986.6	1078.8	36.1	1907.8	63.9	-829
-45	1922.8	582	30.3	1340.8	69.7	-758.9	2198.7	678.1	30.8	1520.7	69.2	-842.6
-33.75	1319.5	333.7	25.3	985.8	74.7	-652.1	1508.2	399.2	26.5	1109	73.5	-709.9
-22.5	815.3	258.8	31.7	556.5	68.3	-297.6	928	318.5	34.3	609.5	65.7	-290.9
-11.25	448.1	167.4	37.4	280.7	62.6	-113.3	508.2	230.7	45.4	277.5	54.6	-46.8

Table 6. The Amount of Energy Received by Vertical Surfaces in Sanandaj and Hamedan (BTU/H/FT2)

Orientation	Sanandaj						Hamedan					
	Total	period				Dif.	Total	period				Dif.
		Cold	%	Hot	%			Cold	%	Hot	%	
North	398.8	185.8	46.6	212.9	53.4	-27.1	392.2	213.2	54.3	179.1	45.7	34.1
11.25	576	327.2	56.8	248.9	43.2	78.3	563.5	349.2	62	214.3	38	134.8
22.5	1040.5	656.8	63.1	383.7	36.9	273.2	1012.2	656.5	64.9	355.7	35.1	300.8
33.75	1670.6	1150.5	68.9	520.1	31.1	630.4	1616.7	1097.8	67.9	518.8	32.1	579
45	2434.7	1591.7	65.4	843	34.6	748.7	2337.6	1550	66.3	787.6	33.7	762.4
56.25	3310.8	2269.4	68.5	1041.4	31.5	1228	3150.6	2143.3	68	1007.2	32	1136.1
67.5	4219.3	2913.9	69.1	1305.4	30.9	1608.5	3985.2	2760.1	69.3	1225.1	30.7	1535.1
78.75	5109.8	3655.8	71.5	1454	28.5	2201.8	4785.2	3419.4	71.5	1365.8	28.5	2053.6
East	5860.5	4007.8	68.4	1852.6	31.6	2155.2	5451.7	3847.9	70.6	1603.8	29.4	2244.2
101.25	6629.9	4677.8	70.6	1952.1	29.4	2725.8	6125.8	4448.9	72.6	1676.9	27.4	2772
112.5	7205.2	5131.3	71.2	2073.8	28.8	3057.5	6615.1	4929.4	74.5	1685.7	25.5	3243.8
123.75	7639.6	5517.1	72.2	2122.6	27.8	3394.5	6968.5	5259.8	75.5	1708.7	24.5	3551
135	7944.3	5811.7	73.2	2132.6	26.8	3679.1	7197.1	5581	77.5	1616.1	22.5	3964.8
146.25	8149.3	5923.1	72.7	2226.2	27.3	3696.9	7330.9	5715.8	78	1615.1	22	4100.8
157.5	8239.3	5980.6	72.6	2258.8	27.4	3721.8	7361.7	5806.2	78.9	1555.4	21.1	4250.8
168.75	8076.5	5859.5	72.6	2216.9	27.4	3642.6	7304.3	5751.9	78.7	1552.3	21.3	4199.6
South	8191.3	5662.5	69.1	2528.8	30.9	3133.7	7265.5	5546.2	76.3	1719.3	23.7	3826.9
-168.75	8076.5	5485.3	67.9	2591.1	32.1	2894.2	7304.3	5401.2	73.9	1903	26.1	3498.2
-157.5	8239.3	5111.8	62	3127.6	38	1984.2	7361.7	5155.5	70	2206.2	30	2949.2
-146.25	8149.3	4611.2	56.6	3538	43.4	1073.2	7330.9	4800.6	65.5	2530.3	34.5	2270.3
-135	7944.3	4130.3	52	3814.1	48	316.2	7197.1	4423.5	61.5	2773.6	38.5	1649.8
-123.75	7639.6	3607	47.2	4032.6	52.8	-425.6	6968.5	4028.1	57.8	2940.5	42.2	1087.6
-112.5	7205.2	3170.4	44	4034.7	56	-864.3	6615.1	3594.2	54.3	3020.9	45.7	573.3
-101.25	6629.9	2610.6	39.4	4019.3	60.6	-1408.7	6125.8	3123.1	51	3002.7	49	120.3
West	5860.5	2114.3	36.1	3746.1	63.9	-1631.8	5451.7	2582.5	47.4	2869.2	52.6	-286.7
-78.75	5109.8	1675.9	32.8	3433.9	67.2	-1758	4785.2	2054.9	42.9	2730.2	57.1	-675.3
-67.5	4219.3	1221	28.9	2998.3	71.1	-1777.3	3985.2	1541.2	38.7	2444	61.3	-902.8
-56.25	3310.8	818	24.7	2492.9	75.3	-1674.9	3150.6	1069.2	33.9	2081.3	66.1	-1012.1
-45	2434.7	489.3	20.1	1945.4	79.9	-1456.1	2337.6	672.3	28.8	1665.3	71.2	-992.9
-33.75	1670.6	263	15.7	1407.6	84.3	-1144.6	1616.7	403.4	25	1213.3	75	-809.8
-22.5	1040.5	198.7	19.1	841.8	80.9	-643.1	1012.2	267	26.4	745.1	73.6	-478.1
-11.25	576	181.3	31.5	394.7	68.5	-213.5	563.5	223.6	39.7	339.9	60.3	-116.3

Table 7. The Amount of Received Energy by the Vertical Surfaces of Studied Forms in Ardabil and Tabriz (BTU/H/FT2)

Form		Ardabil						Tabriz					
		Total	period				Dif.	Total	period				Dif.
			Cold	%	Hot	%			Cold	%	Hot	%	
Square		4162.9	2699.6	64.9	1463.3	35.1	1236.4	4672	3005.5	64.3	1666.5	35.7	1339
EW Rectangle	1:1.2	4112.6	2698.2	65.6	1414.4	34.4	1283.8	4611.7	2996.6	65	1615.1	35	1381.5
	1:1.4	4070.7	2697	66.3	1373.7	33.7	1323.2	4561.4	2989.2	65.5	1572.3	34.5	1416.9
	1:1.6	4035.2	2695.9	66.8	1339.3	33.2	1356.6	4518.9	2982.9	66	1536	34	1446.8
	1:1.6	4004.8	2695	67.3	1309.8	32.7	1385.3	4482.5	2977.5	66.4	1505	33.6	1472.5
	1:2	3978.5	2694.3	67.7	1284.2	32.3	1410.1	4450.9	2972.8	66.8	1478	33.2	1494.8
NS Rectangle	1:1.2	4213.2	2701.1	64.1	1512.1	35.9	1189	4732.3	3014.4	63.7	1717.9	36.3	1296.4
	1:1.4	4255.1	2702.3	63.5	1552.8	36.5	1149.5	4782.5	3021.8	63.2	1760.7	36.8	1261
	1:1.6	4290.6	2703.4	63	1587.2	37	1116.1	4825	3028	62.8	1797	37.2	1231.1
	1:1.6	4321	2704.2	62.6	1616.7	37.4	1087.5	4861.4	3033.4	62.4	1828	37.6	1205.4
	1:2	4347.3	2705	62.2	1642.3	37.8	1062.7	4893	3038.1	62.1	1855	37.9	1183.1
Hexagon		4208.6	2702.5	64.2	1506.2	35.8	1196.3	4726.9	3028.2	64.1	1698.7	35.9	1329.5
Octagon		4209.2	2695.8	64	1513.3	36	1182.5	4728.6	3021.8	63.9	1706.8	36.1	1315
Hexadecagon		4225.1	2708.8	64.1	1516.3	35.9	1192.5	4745.4	3040.8	64.1	1704.6	35.9	1336.2
Triacontadigon		4228.5	2714.4	64.2	1514.1	35.8	1200.4	4749.3	3048.6	64.2	1700.8	35.8	1347.8

Table 8. The amount of received energy by the vertical surfaces of studied forms in Sanandaj and Hamedan (BTU/H/FT2)

Form		Sanandaj						Hamedan					
		Total	period				Dif.	Total	period				Dif.
			Cold	%	Hot	%			Cold	%	Hot	%	
Square		5077.8	2992.6	58.9	2085.1	41.1	907.5	4640.3	3047.4	65.7	1592.8	34.3	1454.6
EW Rectangle	1:1.2	5006.6	2986.4	59.6	2020.2	40.4	966.2	4566.5	3032.2	66.4	1534.3	33.6	1497.9
	1:1.4	4947.3	2981.2	60.3	1966.1	39.7	1015.1	4505	3019.5	67	1485.5	33	1533.9
	1:1.6	4897.1	2976.8	60.8	1920.3	39.2	1056.5	4453	3008.7	67.6	1444.3	32.4	1564.4
	1:1.6	4854.1	2973.1	61.2	1881.1	38.8	1092	4408.4	2999.5	68	1408.9	32.0	1590.6
	1:2	4816.9	2969.8	61.7	1847	38.3	1122.8	4369.8	2991.5	68.5	1378.3	31.5	1613.2
NS Rectangle	1:1.2	5148.9	2998.8	58.2	2150.1	41.8	848.8	4714	3062.7	65	1651.3	35	1411.4
	1:1.4	5208.2	3004	57.7	2204.2	42.3	799.9	4775.5	3075.4	64.4	1700.1	35.6	1375.3
	1:1.6	5258.4	3008.4	57.2	2250	42.8	758.5	4827.5	3086.2	63.9	1741.4	36.1	1344.8
	1:1.6	5301.4	3012.2	56.8	2289.2	43.2	723	4872.1	3095.4	63.5	1776.7	36.5	1318.6
	1:2	5338.7	3015.4	56.5	2323.2	43.5	692.2	4910.7	3103.4	63.2	1807.4	36.8	1296
Hexagon		5140.9	3021.6	58.8	2119.3	41.2	902.2	4709.2	3065.6	65.1	1643.6	34.9	1422
Octagon		5133.6	2999.2	58.4	2134.4	41.6	864.7	4703.8	3052.1	64.9	1651.7	35.1	1400.3
Hexadecagon		5154.8	3023.6	58.7	2131.2	41.3	892.4	4723.7	3070.4	65	1653.3	35	1417.2
Triacontadigon		5150.1	3031.6	58.9	2118.5	41.1	913.1	4727.2	3075.5	65.1	1651.6	34.9	1423.9

According to the results of Tables 7 and 8, the maximum amount of received energy by vertical surfaces is related to the rectangular form with a north-south orientation and the minimum amount is related to the rectangular form with an east-west orientation. In the north-south rectangle (especially with aspect ratios of 1:1.4 to 1:2), due to the larger eastern and western surfaces and much more time of receiving radiation by these surfaces, the amount of received energy during the hot period of the year is higher than in other forms but, these forms have different performance due to the shift of angles of surfaces to receive solar energy in cold and hot weather. Due to the cold climate of the studied cities, the optimal form of the building is determined, based on the maximum amount of energy received in the cold period. The highest amount of energy in the cold period in the studied cities is related to the rectangular form with an east-west orientation and the lowest amount of energy in the cold period is related to the rectangular form with a north-south orientation. Therefore, according to the established criteria, the optimal form of building in the studied cities is the rectangular form with an east-west orientation and then the square form.

Heat loss depends on some factors such as surface area, the difference between internal and external temperature, and the overall heat transfer coefficient of walls. According to Fourier's law, for two materials with equal temperature and conductivity coefficient, the amount of energy transfer has a direct relation with the external area (Bergman et al., 2011). Therefore, under constant temperature and conductivity coefficient of the surfaces, by increasing the aspect ratio of the form, the area of external surfaces increases, and the amount of obtained and transferred energy from the walls increases by the same ratio, as well.

The form's optimal aspect ratio is a relation in which, the amount of energy loss in the cold season and energy absorption during the hot season is minimum. According to the balance principle between received and lost energy, the minimum amount of absorbed energy in the cold period for the aspect ratios of 1:1.2 to 1:2, in relation to the square form, are 1.004, 1.014, 1.027, 1.043, and 1.06 percent, and the maximum absorbed energy in the hot period is 0.996, 0.986, 0.973, 0.957, and 0.94 percent, respectively. The ratio of energy received by rectangle to square form during cold and hot periods is presented in table 9.

Therefore, considering the amount of lost and gained energy in the cold period in Ardabil, Tabriz, Sanandaj, and Hamedan cities, the optimal aspect ratio is 1:1.2 for NS rectangular form. Also, regarding the minimum heat energy received in the hot period, the optimal aspect ratio is 1:1.8 and 1:2 for the EW rectangle form.

Based on the relation "(the difference between the maximum required and received energy × hot period in percent) + (the difference between the minimum required and received energy × duration of the cold period in percent)", the best aspect ratios for the EW rectangle in Ardabil, Tabriz, Sanandaj, and Hamedan cities are 1:1.2, and then 1:1.4. Figures 1 to 4 show the performance of different aspect ratios of rectangle form compared to the square form in receiving energy.

Table 9. The Ratio of Energy Received by Rectangle to Square Form (%)

period	City	EW rectangle					NS rectangle				
		1:1.2	1:1.4	1:1.6	1:1.8	1:2	1:1.2	1:1.4	1:1.6	1:1.8	1:2
Cold	Ardabil	0.999	0.999	0.999	0.998	0.998	1.001	1.001	1.001	1.002	1.002
	Tabriz	0.997	0.995	0.992	0.991	0.989	1.003	1.005	1.008	1.009	1.011
	Sanandaj	0.998	0.996	0.995	0.993	0.992	1.002	1.004	1.005	1.007	1.008
	Hamedan	0.995	0.991	0.987	0.984	0.982	1.005	1.009	1.013	1.016	1.018
Hot	Ardabil	0.966	0.939	0.915	0.895	0.878	1.033	1.061	1.085	1.105	1.122
	Tabriz	0.969	0.943	0.922	0.903	0.887	1.031	1.057	1.078	1.097	1.113
	Sanandaj	0.969	0.943	0.921	0.902	0.886	1.031	1.057	1.079	1.098	1.114
	Hamedan	0.963	0.933	0.907	0.885	0.865	1.037	1.067	1.093	1.115	1.135

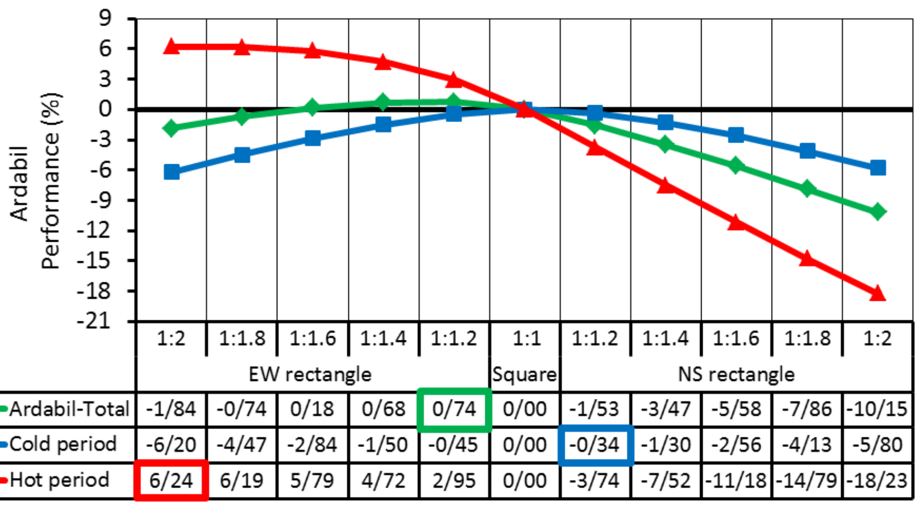
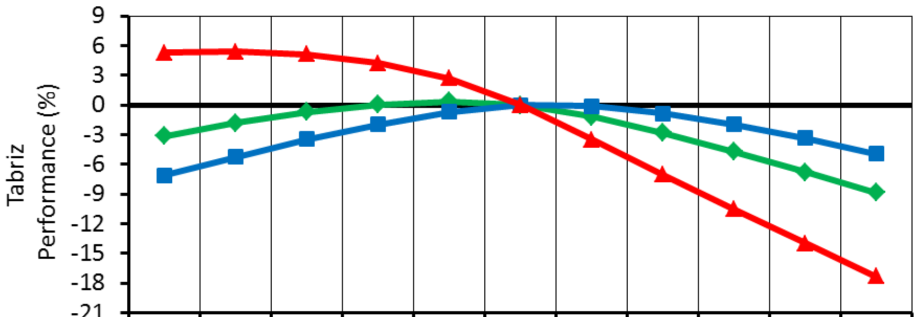
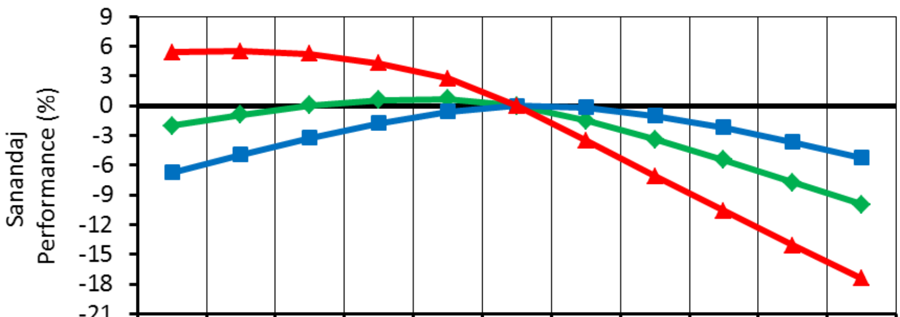


Fig 1. Energy performance in rectangle and square forms in Ardabil (%)



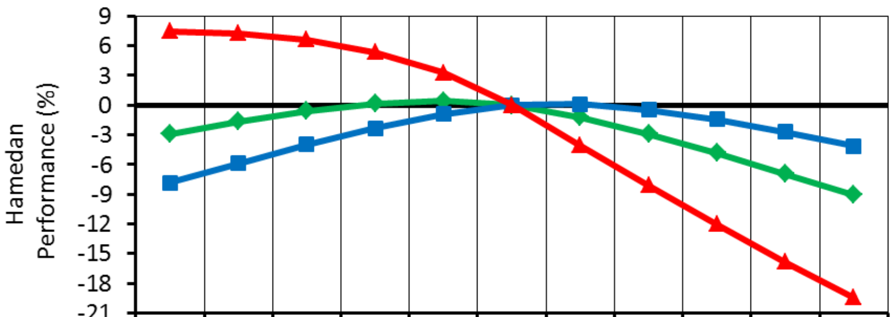
	1:2	1:1.8	1:1.6	1:1.4	1:1.2	1:1	1:1.2	1:1.4	1:1.6	1:1.8	1:2
	EW rectangle					Square	NS rectangle				
Tabriz-Total	-3/12	-1/83	-0/70	0/04	0/39	0/00	-1/19	-2/84	-4/70	-6/77	-8/88
Cold period	-7/09	-5/23	-3/45	-1/94	-0/70	0/00	-0/10	-0/86	-1/95	-3/37	-4/92
Hot period	5/31	5/39	5/14	4/25	2/69	0/00	-3/49	-7/05	-10/54	-13/99	-17/31

Fig 2. Energy performance in rectangle and square forms in Tabriz (%)



	1:2	1:1.8	1:1.6	1:1.4	1:1.2	1:1	1:1.2	1:1.4	1:1.6	1:1.8	1:2
	EW rectangle					Square	NS rectangle				
Sanandaj-Total	-2/01	-0/88	0/07	0/59	0/69	0/00	-1/49	-3/39	-5/47	-7/72	-9/99
Cold period	-6/76	-4/95	-3/23	-1/78	-0/61	0/00	-0/19	-1/02	-2/17	-3/65	-5/24
Hot period	5/42	5/49	5/22	4/31	2/72	0/00	-3/52	-7/11	-10/62	-14/09	-17/42

Fig 3. Energy performance in rectangle and square forms in Sanandaj (%)



	1:2	1:1.8	1:1.6	1:1.4	1:1.2	1:1	1:1.2	1:1.4	1:1.6	1:1.8	1:2
	EW rectangle					Square	NS rectangle				
Hamedan-Total	-2/94	-1/67	-0/58	0/13	0/44	0/00	-1/24	-2/93	-4/82	-6/92	-9/06
Cold period	-7/83	-5/87	-3/97	-2/32	-0/90	0/00	0/10	-0/48	-1/43	-2/73	-4/16
Hot period	7/47	7/24	6/64	5/33	3/28	0/00	-4/09	-8/14	-12/04	-15/85	-19/47

Fig 4. Energy performance in rectangle and square forms in Hamedan (%)

Table 10 shows the amount of energy received by optimal aspect ratios, in different orientations in the studied cities.

According to the results of Table 10, in surveyed aspect ratios, the maximum amount of energy received by vertical surfaces is related to the orientations of 120° SE and SW and the minimum amount relates to the South orientation. As the form rotates toward the east and west, the amount of received energy increases during the hot period and decreases during the cold period. Considering the cold climate of the studied cities, the best building orientation is determined due to the minimum receiving energy in the hot period and the maximum energy in the cold period. Therefore, according to the established criteria, the best orientation for the selected aspect ratios in the cities of Ardabil, Tabriz, Sanandaj, and Hamedan is 165° SE.

4. CONCLUSION

Due to the cold climate of the cities of Ardabil, Tabriz, Sanandaj, and Hamedan, the buildings should be designed in such a way that during the cold period the highest amount of energy, and in the hot period the least amount of energy could be received by the vertical surfaces. In this research, to determine the optimal form, aspect ratios, and orientation of the building, six polygonal forms, including square, rectangle (with north-south and east-west orientations), hexagon, octagon, hexadecagon (16-sided), and triacontadigon (32-sided) with equal area and height, were investigated. The amount of received radiation energy on vertical surfaces was calculated using the "Law of cosine" computational method. The results show that the highest amount of energy received in the cold period in the studied cities is related to the rectangular form with an east-west orientation and the lowest amount of energy is related to the rectangular form with a north-south orientation. The optimal form of building in the studied cities is rectangular with an east-west orientation. The most appropriate aspect ratio for the rectangle with east-west orientation in all the cities is 1:1.2. The most suitable orientation for the selected aspect ratios in the studied cities is 165°C southeast. The results of this study support the hypothesis that in the cold climate of northwestern cities, to receive optimal solar energy, a rectangular shape with a lower W / L ratio, and an east-west orientation, is efficient. This research has developed a framework that can be used in future research to determine the optimal geometric characteristics of buildings in other climates based on solar radiation.

Table 10. The Amount of Received Energy by the EW Rectangle Based on Optimal Aspect Ratios (BTU/H/FT2)

A.R= 1:1/2			Southwest					180	Southeast				
			-105	-120	-135	-150	-165		+165	+150	+135	+120	+105
Ardabil	Total		4261.6	4275.9	4255.3	4229.4	4175.1	4112.6	4175.1	4229.4	4255.3	4275.9	4261.6
	period	Cold	2749.7	2713.8	2689.3	2702.5	2702.9	2698.2	2752.2	2719.6	2694.6	2708.6	2709.6
		%	64.5	63.5	63.2	63.9	64.7	65.6	65.9	64.3	63.3	63.3	63.6
		Hot	1511.9	1562.1	1566.0	1526.9	1472.2	1414.4	1422.9	1509.8	1560.8	1567.2	1552
		%	35.5	36.5	36.8	36.1	35.3	34.4	34.1	35.7	36.7	36.7	36.4
	Difference		1237.8	1151.7	1123.3	1175.6	1230.7	1283.8	1329.3	1209.8	1133.8	1141.4	1157.6
Tabriz	Total		4788.1	4805.8	4785.2	4749.8	4684.3	4611.7	4684.3	4749.8	4785.2	4805.8	4788.1
	period	Cold	3092.5	3058.7	3035.4	3034.6	3024.1	2996.6	3084.7	3061.5	3040.8	3050.9	3044.9
		%	64.6	63.6	63.4	63.9	64.6	65.0	65.9	64.5	63.5	63.5	63.6
		Hot	1695.7	1747.2	1749.8	1715.3	1660.2	1615.1	1599.6	1688.3	1744.4	1754.9	1743.2
		%	35.4	36.4	36.6	36.1	35.4	35.0	34.1	35.5	36.5	36.5	36.4
	Difference		1396.8	1311.5	1285.6	1319.3	1363.8	1381.5	1485.1	1373.3	1296.4	1296	1301.7
Sanandaj	Total		5206.7	5226.1	5189.5	5158.5	5083.5	5006.6	5083.5	5158.5	5189.5	5226.1	5206.7
	period	Cold	3058.5	3029.7	2992.6	3007.5	3045.6	2986.4	3054.4	3041.9	3018.9	3034.9	3069.4
		%	58.7	58	57.7	58.3	59.9	59.6	60.1	59	58.2	58.1	59
		Hot	2148.2	2196.3	2196.9	2151	2038.0	2020.2	2029.1	2116.6	2170.6	2191.2	2137.3
		%	41.3	42	42.3	41.7	40.1	40.4	39.9	41	41.8	41.9	41
	Difference		910.4	833.4	795.7	856.6	1007.6	966.2	1025.3	925.3	848.3	843.7	932
Hamedan	Total		4772.1	4798.9	4767.4	4728.8	4644.5	4566.5	4644.5	4728.8	4767.4	4798.9	4772.1
	period	Cold	3129.3	3092	3050.3	3051.5	3056.2	3032.2	3107.8	3085.2	3063.1	3074.8	3087.4
		%	65.6	64.4	64.0	64.5	65.8	66.4	66.9	65.2	64.3	64.1	64.7
		Hot	1642.7	1706.9	1717	1677.3	1588.3	1534.3	1536.7	1643.6	1704.3	1724.1	1684.7
		%	34.4	35.6	36	35.5	34.2	33.6	33.1	34.8	35.7	35.9	35.3
	Difference		1486.6	1385.1	1333.3	1374.2	1467.9	1497.9	1571.2	1441.6	1358.8	1350.6	1402.7

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