Three-Dimensional Dynamic Numerical Simulation of the Holy Mosque Area

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Abstract. A significant development occurred in the Holy Mosque area in the last twenty years. To increase the capacity mosque and the surrounding hotels, thus accommodating visitors and pilgrims over the year to keep pace with the increase in the number of Muslims. Accordingly, the air envelope of the Holy Mosque continuously varies. These buildings' effect on the Holy Mosque's aerodynamics can be noticed. Consequently, new wind currents appeared with different altitudes, directions, and intensities. Also, new dead zone areas occurred. A dynamic three-dimensional model has been developed using computational fluid dynamics CFD to simulate the Holy Mosque and its surrounding area. The model covers a square area of 1800m in length and comprises the Holy Mosque near its center and the main buildings surrounding the Mosque. The accuracy of the CFD model was verified by comparing its result with one of the wind tunnel studies. Some fixed locations have been selected within the Holy Mosque to study the development of wind velocity over the last two decades. The recent areas of wind currents and dead zones were defined. Some solutions are recommended to enhance the aerodynamics of the Holy Mosque.

1. Introduction: -

Many new buildings, including several high-rise buildings, were recently constructed in Holy Makkah, especially nearby the Holy Mosque, to accommodate the rise in Umrah visitors and pilgrims, achieving nearly 7 million people in 2022 after ending the constrictions of the covid epidemic. While the Kingdom targets to reach 15 million shortly. One of the main cons of high-rise buildings is the significant effect on the wind envelope of the surrounding area because of the fluid-structure interaction. Since the beginning of the construction of tall buildings in cities, there has been a public outcry about unpleasant and dangerous high-speed wind found near the base of tall buildings. Many such incidents were recorded in different countries, such as the United States [1], Canada [2], and Japan [3]. The strong wind flows found near tall buildings result from intense downwash. That brings high-speed winds from higher altitudes down to the ground level, forming strong separation layers at the sharp corners of tall buildings [4].

Computational fluid dynamics (CFD), applied in this research, has been considered one of the most powerful tools for studying aerodynamic cases over the last two decades. CFD has been used to calculate the axial forces, the bending and torsion moments, and the maximum stresses on the cladding for complex and high-rise buildings [5-7]. Also, It is applied to study the comfort of the pedestrian [8,9]. In addition, it can be applied for artificial [10] and natural ventilation [11]. Besides, it may be used to study the acceleration of high-rise buildings to check the occupants'

comfort [12,13]. Finally, CFD is used to study air quality and detect dead zones (stagnant points), especially in epidemics [14-15].
In this research, a three-dimensional model has been developed using CFD to simulate the Holy Mosque and its surrounding area. The model covers a square area of 1800m in length and comprises the natural terrain of the studied area, the Holy Mosque, the king Abdel-Aziz Endowment, Jabal Omar, and other prominent structures surrounding the Mosque. The model is dynamic since it is regularly updated with the area's new development. The accuracy of the CFD model was verified by comparing its result with wind tunnel studies. This model's objectives are precisely defining the wind gusts, checking the prayer comfort, and examining the air quality (stagnant locations) at the Holy Mosque piazza. The model is manually revised based on the studied objective. In this research, some fixed places have been selected within the Holy Mosque to achieve the above goals. Some solutions are recommended to enhance the aerodynamics of the Holy Mosque.

2. The CFD model:

ANSYS Fluent has been used to develop the CFD simulation of the Holy Mosque area. The geometry of the model, the grid generation and sensitivity analysis, the validation of the model, the wind velocity, and the wind directions are briefly discussed below.

2.1. The geometry of the model:

The model area is square, with a side length of 1.8km. The actual terrain of the studied area was considered. The digital elevation model (DEM) for the Holy Mosque area has been used to create the existing terrain surface in the model. Then the main buildings were added to the model, such as the old Holy Mosque, its piazza, the Makkah hotel, the royal palace on mount Abu Kubais, dar el tauheed & other hotel buildings. Next, any new nearby building was added to the model to be constantly updated and simulate the current case of the Holy Mosque area, such as the Jabal Omar, the third extension, and other hotels, as shown in Figure (1)

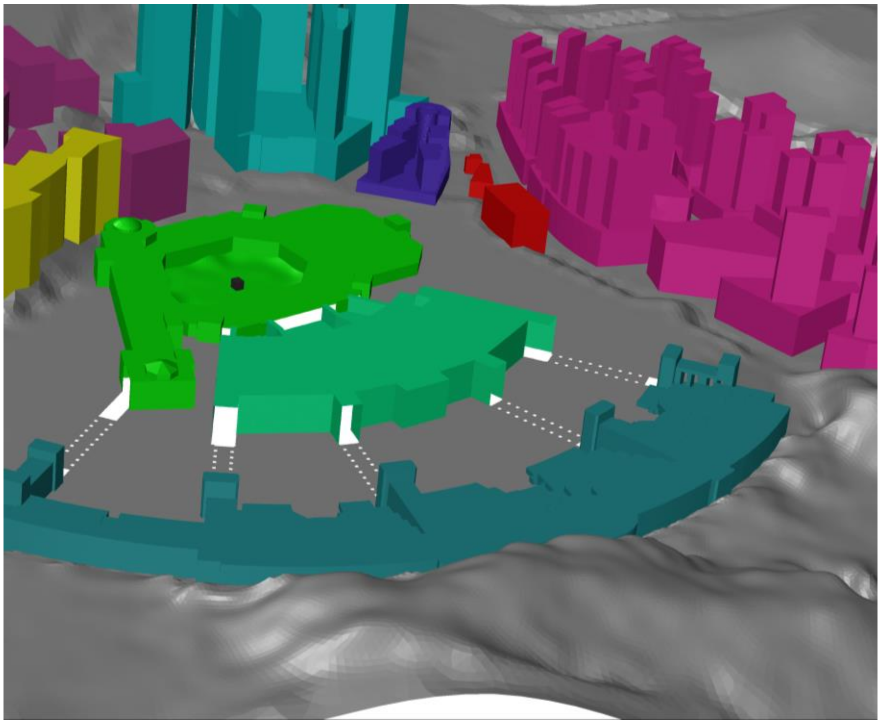

Figure (1): The geometry of the CFD model

2.2. The grid generation and sensitivity analysis:

The accuracy of the results achieved from the CFD modeling dramatically depends on the mesh quality, which also has implications for model convergence. This research applies a non-uniform mesh to the volumes of all CFD models. The grid is smoothened around the Holy Mosque structures and its piazza, which are the main objective of the current study. Different mesh sizes were generated to investigate the solution of independence from the grid. Grid sensitivity analysis is used to validate the CFD model.

2.3. The CFD model validation:

The CFD model has been validated by comparing its results with wind tunnels by Alan G. Davenport Wind Engineering Group and Rowan Williams Davies & Irwin Inc.(RWDI) [confidional studies]. The wind velocities, the stress on cladding, and bending moments were validated with maximum discrepancies of less than 10%.

2.4. The wind velocity:

According to the Saudi Building code, the maximum wind speed in Jeddah and Taif cities is 152km/h [16]. Therefore it can be considered that it is the same in Holy Makkah. The terrain exposure constants are relevant to category B.

2.5. The wind directions:

The sixteen wind directions have been studied for each wind speed with an equal interval of 22.5^{o} to cover all the possible directions.

3. The results and discussion:

Four different cases are studied in this research study, and 16 wind directions were conducted for each case study, with a total of 64 runs. The first model was performed to study the wind gusts on the entire Holy Mosque and its piazza. In the second model, the collapsed tower crane in 2015 was added to the model to analyze the wind forces acting on it. The third model was developed to check the prayer comfort at the piazza. The last model was carried out to define the location of dead zones. Each issue is discussed briefly below:

3.1. The wind gust results:

All wind directions have been studied. The hazards of the wind gust in the Holy Mosque area were generally reduced because of the development of new high-rise buildings around the Holy Mosque. However, the wind gust risk increases at different levels and in specific directions. Two locations were selected to be represented in this research study. The locations are the roof of the third expansion of the Holy Mosque and the tower crane collapse in 2015.

3.1.1. The roof of the extension of the Holy Mosque:

A strong wind current is expected to attack the roof surface of the Holy Mosque, as shown in Figure (2), in case of blowing wind gust from the south-southwest direction. The current will passes between the king Abdel-Aziz Endowment towers and Jabal Omar buildings. This wind current will pass above Makkah Hotel. The forces acting on the attacked area will be nearly 40% more than the standard design wind loads

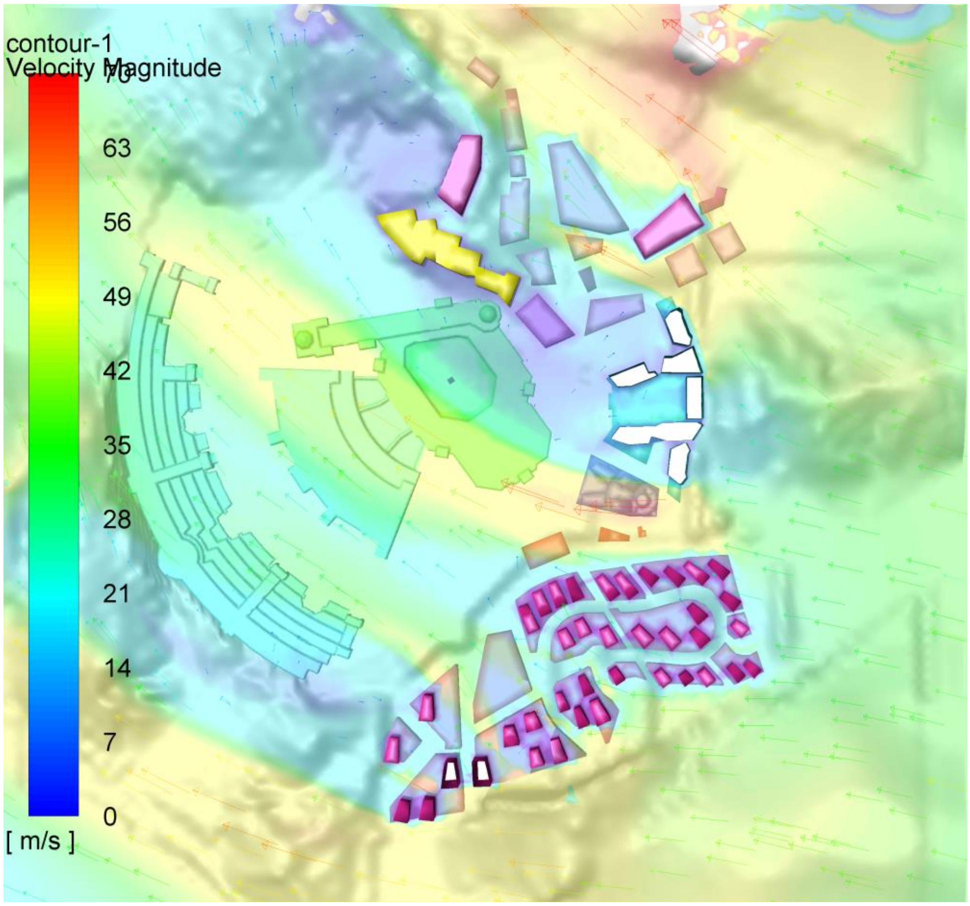

Figure (2): The wind gust attacking the roof of the third extension of the Holy Mosque

3.1.2. The tower crane accident in 2015:

On 11th September 2015, 27th Thul-Qida 1436, 107 people died, and at least 238 were injured after the collapse of a tower crane at the Holy Harm piazza during rest due to a strong wind. This case is considered the worst disaster ever for the tower crane collapse. However, it happened during the off-peak hours.

The tower crane is added to the dynamic CFD model to study the wind force acting on the tower crane during the accident. The wind forces acting on the tower crane were considerably limited to the wind blowing from 11 out of the 16 known directions. Two critical wind directions are noticed: the north-northeast and the west-southwest. The maximum overturning moment acting on the tower crane occurred in the north-northeast wind direction, which is the wind direction causing the accident, as shown in Figure (3). The overturning moment nearly doubled when the tower crane was placed in an open area.

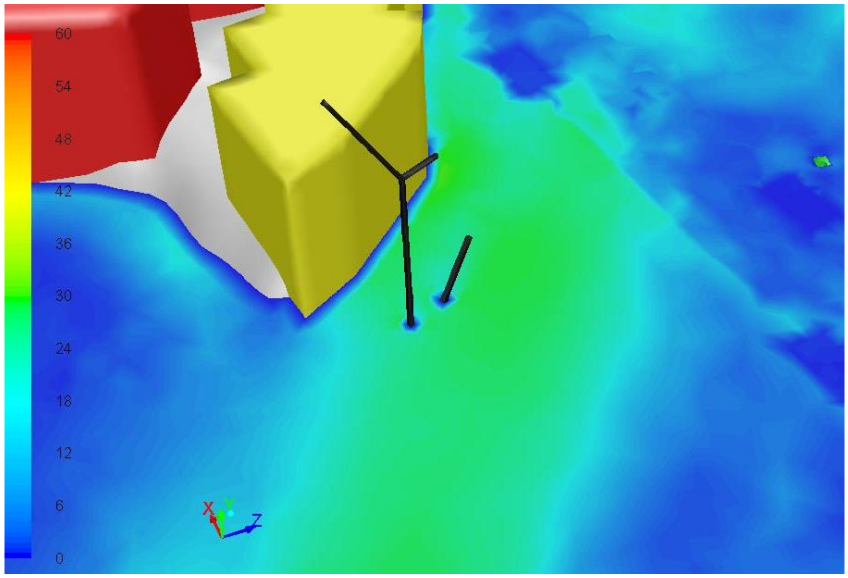

Figure (3): the velocity contour map for the northeast wind direction case of the collapsed crane (plan over the old Holy mosque level)

3.2. The comfort of the prayer:

A study has been conducted to study the comfort of the prayer in the Holly Mosque piazza. The criteria used in this research study to judge the acceptability and safety of pedestrian-level winds as defined in the research [17-19]. These standards reduce the comfort level and/or tolerance of people who engage in more leisurely activities. The type selected for prediction in this study is when the wind speed exceeds 5% of the time annually.

The study revealed that the wind speed below the limit starts annoying the prayers' comfort except in only one wind direction, which is the northwest, as shown in Figure (4)

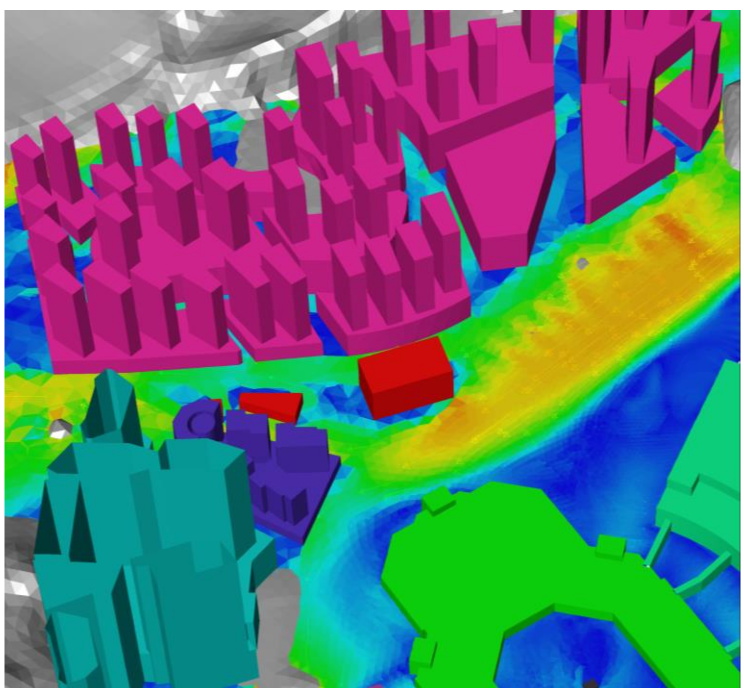

Figure (4): The velocity contour at the prayer level for the northwest wind

3.3. The air quality (dead zones):

The study of the air quality (dead zones) was tackled for calm wind cases in 16 directions. In nearly all wind directions, several quiet areas (wind-stagnant) were noticed around the Holy Mosque. The high-rise buildings surrounding the Mosque considerably reduce the wind speed around the studied area. Figure (5) illustrates the velocity contour at the level of the prayers for the north wind, where the blue color represents the areas exposed to lower air quality. Stagnant regions are generally not recommended to maintain better air quality. Therefore artificial aeration (large-scale fans) is recommended in those areas. Some missing details should be added to a new model to give an accurate design of the fans (number, height, power, and direction). The effect of the air conditioning inside the Holy Mosque, the locations and dimensions of the doors, and the precise terrain level should be added to the recommended new model.

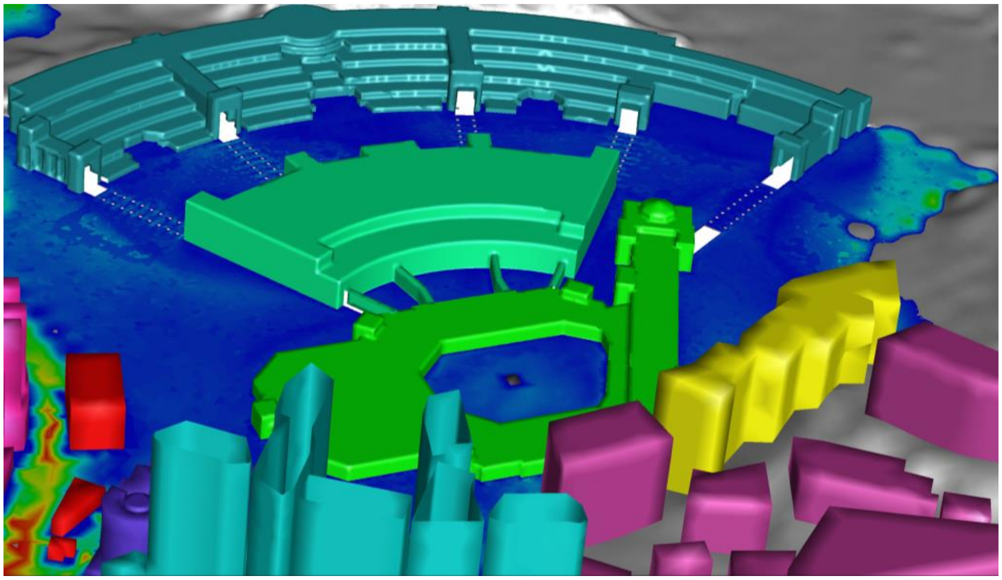

Figure (5): the stagnant locations (dead zones) at the prayer level case of a calm north wind

4. Conclusions and recommendations:

A dynamic CFD model has been developed for the Holy Mosque and its surrounding area. The model was validated and can be updated to simulate new developments in this area. The model can specify axial forces, bending, and torsion moments on any structure. Also, it can be used to precisely determine the maximum tension and compression stresses for cladding safety. In this research, two places exposed to wind gusts are selected to be discussed. The first is the roof surface of the Holy Mosque extension in case of blowing wind from the south-southwest direction. The forces, stresses, and moments acting on the attacked area will be nearly 40% more than the standard design wind loads. The second was the simulation of the tower crane accident in 2015. The results revealed that the attacking wind direction was the worst scenario for the crane because the overturning moment was nearly double that for the tower crane in an open area. Also, the model was adjusted to check the comfort of the prayers in the Holly Mosque piazza. The study revealed that the wind speed below the limit annoys the prayers' comfort except in the northwest direction. In different wind directions, some wind-stagnant (dead zones) locations were detected around the

Holy Mosque. Large-scale fans are recommended in these locations to avoid lowering the air quality in these areas. Further studies should be carried out on the fans' number, power, and direction after adding missing details to the model.

References

[1] Durgin, Frank H. "Pedestrian level wind studies at the Wright brothers facility." Journal of Wind Engineering and Industrial Aerodynamics 44, no. 1-3 (1992): 2253-2264. https://doi.org/10.1016/0167-6105(92)90016-4

[2] Isyumov, N., 1978. Studies of the pedestrian level wind environment at the boundary layer wind tunnel laboratory of the University of Western Ontario. *Journal of Wind Engineering and Industrial Aerodynamics*, *3*(2-3), pp.187-200. https://doi.org/10.1016/0167-6105(78)90009-0

[3] Kamei, I., and E. Maruta. "Study on wind environmental problems caused around buildings in Japan." *Journal of Wind Engineering and Industrial Aerodynamics* 4, no. 3-4 (1979): 307-331. https://doi.org/10.1016/0167-6105(79)90010-2

[4] Durgin, Frank H. "Pedestrian level wind criteria using the equivalent average." Journal of Wind Engineering and Industrial Aerodynamics 66, no. 3 (1997): 215-226.

https://doi.org/10.1016/S0167-6105(97)00130-X

[5] Thordal, Marie Skytte, Jens Chr Bennetsen, and H. Holger H. Koss. "Review for practical application of CFD for the determination of wind load on high-rise buildings." Journal of Wind Engineering and Industrial Aerodynamics 186 (2019): 155-168. https://doi.org/10.1016/j.jweia.2018.12.019

[6] Tamura, Tetsuro, Kojiro Nozawa, and Koji Kondo. "AIJ guide for numerical prediction of wind loads on buildings." Journal of Wind Engineering and Industrial Aerodynamics 96, no. 10-11 (2008): 1974-1984. https://doi.org/10.1016/j.jweia.2008.02.020

[7] Farouk, M. I., S. A. Mourad, and A. S. Salaheldin. "Numerical simulation of wind effects on an airport air traffic control tower." WIT Transactions on The Built Environment 92 (2007). https://doi.org/10.2495/FSI070171

[8] Blocken, Bert, and J. Persoon. "Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard." Journal of wind engineering and industrial aerodynamics 97, no. 5-6 (2009): 255-270. https://doi.org/10.1016/j.jweia.2009.06.007

[9] Zhang, Xinyue, Asiri Umenga Weerasuriya, Xuelin Zhang, Kam Tim Tse, Bin Lu, Cruz Yutong Li, and Chun-Ho Liu. "Pedestrian wind comfort near a super-tall building with various configurations in an urban-like setting." In Building simulation, vol. 13, pp. 1385-1408. Tsinghua University Press, 2020. https://doi.org/10.1007/s12273-020-0658-6

[10] Ang, Chin Ding Edmund, Guillermo Rein, Joaquim Peiro, and Roger Harrison. "Simulating longitudinal ventilation flows in long tunnels: Comparison of full CFD and multi-scale modelling approaches in FDS6." Tunnelling and Underground Space Technology 52 (2016): 119-126. https://doi.org/10.1016/j.tust.2015.11.003

[11] Farouk, Mohamed. "Comparative study of hexagon & square windcatchers using CFD simulations." Journal of Building Engineering 31 (2020): 101366.

https://doi.org/10.1016/j.jobe.2020.101366

[12] Elias, Said, and Vasant Matsagar. "Wind response control of tall buildings with a tuned mass damper." Journal of Building Engineering 15 (2018): 51-60.

https://doi.org/10.1016/j.jobe.2017.11.005

[13] Farouk, Mohamed I. "Check the comfort of occupants in high rise building using CFD." Ain Shams Engineering Journal 7.3 (2016): 953-958. https://doi.org/10.1016/j.asej.2015.06.011

[14] Bhattacharyya, Suvanjan, Kunal Dey, Akshoy Ranjan Paul, and Ranjib Biswas. "A novel CFD analysis to minimize the spread of COVID-19 virus in hospital isolation room." *Chaos, Solitons & Fractals* 139 (2020): 110294. https://doi.org/10.1016/j.chaos.2020.110294

[15] Farouk, Mohamed Ismail, Ahmed Fayez Nassar, and Mohamed Hassan Elgamal. "Numerical Study of the Transmission of Exhaled Droplets between the Instructor and Students in a Typical Classroom." *Applied Sciences* 11, no. 20 (2021): 9767.

https://doi.org/10.3390/app11209767

[16] "Saudi Building Code Requirements (SBC301)

[17] Davenport, Alan G. "An approach to human comfort criteria for environmental wind conditions." Colloquium on building climatology. 1972.

[18] Isyumov, N. "The ground level wind environment in built-up areas." proc. of 4^< th> Int. Conf. on Wind Effects on Buildings and Structures, London, 1975. 1975.

[19] Zhang, Xinyue, Asiri Umenga Weerasuriya, Xuelin Zhang, Kam Tim Tse, Bin Lu, Cruz Yutong Li, and Chun-Ho Liu. "Pedestrian wind comfort near a super-tall building with various configurations in an urban-like setting." In Building simulation, vol. 13, pp. 1385-1408. Tsinghua University Press, 2020. https://doi.org/10.1007/s12273-020-0658-6