Assessing Self-shading Benefits of Twisting Towers

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Abstract
Over the last number of decades, tall building geometries have been shifting from rectangular boxes towards shapes that are defined through geometrical transformations such as twisting. While, from an aesthetical point of view, these twisting geometries make tall buildings appear contemporary and iconic, from an environmental point of view, however, the benefits are not as straightforward. They may vary significantly based on climatic loads and urban conditions, among others.

This study aims to assess the self-shading benefits of twisting geometries by finding a correlation between floor-to-floor rotation and façade solar irradiation across climates, primarily focusing on hot ones, where self-shading is used as a passive solar design strategy. The study analysed three types of irradiation studies: Cumulative Annual Irradiation, Cumulative Harmful Irradiation during Cooling Design Day, and lastly, Solar Irradiation Self-Shading Balance. The latter compares beneficial and harmful solar irradiation during Hot and Cold Degree Days to quantify the impact of floor-to-floor rotation on optical and thermal performance. The study explored hundreds of possible scenarios across different climates and various floor-to-floor rotation angles, revealing a variety of positive, negative, and neutral situations. The study recommends careful examination of environmental conditions via a combination of multiple irradiation studies, particularly in the case of a smooth façade scenario.

Keywords
Climate, energy and sustainable building façades, self-shading, solar radiation benefit, passive solar design, twisting towers

DOI 10.7480/jfde.2020.1.5043

1 INTRODUCTION

There are currently more than 1600 completed skyscrapers in the world, more than 500 under construction, and more than 1800 proposed and envisioned ones (CTBUH, 2020). These numbers are always on the rise, especially over the last decade, with an almost exponential progression of the number of skyscrapers and an increased pace of breaking world height records, with the current record now approaching 1km (CTBUH, 2019). Since increased height imposes an exponential increase of wind loads, most of the skyscrapers' volumes tend to soften the edges and reduce size with increasing altitude. The volume reduction is usually achieved in the form of tapering or the setting back of volumes to reduce wind pressure on façades or due to the right to light regulations, and consequently to minimise vortex shedding and swaying. Yet, the most effective technique in channelling wind flows and reducing wind pressure and swaying is via twisting. The twisting method has been known to engineers for a long time, for example, in industrial chimneys and antennae. However, the first building tower to implement twisting technique was Turning Torso in Malmö, Sweden, designed by Santiago Calatrava Architects in 2005 – just 15 years ago – Fig. 1 and Fig. 5. Since then, many skyscrapers have followed this idea. For some, it was due to performance concerns, while others mainly used it due to the aesthetics.

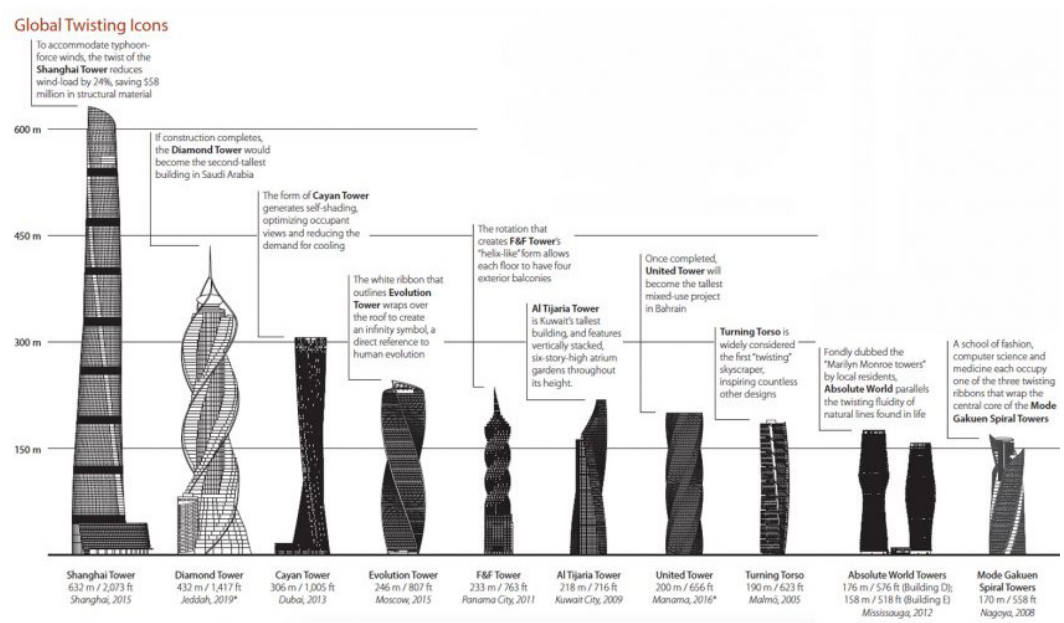

FIG. 1 Global twisting icons by height (CTBUH, 2016)

Recognising this trend, CTBUH made a report (CTBUH, 2016) that analysed 28 twisting towers across the globe and their respective average floor rotations as well as total rotations (Fig. 2). They defined the twisting building as "one that progressively rotates its floor plates or its façade as it gains height". With a 5.9° rotation, F&F Tower in Panama holds the record for the maximum floor to floor rotation, while the diamond tower will be the only twisting tower with a 360° total rotation (Fig. 1). The report demonstrates the growing trend for twisting towers that is "creating a new generation of iconic buildings throughout the world".

No.	Building	City	Country	Completion Year	Architectural Height (m)	Floor Count	Average Floor Rotation	Total Rotation
1	Shanghai Tower	Shanghai	China	2015	632	128	0.938°	120°
2	Lakhta Center	St. Petersburg	Russia	2018 (expected)	462	86	1.047°	90.0°
3	**Diamond Tower**	Jeddah	Saudi Arabia	2019 (expected)	432	93	3.871°	**360°**
4	Ocean Heights	Dubai	United Arab Emirates	2010	310	83	0.482°	40.0°
5	Cayan Tower	Dubai	United Arab Emirates	2013	306	73	1.233°	90.0°
6	Supernova Spira	Noida	India	2017 (expected)	300	80	1.825°	146°
7	Evolution Tower	Moscow	Russia	2015	246	55	2.836°	156°
8	**F&F Tower**	Panama City	Panama	2011	233	53	**5.943°**	315°
9	Al Majdoul Tower	Riyadh	Saudi Arabia	2016 (expected)	232	54	2.500°	135°
10	Al Tijaria Tower	Kuwait City	Kuwait	2009	218	41	1.951°	80.0°
11	United Tower	Manama	Bahrain	2016 (expected)	200	47	3.830°	180°
12	Al Bidda Tower	Doha	Qatar	2009	197	44	1.364°	60.0°
13	SOCAR Tower	Baku	Azerbaijan	2015	196	40	0.500°	20.0°
14	Turning Torso	Malmo	Sweden	2005	190	57	1.580°	90.0°
15	Trump International Hotel & Tower Vancouver	Vancouver	Canada	2016 (expected)	188	63	0.714°	45.0°
16	Generali Tower	Milan	Italy	2017 (expected)	185	44	1.127°	49.6°
17	Absolute World Building D	Mississauga	Canada	2012	176	56	3.732°	209°
18	Mode Gakuen Spiral Towers	Nagoya	Japan	2008	170	38	3.000°	114°
19	Absolute World Building E	Mississauga	Canada	2012	158	50	4.000°	200°
20	Baltimore Tower	London	United Kingdom	2017 (expected)	149	44	2.182°	96.0°
21	Avaz Twist Tower	Sarajevo	Bosnia and Herzegovina	2008	142	39	1.539°	60.0°
22	The Point	Guayaquil	Ecuador	2014	137	36	5.833°	210°
23	Sichuan Radio & TV Centre	Chengdu	China	2010	136	31	2.903°	90.0°
24	PwC Tower	Midrand	South Africa	2018 (expected)	106	26	1.154°	30.0°
25	Xiamen Suiwa Tower	Xiamen	China	2016 (expected)	100	22	4.091°	90.0°
26	Grove at Grand Bay North Tower	Miami	United States of America	2016 (expected)	94	21	1.843°	38.7°
27	Grove at Grand Bay South Tower	Miami	United States of America	2016 (expected)	94	21	1.843°	38.7°
28	Tao Zhu Yin Yuan	Taipei	Taiwan	2016 (expected)	93	21	4.286°	90.0°

FIG. 2 Global twisting icons – list (CTBUH, 2016

The report also noticed that "Aided by new technologies assisting architectural and structural design, a proliferation of tall twisting towers is now spreading across the globe". Finally, the report tackled performance aspects as well: "A stunning variety of textures, view angles, and ripple effects result from these manipulations, making these 'twisters' some of the world's most iconic buildings – and in many cases, aerodynamic and energy-efficient." From an aesthetical point of view, these twisting geometries make tall buildings appear fluid and contemporary. From an environmental point of view, however, the benefits are not as straightforward and may vary significantly, based on climatic loads and urban conditions. Some cases have proven, through simulations and testing, that twisting may lead to reduced wind loads and consequent savings on structural weight and costs. On the other hand, other environmental aspects such as energy savings, daylighting potential, glare control, and views are poorly documented.

Since the impact of twisting on building performance was never examined in detail and on a global scale, this research aims to address the benefits of twisting building geometries from a holistic perspective. It analyses a global potential for self-shading of twisting towers, mainly focusing on environmental performance in hot climates where self-shading has the highest potential to be used as a very effective passive solar design strategy. This study assesses the self-shading benefits of twisting geometries, analysing how climatic conditions, floor-to-floor rotation, as well as façade smoothness, influence building performance. In particular, the study performed three types of irradiation studies: Cumulative Annual Irradiation; Cumulative Harmful Irradiation during Cooling Design Day, and lastly; Solar Irradiation Self-Shading Balance compares beneficial and harmful solar irradiation during Hot and Cold Degree Days. This comparative approach provides resourceful and specific data for effectively quantifying the twisting impact on optical and thermal performance. A global potential with particular recommendations for twisting and façade smoothness offers a useful resource for all stakeholders to be used in early-stage design discussions on twisting strategies.

2 CASE STUDIES

As shown in the CTBUH report, there are many twisting towers in the world, with some claiming performance improvements with twisting. This section aims to demonstrate a range of benefits that some of the case studies have achieved, ranging from structural, wind, and energy efficiency, among others.

AGORA GARDEN, TAIPEI, TAIWAN
VINCENT CALLEBAUT ARCHITECTURES
(FREARSON A., 2013)

ABSOLUTE TOWERS, MISSISSAUGA, CANADA
MAD ARCHITECTS
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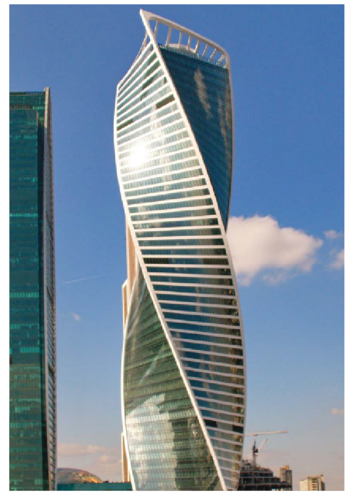


EVOLUTION TOWER, MOSCOW, RUSSIA
RMJM, TONY KETTLE, PHILIPP NIKANDROV (GORPROJECT)
(CTBUH, 2016)

FIG. 3 Twisting towers case studies

Agora Garden, Taipei, Taiwan by Vincent Callebaut Architectures.

"The tower is a prototype of Carbon-Absorbing Green Building, and it will carry 23,000 trees planted on the ground and balconies, which can absorb 130 tonnes of CO_2 annually in Taipei. The sunlight, thermal, and wind analyses have enabled us to improve the bioclimatic design of the project" (Vincent Callebaut Architectures, 2020). The project received LEED Gold green certification from US Green Building Council, as well as Diamond Level from Low Carbon Building Alliance. However, apart from hand sketches, there was no demonstrated evidence of the impact of twisting on performance improvement (Fig. 3).

Absolute Towers, Mississauga, Canada by MAD architects.

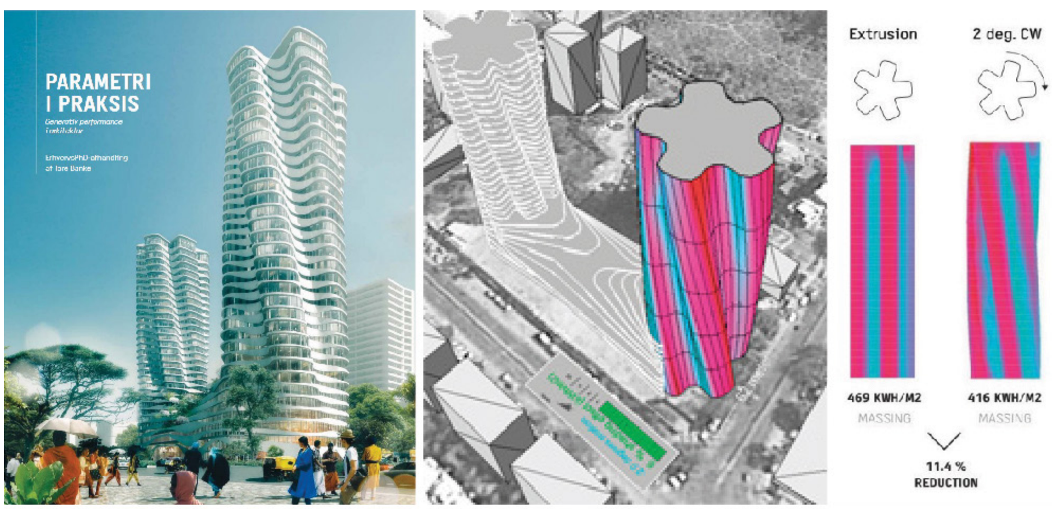
This is one of the few examples in which twisting was very loose, and instead of being very regular, in combination with smooth slabs/balconies, it created a fluid volume. Besides its unique shape, balconies were used to improve energy performance. Still, no specific quantitative value has been provided: "Besides providing every resident with a nice exterior place to enjoy views of Mississauga, the balconies naturally shade the interior from the summer sun while soaking in the winter sun, reducing air conditioning costs." (Frearson, 2012) (Fig. 3).

Evolution Tower, Moscow, Russia by RMJM, Tony Kettle, Philipp Nikandrov (GORPROJECT).

One of the juries of CTBUH said of the tower: "The world has seen an increasing number of twisting towers in the last decade or so, but Evolution Tower takes the record for the most extreme twist" (CTBUH, 2016). The main reason for such an extreme twist is purely aesthetical. "The sculptural DNA-shaped twisting tower symbolises the evolution spiral with the white façade ribbon wrapping over the roof in the form of a 90-degree twisting infinity symbol, which speaks of the philosophical concept of evolution and celebrates the development of human civilisation. From spiralling onion domes of St. Basil to the iconic Tatlin Tower concept the Russian architecture was obsessed with the idea of a spiral." (Nikandrov, 2020) (Fig. 3).

Tore Banke - PhD Thesis "Parametri i praksis - Generativ performance i arkitektur" (Parametric design in practice - Generative performance in architecture).

The last case study is the most documented in terms of the environmental benefit of twisting towers. The towers have a star-like floor plan with smooth corners that rotate 2 degrees floor to floor (Fig. 4). The author of this work has demonstrated 11.4% of cumulative irradiation reduction over the year (Banke, 2013). Yet, as it is shown in the results part of this research, such a parameter is not enough to prove to what extent this irradiation was harmful or beneficial. Moreover, it does not reflect the seasonal and daily dynamic of solar radiation and its combination with the external temperature that produces a specific thermal load on a building envelope.



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TORE BANKE, CITA, 3XN/GXN

FIG. 4 Twisting towers case studies (Banke, 2013)

As demonstrated in most of the described cases, if authors emphasised performance improvement, they mostly used the twisting effect to improve wind flows and consequently, structural performance. In some of the cases, blocking solar radiation was mentioned with minimal reference to the location-specific climatic loads and estimated energy savings. Therefore, since there was no significant evidence to conclude how twisting impacts performance on a global level, this paper uses a methodology based on simulations.

3 METHODOLOGY

The methodology of this paper uses an automated assessment procedure which utilises the simulation of solar radiation on façade surfaces to estimate the global self-shading potential of twisting forms, considering twisting angle and façade smoothness. Like similar methodologies used in green building certifications (US Green Building Council, 2014), the study used a baseline geometry in the form of a simple box obtained via vertical extrusion from a square rectangle. The baseline tower had four planar façades facing four cardinal directions. The study continued with gradually introducing and consequently increasing the twisting angle clockwise in increments of 1° up to 10°. Since the case study research revealed two façade cases, smooth/continuous, and discreet, the methodology assessed the solar self-shading potential for both façade options. For every twisting angle, an automated script developed explicitly for this study recorded results of each of the two façade states and repeated the process for all climates. Three different analyses process and extract quantitative data that is relevant to this study. Results of all three studies of self-shading potential are then summed up in tables with both absolute values and relative improvement compared to the baseline. The following paragraphs provide more detail of the sub-processes.

3.1 GEOMETRY AND TWISTING

The twisting tower has a 40x40m square floor shape that could rotate as it gained height. The testing building volume had 90 floors with 4m floor-to-floor height. Twisting has floor-to-floor rotation angle covering a range from 0° to 10° for the baseline tower, with continuous planar façade surfaces and maximum twisting tower, respectively. The direction of the twist was addressed in the preliminary analyses, where the design variable showed no influence on overall results.

Since irradiation on the surface was highly dependent on the angle setting and shading overhang, two different façade types were analysed. The first one represents a continuous, smooth façade without overhangs. The second one represents a discretised façade with all vertical surfaces and slabs that behaved as overhang shadings. The façade surface of each floor was tessellated into a 2x2m mesh grid that represented an optimal spatial resolution to provide reasonable accuracy vs computation time trade-off. Moreover, this spatial resolution was able to account for relatively small shaded areas below the slabs, particularly at small twisting angles. Examples of two façade types at an 8° floor-to-floor rotation angle are shown in Fig. 5.

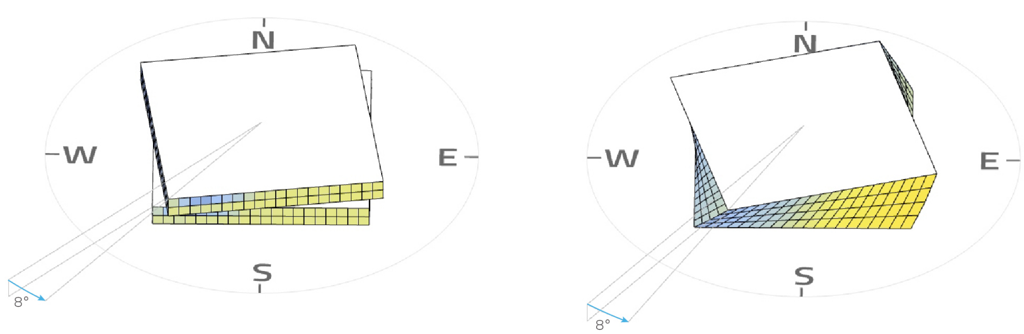

FIG. 5 Two façade types at 8° floor-to-floor rotation angle

3.2 CLIMATES

To address a full range of possible scenarios, this paper analysed twisting towers in all 17 different climates according to the ASHRAE (ASHRAE, 2013) and IECC climate classifications (ICC. 2000) (Fig. 6).

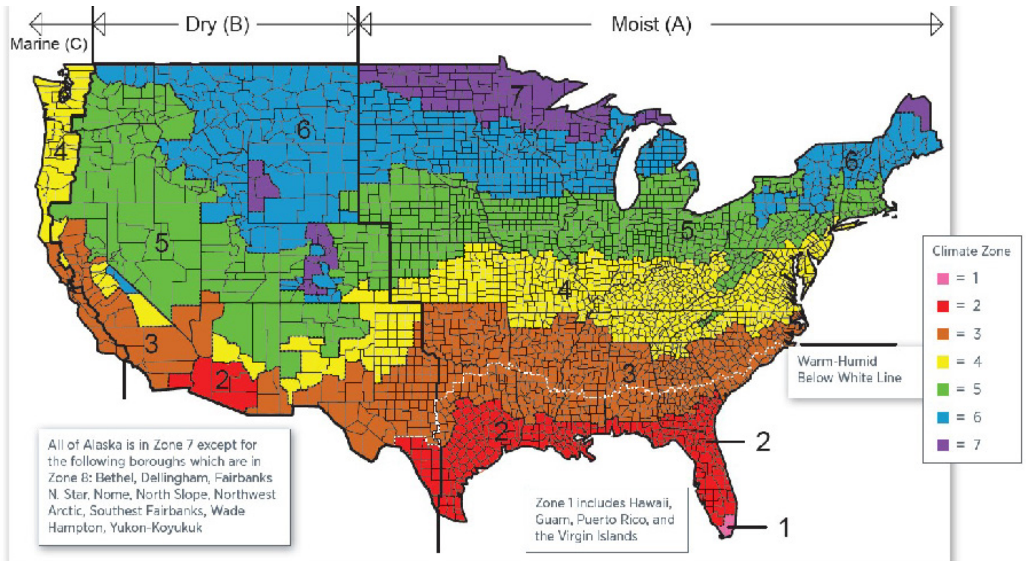

FIG. 6 ASHRAE and IECC climate classifications

Each of the climates had its specific combination of ASHRAE Cooling and Heating Degree Days that are used to estimate thermal loads on the building and give an estimate on HVAC sizing. A list of cities, representing each climate from the set, is shown in Table 1, along with climatic and site parameters extracted from (ASHRAE, 2013).

TABLE 6 A list of climates with the most relevant climatic parameters (Skalko et al., 2013)

ZONE NUMBER	ZONE NAME	THERMAL CRITERIA (SI UNITS)	LOCATION	LATITUDE	SHGC	HARMFUL IRRADIATION THRESHOLD [WH/M2]
1A	Very Hot - Humid	5000<CDD10°C	Miami, USA	25.82	0.25	380
1B	Very Hot - Dry	5000<CDD10°C	Dubai, UAE	25.25	0.25	380
2A	Hot-Humid	3500< CDD10°C≤5000	Houston, USA	29.97	0.25	380
2B	Hot - Dry	3500< CDD10°C≤5000	Phoenix, USA	33.43	0.25	380
3A	Warm - Humid	2500< CDD10°C≤3500	Atlanta, USA	33.65	0.25	380
3B	Warm - Dry	2500< CDD10°C≤3500	El Paso, USA	31.77	0.25	380
3C	Warm - Marine	CDD10°C≤2500 AND HDD18°C≤2000	San Francisco, USA	37.62	0.25	380
4A	Mixed - Humid	CDD10°C≤2500 AND HDD18°C≤3000	New York, USA	40.78	0.40	237.5
4B	Mixed - Dry	CDD10°C≤2500 AND HDD18°C≤3000	Albuquerque, USA	35.05	0.40	237.5
4C	Mixed - Marine	2000<HDD18°C≤3000	Seattle, USA	47.45	0.40	237.5
5A	Cool - Humid	3000<HDD18°C≤4000	Chicago, USA	41.78	0.40	237.5
5B	Cool - Dry	3000<HDD18°C≤4000	Denver, USA	39.76	0.40	237.5
5C	Cool - Marine	3000<HDD18°C≤4000	Vancouver, CAN	49.18	0.40	237.5
6A	Cold - Humid	4000<HDD18°C≤5000	Minneapolis, USA	44.88	0.40	237.5
6B	Cold - Dry	4000<HDD18°C≤5000	Helena, USA	46.60	0.40	237.5
7	Very Cold	5000<HDD18°C≤7000	Duluth, USA	46.83	0.45	211.1
8	Subarctic	7000<HDD18°C	Fairbanks, USA	64.82	0.45	211.1

3.3 IRRADIATION ANALYSES

The methodology analyses irradiation on the façade surface using the raytracing method within the Ladybug tools plug-in for grasshopper and Rhino. Solar radiation is considered as one of the most critical parameters in passive solar design techniques for estimating energy balance and solar shading potential (Olgyay & Olgyay, 1957; Olgyay et al., 1963; Givoni, 1969). For every climate, one sky-matrix was produced, combining both direct and diffuse solar radiation components for all 8760 hours of the year. An intersection matrix was used to compute irradiance falling on each of the 14,400 mesh faces at each timestep for both façade types, twisting state, and climate. In total, 126,144m data points were computed for each of the 374 design states (2 façade types x 11 twisting angles x 17 climates). Simulations excluded multiple reflections as this would drastically increase the time for an already highly demanding computation. Moreover, solar radiation analyses neglected indoor and material-specific parameters of the façade such as thermal conductivity, building energy systems, and HVAC. These parameters would impose many additional climate-specific criteria and therefore, drastically increase discrepancies of results between climates.

Irradiation data were processed and analysed in three different ways. The first analysis was the most common cumulative annual irradiation that integrated all timesteps and produced a cumulative irradiation value for each mesh face. An average irradiation value was recorded for every twisting state and both façade types. This analysis was capable of quantitatively demonstrating an increase or decrease of average irradiation levels for different twisting states (Fig. 7). However, climate conditions differ significantly, ranging from the extreme cold to hot environments. Therefore, assuming that irradiation is always harmful is far from accurate. Yet, the primary purpose of this analysis is to show a correlation between higher temporal resolutions used in this study with the lower temporal resolutions commonly used in passive solar design.

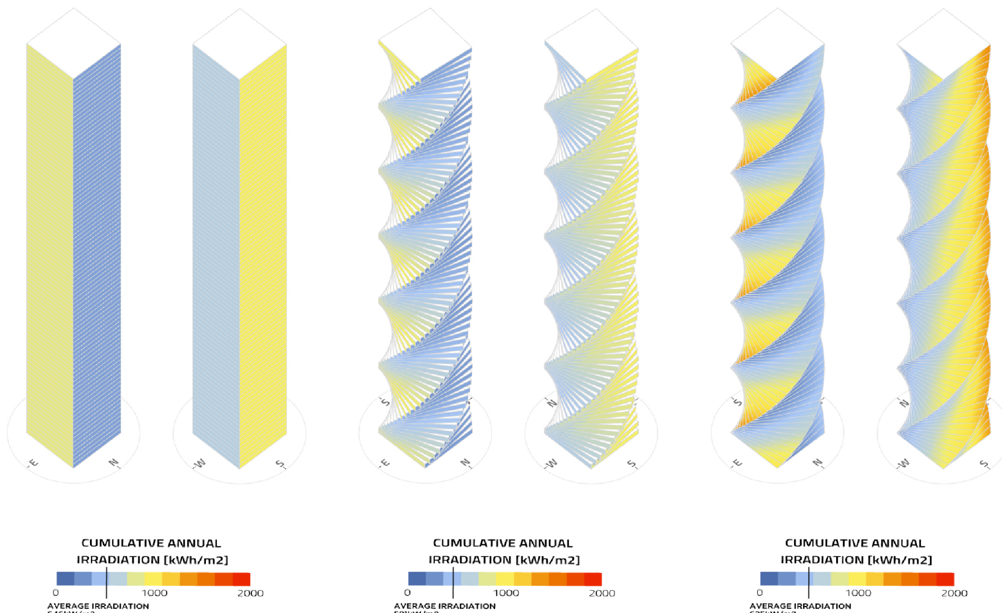

FIG. 7 Cumulative Annual Irradiation Analysis

To be able to quantify harmful and beneficial radiation throughout the year, it was necessary to consider dry bulb temperature to determine whether irradiation would improve or reduce thermal balance for every time step. The analysis assumed that solar radiation might contribute to the thermal load balance between indoor and outdoor environments in both negative and positive ways. "The following sources of heat flow are typically considered in buildings: conduction through walls and windows, infiltration and ventilation, solar as well as internal heat gains for occupants, equipment and electric lighting. ... For all buildings, there is a temperature range at which these heat flows cancel each out over the day, keeping the building within a desired interior temperature range without the need for active heating and cooling. This temperature range is called the balance point temperature range of the building." (Reinhart, 2014). The authors used the following assumptions to calculate the balance point temperature range:

Indoor environments have constant internal heat gains from occupants for a standard office that is the sum of the mean occupancy load (13.5 W/m^2), the mean lighting load (10.1 W/m^2) and the mean equipment load (8 W/m^2). Solar gains for mid-latitudes in June are roughly 2.9 kWh/m^2. Ventilation losses were set to 0.5h^{-1} ACH (air changes per hour) and forced ventilation for a fresh air supply rate of 10l/s per occupant during office hours (8 am - 6 pm). Conduction losses were set to 0.391 W/m2K for walls and 1.6 W/m^{2}K for windows with a glazing ratio of 40%.

Assuming the desired temperature range from 20°C to 26°C, the authors calculated the balance point temperature to be 8-14 °C for June for mid-level latitudes. These temperatures may seem quite low, yet it shows that an internal load-dominated space such as the reference office tends to receive more internal and solar gains than it loses through the building envelope.

To compute the exact balance temperature point, it was necessary to calculate solar heat gains and heat losses for every mesh face throughout every time step. This would provide different balance point temperatures across the façade surface and different seasons. Since this was not practical, and the study was focused on overall building performance, this analysis assumed a unique balance point temperature of 12°C and a balance temperature range of 8-14°C. The fluctuation of balance point temperature throughout the seasons and in different climates was set to ±2°C. It could have been expected that this approximation could introduce an error range that was estimated to be within a 10% range.

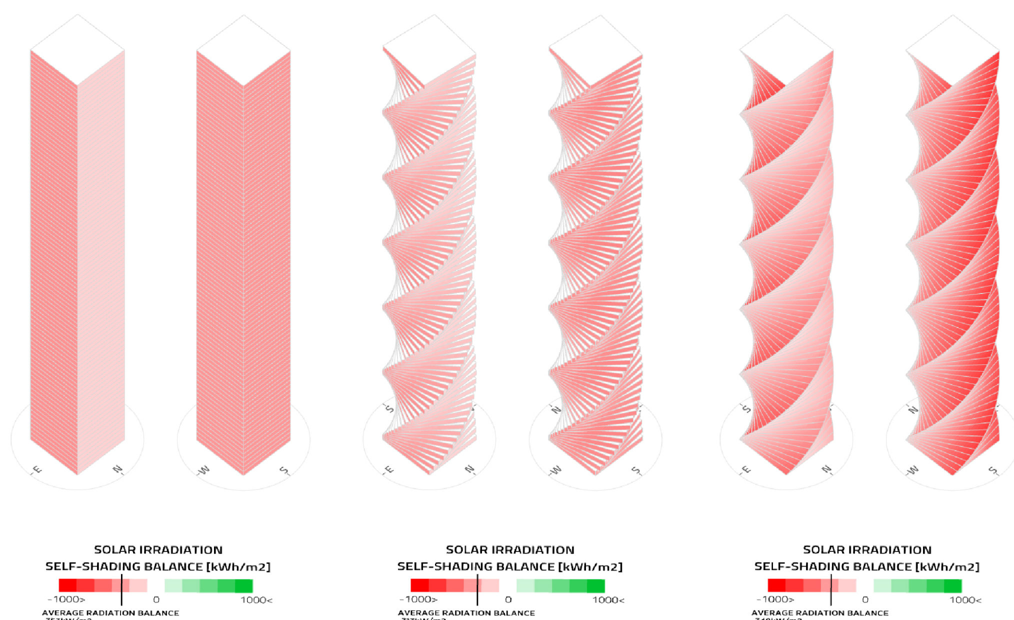

FIG. 8 Solar Irradiation Self-Shading Balance Analysis

For every time step, the algorithm checked if outdoor dry bulb temperature was above or below the balance point temperature range and the irradiance of this time step was classify into two sets of sky matrices. Whenever outdoor dry bulb temperature was above the balance point temperature, it sorted irradiance for that time step into a harmful irradiation set, as this irradiation would likely decrease thermal comfort by adding more heat. Harmful irradiation was presented as negative. On the contrary, if outdoor dry bulb temperature was below the balance point temperature, it classified irradiance for that time step into beneficial irradiation, as this irradiation will likely increase thermal comfort by adding more heat. Beneficial irradiation was presented as positive. At the end of the hour classification, two lists of hours of the year were created and two irradiation values were integrated for every mesh face, beneficial and harmful cumulative irradiation. These two cumulative values were then summed up. If harmful (negative) values prevailed, additional shading would be needed. On the other hand, if beneficial irradiation prevailed, more solar heat gain would be required to heat the space and reduce energy consumption for heating passively. By considering both beneficial and harmful radiation at the same time, it was possible to estimate the impact of self-shading across climates, including both hot and cold extremes. Performance improvement of twisting was confirmed if the overall sum of irradiations approached 0 in comparison to the baseline. In this sense, zero represented an irradiation balance point in which shading was neither beneficial nor harmful (Fig. 8).

The third type of analysis focused on hot climates and considered cumulative irradiation to estimate a self-shading potential on a Cooling Design Day, as this day is commonly used to determine cooling loads and HVAC sizing. The increase of irradiation above a threshold was considered as being always harmful, and therefore increased average irradiation represented a decrease in performance. In other words, negative values represent decreased performance as harmful irradiation increases (Fig. 9). The transmitted luminous intensity threshold was set to 95W/m^2 (Skalko et al., 2013), which, in combination with the prescribed Solar Heat Gain Coefficients (SHGC) from Table 5.5-1 – 5.5-8 Building Envelope Requirements for Climate Zones 1-8 (SI) of the same document, for different climates, produced different irradiance thresholds (Table 1).

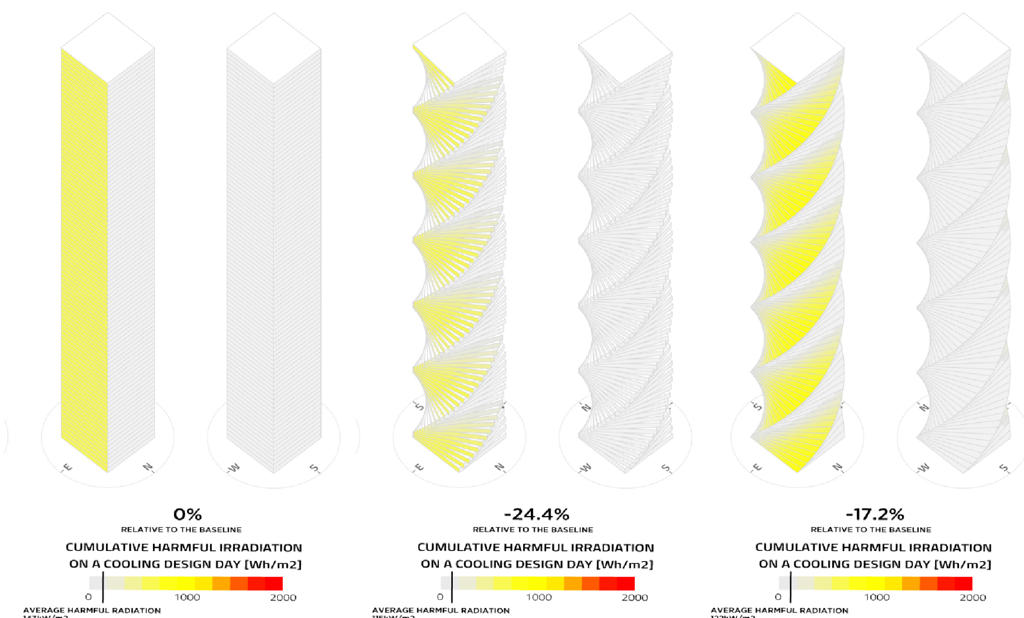

FIG. 9 Cumulative Harmful Irradiation during Cooling Design Day Analysis

4 RESULTS

The automated script calculated all twisting states in all the climates for both façade types and all three analyses. The results of this assessment are summarised in 6 charts. Cumulative Annual Irradiation for smooth façades (Fig. 10) shows differences in average baseline irradiation levels of around 300kWh/m2. In most of the climates, twisting reduces irradiation levels by up to 80kWh/m2. However, results exhibit a small anomaly in the lower twisting angle range, where the irradiation first slightly increases and then gradually drops. This trend is present in all climates but more dominant in hot ones.

SMOOTH - Cumulative Annual Irradiation [kWh/m2]																	
Rotation	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
0	665	788	635	885	646	863	747	551	888	572	652	830	597	705	719	672	530
1	670	796	641	896	652	871	754	554	895	576	657	837	603	709	724	676	532
2	666	792	638	892	649	867	750	551	891	574	654	832	600	706	721	673	529
3	662	787	634	885	645	861	745	547	885	569	650	826	595	701	716	668	526
4	656	780	628	878	639	854	738	542	877	564	644	819	590	694	709	662	521
5	649	772	622	868	632	845	730	537	868	558	637	810	583	687	701	655	515
6	642	763	614	858	625	835	721	530	857	551	629	800	576	679	693	647	509
7	634	753	606	847	617	824	712	523	846	544	621	790	568	670	684	638	502
8	625	743	598	836	609	813	703	516	835	536	613	779	560	660	674	629	494
9	616	732	589	823	600	801	692	508	822	528	603	767	552	650	664	620	486
10	605	720	579	809	589	787	681	500	809	520	593	754	543	639	653	609	478

FIG. 10 Cumulative Annual Irradiation Analysis Results for a Smooth Façade

Cumulative Annual Irradiation for the discrete façade (Fig. 11) shows similar trends in baseline irradiance but has slightly greater irradiance reduction of up to 100kWh/m2 with twisting. Similarly, it exhibits the same small increase in the lower twisting angle range, but with a limited effect. As expected, it was proven wrong to assume that the irradiance reduction is always beneficial. Furthermore, it would be impossible to make a clear division of climates into two groups, hot and cold climates, and assume irradiation reduction is beneficial for one group and harmful for the other. Instead, irradiation assessment would be much more meaningful with an increased temporal resolution in which irradiation is assessed concerning the temperature for every time step, as shown in the second analysis.

DISCRETE - Cumulative Annual Irradiation [kWh/m2]																	
Rotation	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
0	665	788	635	885	646	863	747	551	888	572	652	830	597	705	719	672	530
1	668	794	639	894	651	870	753	553	894	576	657	836	602	709	724	676	532
2	657	781	630	882	641	857	742	546	882	569	649	826	596	701	717	669	528
3	643	763	616	864	628	840	726	535	865	559	637	810	586	689	705	658	522
4	625	742	600	842	612	819	707	522	844	546	622	792	573	675	691	644	513
5	609	722	584	822	596	799	689	510	825	534	608	774	561	661	677	631	505
6	594	703	570	802	581	780	672	498	805	523	595	756	549	647	663	618	496
7	581	688	557	785	569	763	657	487	789	513	583	741	539	635	651	607	488
8	568	673	546	769	557	748	643	478	773	503	572	726	529	624	639	597	481
9	559	661	537	757	547	736	632	470	760	495	563	714	521	614	630	588	474
10	547	647	525	741	536	720	618	460	745	485	552	700	511	602	618	577	466

FIG. 11 Cumulative Annual Irradiation Analysis Results for a Discrete Façade

As explained, the self-shading benefit analysis shows results with much higher resolution and therefore, more reliable data. Regarding baseline irradiation balance for the smooth façade, results show high levels of excessive irradiation in hot climates on average. On the contrary, irradiation is not sufficient in cold climates. Fig. 12 shows that twisting generally improves performance in all climates to a variable degree. However, the effectiveness of the self-shading is almost negligible for a range of moderate to cold climates, 4A to 8. Moreover, the real effect may be seen only in hot climates where reduction of irradiance can be up to 70kWh/m^2 on average. Similarly to the previous analyses, small twisting angles tend to slightly decrease performance, while higher angles always improve the balance.

SMOOTH - Self-shading Balance [kWh/m2]																	
Rotation	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
0	-650	-786	-529	-774	-353	-585	-444	-173	-344	-238	-165	-195	-210	-126	-103	49	19
1	-655	-794	-536	-787	-362	-600	-451	-178	-360	-241	-172	-206	-215	-133	-109	43	19
2	-652	-790	-534	-784	-360	-597	-448	-177	-358	-240	-171	-205	-213	-132	-108	43	19
3	-647	-785	-530	-778	-358	-593	-445	-175	-355	-238	-170	-204	-212	-131	-107	43	19
4	-642	-778	-526	-771	-355	-588	-441	-174	-352	-236	-168	-202	-210	-130	-106	42	19
5	-635	-770	-520	-763	-352	-582	-437	-172	-349	-233	-167	-200	-207	-129	-105	42	18
6	-628	-761	-514	-754	-348	-575	-432	-170	-345	-231	-165	-198	-205	-127	-104	41	18
7	-620	-751	-508	-745	-343	-568	-426	-169	-341	-228	-163	-196	-202	-126	-103	40	18
8	-611	-741	-501	-735	-339	-561	-421	-167	-337	-225	-161	-194	-200	-125	-101	39	18
9	-602	-730	-493	-724	-334	-553	-415	-164	-333	-222	-159	-191	-197	-123	-100	38	17
10	-592	-718	-485	-712	-329	-543	-408	-162	-327	-218	-157	-188	-194	-121	-99	38	17

FIG. 12 Solar Irradiation Self-Shading Benefit Analysis Results for a Smooth Façade

On the other hand, discrete façade analysis shows slightly different results (Fig. 13). In all climates except 7 and 8, twisting improves irradiation balance in general. The baseline comparison reveals that hot climates have proportionally higher irradiance levels in contrast to the hot ones that are closer to the balance point as climates become colder. This implies that all irradiation in colder climates can be considered beneficial and there is no risk of excessive radiation and therefore no need for self-shading. A similar bump of adverse effect from twisting is visible when a small amount of twisting is applied. Values first go off the balance point and then get closer. In that sense, the baseline and 4° twisting solutions have almost equal performance.

DISCRETE - Self-shading Balance [kWh/m2]																	
Rotation	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
0	-650	-786	-529	-774	-353	-585	-444	-173	-344	-238	-165	-195	-210	-126	-103	49	19
1	-653	-791	-535	-786	-361	-598	-449	-177	-358	-241	-172	-206	-214	-133	-108	43	19
2	-643	-779	-526	-774	-354	-587	-441	-173	-349	-237	-167	-199	-211	-128	-105	45	19
3	-628	-761	-513	-756	-344	-572	-428	-167	-338	-230	-161	-191	-205	-122	-99	48	21
4	-611	-740	-499	-736	-333	-555	-415	-160	-325	-223	-154	-181	-198	-116	-93	50	23
5	-595	-720	-486	-717	-322	-539	-402	-154	-313	-216	-148	-173	-192	-110	-87	52	24
6	-580	-701	-473	-699	-313	-525	-390	-149	-303	-210	-143	-166	-186	-105	-83	53	26
7	-567	-685	-462	-683	-305	-512	-380	-144	-294	-204	-138	-160	-181	-101	-79	54	27
8	-555	-671	-452	-669	-297	-501	-371	-140	-286	-199	-134	-154	-176	-97	-75	55	27
9	-546	-659	-444	-657	-292	-491	-363	-137	-280	-195	-131	-150	-173	-94	-72	56	28
10	-534	-644	-434	-643	-285	-480	-354	-134	-273	-190	-127	-145	-168	-91	-69	56	29

FIG. 13 Solar Irradiation Self-Shading Benefit Analysis Results for a Discrete Façade

The last analysis is more relevant for hot climates as it shows a self-shading benefit on the Cooling Design Day. All results are normalised, and positive values represent an increase in harmful irradiation, whereas negative values represent decreased irradiation. Fig. 14 shows results for the smooth façade with high variability of results across climates. Only climates 1A and 3A show self-shading potential for all twisting angles. In climates 1B, 2A, 2B, 3B, and 3C, twisting angles up to 4° - 5° show self-shading potential, while larger twisting angles exhibit a linear increase of harmful irradiation. Climate 4A is quite neutral, showing the only slight benefit of twisting. Climates 4B to 8 show a slight increase of harmful radiation, but these climates are less relevant for this analysis.

SMOOTH - Harmful Radiation during the Cooling Design Day relative to Baseline [%]																	
Rotation	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	-15.6	-43.5	-12.9	-16.3	-10.4	-14.1	-14.1	-2	6.7	4.3	0	4.8	2.3	0.1	3.9	1.6	-2.1
2	-15.7	-34.5	-9.8	-13.1	-11.1	-10.3	-11	-2	8.4	4.4	0.5	5.3	2.5	0.4	4	1.8	-1.7
3	-15.8	-22.1	-5.2	-8.6	-12.1	-5.7	-6.5	-2	10.4	4.6	1.6	6	2.7	0.8	4	2	-1.2
4	-15.7	-9.1	0.2	-3.9	-13.5	-0.7	-1.8	-2	12.4	4.9	3	6.7	3	1.4	3.9	2.1	-0.7
5	-15.4	2.3	5.5	0.4	-15.2	4	2.5	-1.9	14	5.4	4.7	7.2	3.3	2	3.8	2.3	0
6	-14.9	11.3	10.2	4	-17.2	8.2	6.4	-1.7	15.2	5.7	6.2	7.6	3.5	2.6	3.6	2.4	0.9
7	-14.3	18.2	14.2	7	-19.2	11.8	9.8	-1.5	15.9	5.9	7.5	7.8	3.6	3.1	3.3	2.5	1.9
8	-14	23.2	17.4	9.5	-20.9	14.6	12.3	-1.3	16.2	5.9	8.5	7.9	3.4	3.5	2.9	2.4	2.7
9	-13.7	26.8	20	11.6	-22.5	16.7	14.3	-1.3	16.3	5.7	9.2	7.8	3.1	3.6	2.3	2	3.1
10	-14	28.8	21.4	12.5	-24.3	17.8	15.2	-1.7	15.6	5.1	9.1	7.2	2.4	3.3	1.5	1.4	3.1

FIG. 14 Cumulative Harmful Irradiation during Cooling Design Day Analysis Results for a Smooth Façade

Lastly, Fig. 15 shows different behaviour in comparison to Fig. 14. For a discrete façade type, all climates from 1A to 4A demonstrate a decrease up to approximately 50% of harmful irradiation on a Cooling Design Day with almost linear progression. Only climate 1B shows huge potential in reduction with a decrease up to 118% for the maximum twisting angle.

SMOOTH - Harmful Radiation during the Cooling Design Day relative to Baseline [%]																	
Rotation	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	-15.6	-43.5	-12.9	-16.3	-10.4	-14.1	-14.1	-2	6.7	4.3	0	4.8	2.3	0.1	3.9	1.6	-2.1
2	-15.7	-34.5	-9.8	-13.1	-11.1	-10.3	-11	-2	8.4	4.4	0.5	5.3	2.5	0.4	4	1.8	-1.7
3	-15.8	-22.1	-5.2	-8.6	-12.1	-5.7	-6.5	-2	10.4	4.6	1.6	6	2.7	0.8	4	2	-1.2
4	-15.7	-9.1	0.2	-3.9	-13.5	-0.7	-1.8	-2	12.4	4.9	3	6.7	3	1.4	3.9	2.1	-0.7
5	-15.4	2.3	5.5	0.4	-15.2	4	2.5	-1.9	14	5.4	4.7	7.2	3.3	2	3.8	2.3	0
6	-14.9	11.3	10.2	4	-17.2	8.2	6.4	-1.7	15.2	5.7	6.2	7.6	3.5	2.6	3.6	2.4	0.9
7	-14.3	18.2	14.2	7	-19.2	11.8	9.8	-1.5	15.9	5.9	7.5	7.8	3.6	3.1	3.3	2.5	1.9
8	-14	23.2	17.4	9.5	-20.9	14.6	12.3	-1.3	16.2	5.9	8.5	7.9	3.4	3.5	2.9	2.4	2.7
9	-13.7	26.8	20	11.6	-22.5	16.7	14.3	-1.3	16.3	5.7	9.2	7.8	3.1	3.6	2.3	2	3.1
10	-14	28.8	21.4	12.5	-24.3	17.8	15.2	-1.7	15.6	5.1	9.1	7.2	2.4	3.3	1.5	1.4	3.1

FIG. 15 Cumulative Harmful Irradiation during Cooling Design Day Analysis Results for a Discrete Façade

5 DISCUSSION

Presented results reveal how temporal resolution impacts the quality of results. It confirmed that cumulative annual irradiation should not be used to quantify the self-shading benefit, unless for very hot climates, where there are no Heating Days so it can be assumed that all irradiation is harmful. For all other cases, there may be some percentage of beneficial radiation that increases as climates have more Heating Days. For general purposes, the Solar Irradiation Self-Shading Benefit analysis that calculates irradiation balance should be used as it provides much more granularity and precision. This is demonstrated in Fig. 14. and Fig. 15. The discrepancy between discrete and smooth façade types can be assigned to several causes. Firstly, the angle setting of smooth façade panels follows the twisting curvature and therefore they have a low sun incidence angle. The reflection of coated glass at a low incidence angle is relatively small in comparison to the reflection of the glass above 56 degrees incidence angle, which is very high due to the exponential behaviour defined by the cosine law. Therefore, façade panels with low sun incidence angles are much more exposed to solar radiation. Secondly, self-shading at meso-level caused by floor volumes in a discrete façade scenario significantly reduces direct solar radiation in the upper part of the glazing that causes a drop in harmful irradiation levels. However, this analysis also has limitations as it is impractical to compute balance points for all façade points and all hours of the year. Therefore, the approximation increases simulation errors, but still provides a reasonable accuracy.

However, it is realistic to assume that these types of studies are practical for understanding trends, while more accurate simulations should be used on the narrow design search set. Moreover, for each specific case, a set of simulations could be extended to daylighting and whole building energy to provide more details on the behaviour of twisting geometries.

Regarding self-shading benefit, results have shown that claiming that twisting is a priori beneficial is not reasonable, as benefits may be highly sensitive to the climatic conditions and twisting angles, as well as façade type. In general, the discrete façade provides more benefit of twisting as it offers more floor-to-floor self-shading while the smooth façade only provides building volume self-shading.

6 CONCLUSION

The study demonstrates hundreds of possible scenarios of twisting towers with a relatively high sensitivity of self-shading benefits across different climates and various floor-to-floor rotation angles, revealing a variety of positive, negative, and neutral scenarios. Therefore, the study provides useful insights into a true global self-shading potential of twisting. It is recommended that all environmental conditions be carefully examined via irradiation studies, instead of automatically assuming self-shading benefits, particularly in the case of a smooth façade scenario.

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