

Classification of Oblique Grids in Curtain Walls: A Case-Study of Design Strategies in Modular Edge-Panels

Marcin Brzezicki¹

1 Faculty of Architecture, Wrocław University of Science and Technology, marcin.brzezicki@pwr.edu.pl

Abstract

Recent developments in façade engineering allow for much more freedom in designing façade grids, including various tessellations. This paper reviews different geometrical configurations in order to provide a framework for the understanding and classification of façades based on oblique grids. On the basis of case studies, this paper analyses oblique grids used in planar light-transmitting façades and evaluates existing geometries. The main difficulties linked to edge panels are: (i) the high number of unique panels and (ii) their irregular shape, which complicates the building process. This paper serves as a review of the currently used technologies and of the possible design solutions aimed at decreasing the number of unique panels. As a result, the applied strategies lower the costs and simplify the manufacturing process and installation of the façade's panels. Technologies that directly link façade geometries created using CAD software with manufacturing processes offer the possibility to use non-rectangular solutions on a much wider scale.

Keywords

building envelope, façade grid, curtain wall, glass façade, façade tessellation

1 INTRODUCTION – RECTANGULAR GRIDS

The invention of the curtain wall – also called the elemental façade (Schittich & Sauer, 2012) – significantly influenced the image of many contemporary cities. Rectangular grids started to dominate architectural design as they were the most economical solutions. Owing to the recent development of free-form volumes, contemporary glass façades have gone far beyond rectangular design and allow for much more complex 3-dimensional geometries than before. This trend has also influenced the design of planar glass façades and paved way for new non-rectangular tessellation options.

1.1 DEFINITIONS/GLOSSARY

A grid is “a three-dimensional geometrical co-ordination system with a regular sequence of equally spaced reference lines” (Herzog, Krippner, & Lang, 2008). Any point on the grid may be defined by a system of rectangular coordinates. Reference lines divide the surface of the façade into regular polygons/regions/bays/cells. These polygons will be further referred to as façade panels – either light-transmitting or opaque. In modular grids, the system of dimensional coordination is usually based on a repetitive module. Such systems are frequently based on unitised façade panels (Knaack, Auer, Klein, & Bilow, 2014).

Given the above, a system of irregular reference lines cannot be defined as a grid as it lacks modularity and equal spacing. Therefore, for the purpose of this article, the definition of a grid has been broadened and shall be defined as “a collection of nodes and cells” (Fundamentals of Visualizing Environmental Data, 2015) without the requirement of being regular. The grids presented in the following sections will be referred to as repetitive grids – in the case of regular tessellations – and arbitrary grids – in the case of arbitrary tessellations. The intersection of reference lines will be referred to as a grid node, while tessellation is defined as the division of the surface into smaller elements without overlaps and gaps. The grid is filled with polygons where the vertices serve as nodes of the grid.

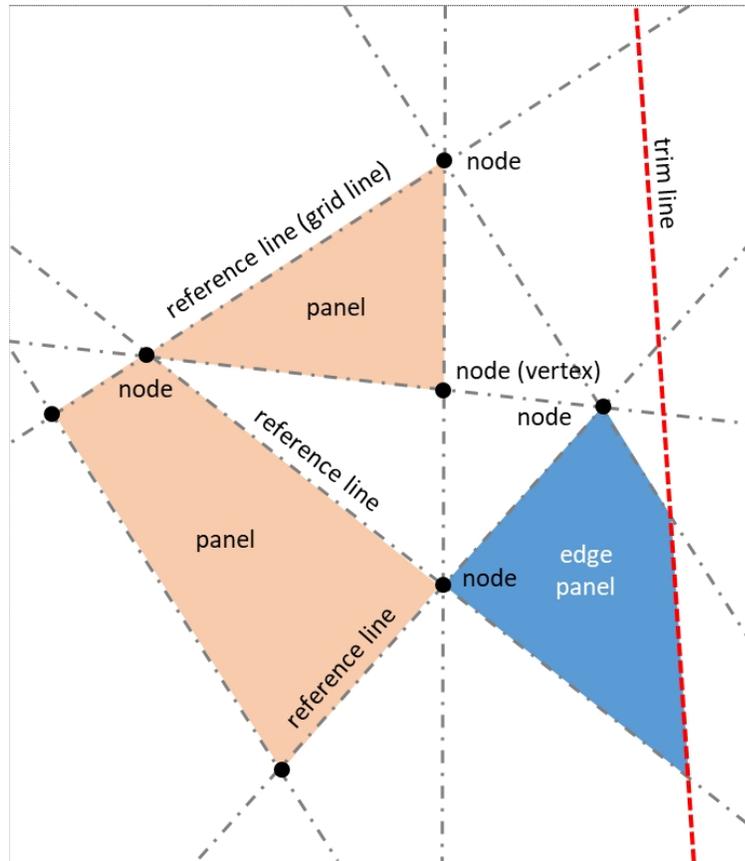


FIG. 1 Diagrammatic presentation of the basic definitions used in the paper (description provided in the diagram)

This paper discusses oblique grids, meaning that at least one reference line of the grid (gridline) is neither horizontal nor vertical. Some of these oblique grids are highly irregular/random and feature arbitrary surface tessellations. One of the problems addressed in this article is related to the panels positioned along the edges of the façade. The function of such edge panels is to fill the spaces between reference lines of the oblique grid (either repetitive or arbitrary) and the trim lines, i.e. the vertical or horizontal edges of the façade of the building (Fig. 1). The main issues related to edge panels are their irregular shape and, in certain cases, the large number of such irregular panels. This increases the manufacturing and installation costs since all individual panels first need to be tagged and then delivered in the proper mounting sequence to the building site, which is expensive, complicated, and prone to a large number of mistakes.

1.2 ORIGINS OF OBLIQUE GRIDS

The origin of oblique façade grids is difficult to determine. Currently, rectangular façade grids are filled with glazed or unglazed rectangular panels. After the discovery of flat rectangular glass production lines, this process of filling has become even easier. However, industrial flat glass manufacturing processes were introduced only in the late 19th century and early 20th century. Until then, flat glass was produced by different methods, e.g. crown glass, which dates back to 1330 (Rersson, 2013), which, in the final stage of production, was formed into flat glass discs. The most rational way to divide such discs without wasting too much material was to cut them into diamond-shaped sections called quarries. The lines were cut at an angle and radiated from the centre of the disc, producing quarries of different sizes depending on the radii, with the largest ones at the edge. This cut also produced less waste than cuts that formed square panels. These quarries were then arranged into a pattern and supported in lead cames, thus creating decorative windows called lead lights. Once the technology of rectangular sheet manufacturing was available, oblique grids for glass façades became the less obvious choice. In the modern era, oblique grids were frequently produced simply by rotating a rectangular grid, e.g. at Hampden Country Club (by architect, Paolo Riani, 1974).

2 METHODOLOGY AND SCOPE OF THE PAPER

This paper concentrates both on the technical and aesthetic aspects of oblique façade grids using a case-study approach. The goal is to analyse examples of oblique grids in planar light-transmitting façades with particular attention given to the so-called edge panels.

The next section discusses the main reasons for the application of oblique façade grids and offers a brief presentation of their typology followed by a geometrical analysis of the corresponding case-studies. In each case, a photograph of the building's façade is juxtaposed with a schematic diagram of the grid's repetitive panels and edge panels, with the pros and cons of each solution clearly presented in a table. Finally, the article examines the possibility of minimising the number of unique façade panels depending on the adopted design strategy. This minimisation process reduces the design effort, streamlines the manufacturing stage, and greatly simplifies the building process.

At the time of writing this article, no publication was available that offered a comprehensive analysis of oblique planar façade grids. An exhaustive geometrical study of the so-called wallpaper groups features a mathematical classification of two-dimensional repetitive patterns. Since the focus of this article is on arbitrary grids, the wallpaper group classification, however valuable, seems insufficient. A comprehensive study of architectural geometries is given by Pottmann and Bentley (2007) in the chapter entitled "Geometrical Aspects, Façade Grids". The issues of "single-curvature strips or flat facets" are also discussed in the paper titled "Freeform surfaces adaptation using developable strips and planar quadrilateral facets" (Gonzalez-Quintial & Artiz-Elkarte, 2015).

This review is intended to fill the aforementioned gap in the literature by presenting well-known examples of oblique façade grids and to suggest optimisation strategies for the design of the panels. Special attention is given to the way in which edge panels are handled, as well as on the possible strategies for limiting the number of unique panels. 90% of all issues arising from the usage of oblique grid façades stem from the inefficient design of the edge panels. Therefore, the optimisation of the design of edge panels in oblique grids contributes to important energy savings in design, material production, handling, and transport. Another important issue explored in this paper is the

reduction in the use of material resulting from optimal cut planning, e.g. when a rectangular pane is cut diagonally in half. This study might also be beneficial for educational purposes and prove useful in formulating strategies for future design.

It must be stressed that this paper focuses on oblique façade grids in planar glass façades, which are made of bona-fide polygonal panels, and not on rectangular panels that only resemble polygons. Such solutions are undoubtedly interesting from an architectural perspective but cannot be regarded as instances of oblique façade grids. An excellent example of such polygon imitations is the Kapok Hotel in Shenzhen Bay (by architect Goettsch Partners, 2012), which features a rectangular grid façade covered with a diagonal decoration.

3 THE REASONS FOR THE APPLICATION OF OBLIQUE FAÇADE GRIDS

It is possible to indicate a few important aesthetic and technical reasons for the application of oblique grids. Oblique grids alter the perception of the building shape making it seem more dynamic compared to an identical building with a rectangular grid. The oblique and diagonal lines are also purposefully used by architects to visually enlarge or decrease the volume of a building and influence the perception of the scale of the building. Oblique façade grids can also be ornamental. From a technical point of view, the most important function of an oblique grid is to stiffen the façade sub-structure, thus enhancing the rigidity of the entire building. Oblique members – in some cases diagonals – act as a bracing. The most striking example of the stiffening function of a diagonal grid façade is the Seattle Public Library (by architects OMA, 2004) where the I-beam sections arranged into lattice-like geometry provide “bracing during a seismic event” (Seattle Central Library Curtain Wall Design, n.d.). Another important technical reason for the use of oblique grids is when the diagonal grid of the façade follows the load-bearing structural diagonal grid of the building, e.g. the so-called diagrid structures, e.g. in J6 Front in Tokyo Omotesando, by architect Matsuda Hirata Design Inc., 2008, (See Fig. 2) or Atlas Building, Wageningen University and Research Center (by architect Rafael Viñoly, 2006).



FIG. 2 J6 Front in Tokyo Omotesando (by architect Matsuda Hirata Design Inc., 2008) features a diagrid of structural supporting elements with a diagonal grid of façade elements.



FIG. 3 The diagonal grid of the façade of MyZeil shopping centre in Frankfurt am Main (by architect M. Fuksas, 2009). The façade smoothly transforms into the triangulated geometry of the free-form roof. The figure shows the sub-structure of the façade grid attached to the floor slabs before the façade profiles were mounted.

Oblique grids also reduce the length of façade profiles. As the geometrical analysis shows, “polygonal tessellation will provide a smaller joint length per surface unit than rectangular grids” (Pell, Hild, Jacob, & Zaera, 2010). Oblique grids also provide a much easier transition from flat parts of the façade into free-form, double-curved geometries (Fig. 3). The use of triangular façade panels is a technical necessity as the only way to achieve a smooth transition from flat to arbitrarily formed geometry. However, such 3-dimensional grids are beyond the scope of this paper.

Modular grids used in building envelopes, curtain walls, and façades are usually related to the structural grid on which the building structure is based. Because “the most common geometrical relationships between the façade and structural grids are the offset and coincident arrangements” (Herzog et al., 2008), façades are usually based on rectangular or Cartesian grids. This dependency is stronger in solutions where the material zones overlap, which means that elements of the façade are somehow related to the structural elements, e.g. by the use of axial controlling lines, than in arrangements with separate material zones. The “separation of material zones enables the loadbearing structure and façade to be arranged independently of each other” (Herzog et al., 2008) and allows for the individual shaping of elements, which might be either identical or completely different.

Based on the presented case studies of oblique grids, at least three types of relationships between the façade grid and the axial controlling lines of the load-bearing structure can be distinguished. The possible arrangements include lines that (i) coincide fully, (ii) coincide partially, and are (iii) arbitrary, i.e. they do not coincide at any point.

In a **coincident arrangement**, the nodes of the façade grid exactly match the building’s structural load-bearing points which usually coincide with the points where the building’s axial controlling lines intersect. This facilitates the transfer of direct loads and eliminates torque/momentum. This solution is feasible when the grid is repetitive, and the curtain wall is loaded only by its own weight and wind pressure. In a **partially coincident arrangement**, only selected nodes are directly supported, while other nodes are either not supported at all, with the load being transferred to other elements of the façade, or are supported sparingly e.g. every second or third node. The façade might also be subjected to other loads. If independent material zones are designed – as in the case of the arbitrary façade grid – the grid has no relationship whatsoever to the building’s orthogonal load-bearing grid and the nodes are distributed freely. This type of façade is either load-bearing or the load is transferred indirectly. A system of additional structural members is usually designed to transfer loads from the arbitrary grid nodes to the load-bearing points of the main structure. Those members usually take the form of struts and brackets. This approach is currently very common in designing arbitrary grid façades, especially in the case of complex tessellations.

The diagram below shows the relationship between façade grids and axial controlling lines of the structure (Fig. 4).

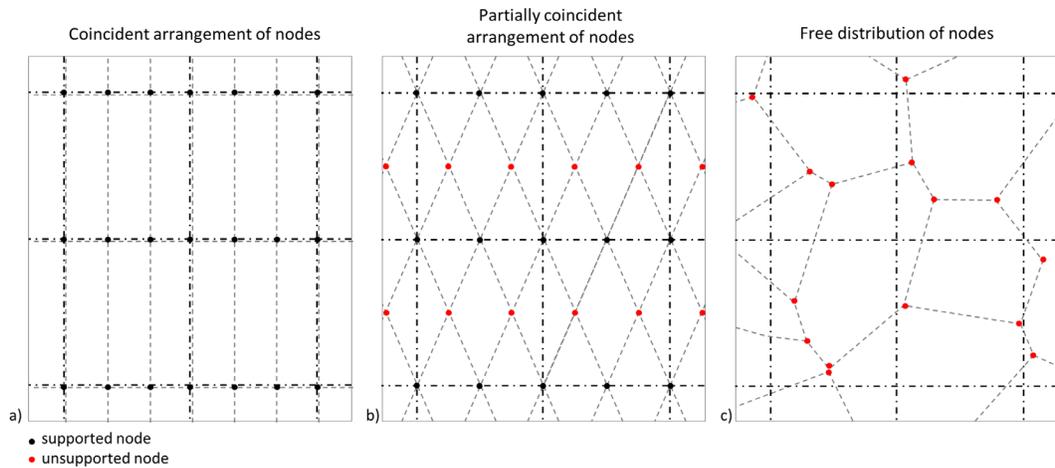


FIG. 4 The relationship between façade grids and axial controlling lines of the structure: a) coincident arrangement, b) partially coincident arrangement, c) free distribution of nodes

4 SIMPLIFIED TYPOLOGY

As mentioned above, the geometrical classification of two-dimensional repetitive patterns is based on the symmetries of the pattern. The following geometrical transformations are observed in 17 types of so-called wallpaper groups: symmetry, translation, and rotation. This approach seems redundant as only some wallpaper groups are used in façade grids. It is also not exhaustive as the wallpaper group classification does not include arbitrary tessellations. The presented simplified typology is based on the number of sides of the base polygon whose vertices/nodes specify the **reference lines** of the grid (Fig. 5). The orientation of the polygon is also a key element in the presented approach because the same quadrilateral grids in different orientations might be labelled differently.

The simplest oblique grid is based on an **equilateral triangle** and could also be referred to as hexagonal. A modification of this grid is a triangular grid based on the **isosceles triangles** or a grid based on **right-angled triangles**, which is a variant of the rectangular grid with an additional diagonal reference line.

Quadrilateral grids are based on the distortion – usually, skew – of the basic rectangular grid. The ones used most often are the rhomboidal grid, using a parallelogram with all sides equal, or quadrilateral, using a parallelogram with unequal sides. A quadrilateral grid with one horizontal reference line is usually labelled oblique, while a rhomboidal grid with diagonals positioned horizontally or vertically is often called a diamond grid. Note that a rectangular square grid rotated 45 degrees is also commonly called a diamond grid.

Voronoi tessellations are created by partitioning a plane into regions on the basis of the mathematical principle established by Georgy Voronoi. This complicated mathematical algorithm determines the shape of individual convex polygons – called “cells” – so that their borders are equidistant from the nodes, which are called “seeds”. This type of tessellation resembles the natural structure of a bone or cell.

An **arbitrary grid** is often inspired by nature as its irregular tessellations are commonly “found everywhere in nature, from cracked glazes to biological tissues to real crystals” (Goodman & O’Rourke, 2004). In architecture, arbitrary grids are often sketched by a designer or inspired by photographs of the surrounding townscape as in the case of Tod’s Omotesando.

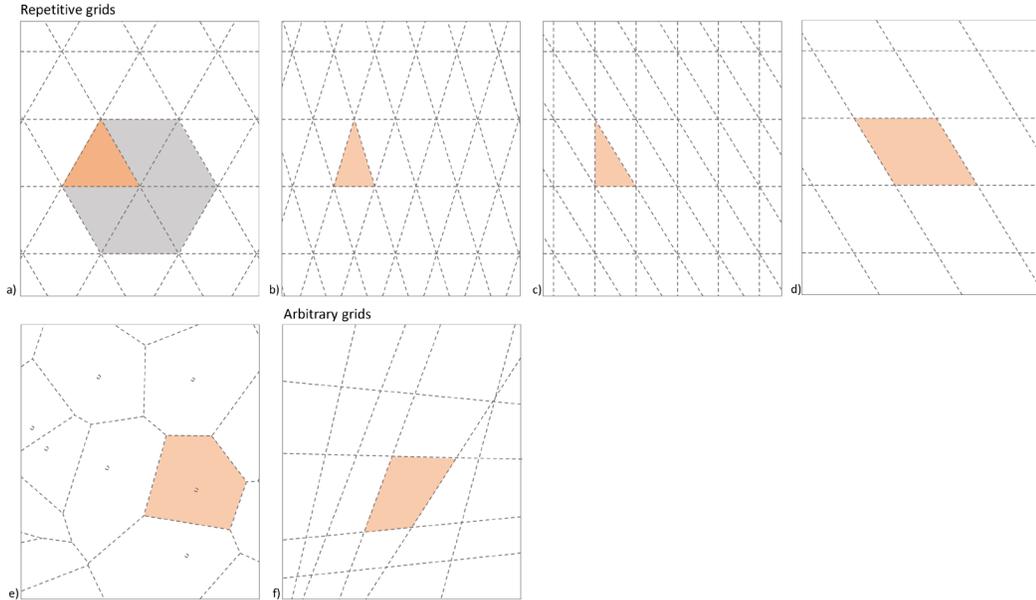


FIG. 5 Representation of a simplified typology based on the number of sides of the polygon: a) triangular (hexagonal grid); b) isosceles triangle grid; c) right triangle grid; d) quadrilateral grids; f) Voronoi tessellation; e) arbitrary grid

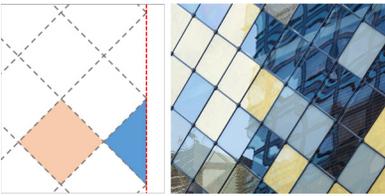
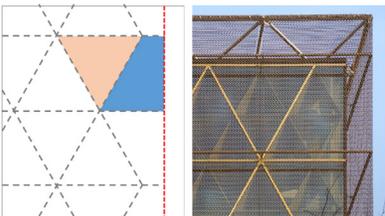
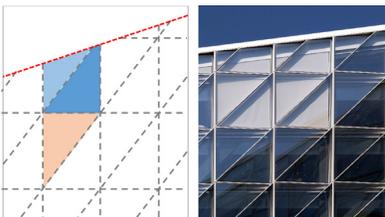
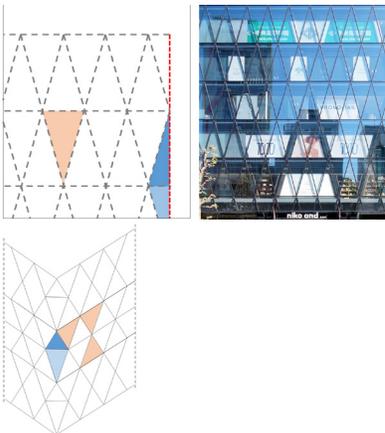
5 CASE-STUDY OF EDGE PANNELLING IN OBLIQUE FAÇADE GRIDS

In repetitive grids, edge panels fill the space between the grid lines and the trim line. In planar façades, the trim line usually coincides with the corner of the building (e.g. around the corners of orthogonal designs or at the intersections of surfaces enveloping non-orthogonal buildings). The following presentation of various strategies for edge panelling in oblique façade grids is based on selected case-studies of both repetitive and arbitrary grids.

The results of the case-study are presented below in a form of a table, which features the photographs of the façade, the schematic diagrams, and some pros and cons of every analysed solution.

5.1 REPETITIVE OBLIQUE GRIDS (PERIODIC TILINGS)

Regular planar façade grids are based on the repetition of identical polygons and different variations of edge panels. Regular diagonal grids most often use periodic panelling (using a modular panel or module). In terms of prefabricated elements of façades, regular diagonal grids minimise the number of unique panels. Various edge panel strategies are discussed below on the basis of particular case studies.

TYPE OF GRID	BUILDING NAME, ARCHITECT AND YEAR	DIAGRAM AND PHOTO (pink – regular/modular panel, blue – edge panel)	PROS.	CONS.
Diamond (rectangular grid rotated 45 deg.)	Yamaha Ginza by architect Nikken Sekkei, 2010	 <p>The diagram shows a grid of squares rotated 45 degrees. A central square is divided into four triangles by a diagonal line. The top-left triangle is pink, the top-right is blue, the bottom-left is blue, and the bottom-right is pink. A red dashed line indicates the edge of a panel. The photo shows the actual facade with a complex, multi-colored glass pattern.</p>	<p>Triangular (half square) edge panels are created by cutting the base square panel in half along the diagonal</p> <ul style="list-style-type: none"> - repetitive edge panel - easy replacement 	<p>Panels are not exchangeable because of the different colour. This increases the number of unique panels. Edge panels are geometrically identical but of a different colour</p>
Triangular	Ohel Jakob synagogue in Munich, by architect Rena Wandel-Hoefer Lorch, 2001	 <p>The diagram shows a grid of squares. A central square is divided into a trapezoid and a rectangle by a vertical line. The trapezoid is pink and the rectangle is blue. A red dashed line indicates the edge of a panel. The photo shows the actual facade with a complex, multi-colored glass pattern.</p>	<p>Edge panel is trapezoidal in shape and consists of a regular triangular panel cut vertically in half and a rectangle. Rectangular extension compensates two different modular zones of the load-bearing structure and the façade.</p> <ul style="list-style-type: none"> - repetitive edge panel - easy replacement 	<p>The glass coating might enforce 2 types of edge panels to be manufactured</p>
	Japan Tobacco Headquarters arch. SOM, 2015	 <p>The diagram shows a grid of squares. A central square is divided into a triangle and a trapezoid by a diagonal line. The triangle is pink and the trapezoid is blue. A red dashed line indicates the edge of a panel. The photo shows the actual facade with a complex, multi-colored glass pattern.</p>		<p>High variety of edge panels is formed with triangular, trapezoidal and polygonal shapes because roof trim line and the bottom trim line are neither anchored to the grid nor parallel to each other</p>
	J6 Front in Tokyo Omotesando, by architect Matsuda Hirata Design Inc., 2008	 <p>The diagram shows a grid of squares. A central square is divided into two triangles by a diagonal line. The top triangle is pink and the bottom triangle is blue. A red dashed line indicates the edge of a panel. The photo shows the actual facade with a complex, multi-colored glass pattern.</p>	<p>No edge panels for horizontal trim. The tessellation of the façade is simple and consists of a repeating isosceles triangle in two orientations (pointing up and pointing down).</p> <ul style="list-style-type: none"> - repetitive edge panel for horizontal trim, - easy replacement 	<p>Edge panels for the vertical trim line were developed as the so-called corner panels, with the faces somewhat sunken in relation to the front façade.</p> <ul style="list-style-type: none"> - complicated and non-standard edge panel for vertical trim, although repetitive every 2 grid lines

>>>

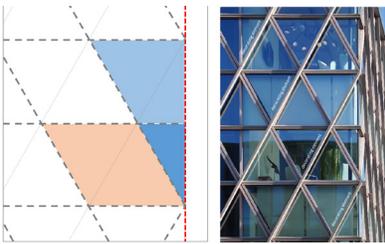
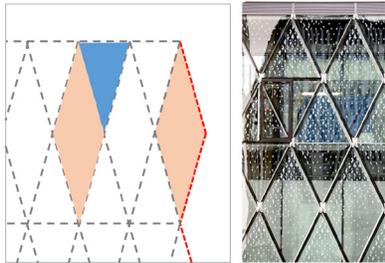
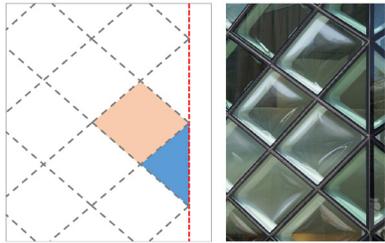
TYPE OF GRID	BUILDING NAME, ARCHITECT AND YEAR	DIAGRAM AND PHOTO (pink – regular/modular panel, blue – edge panel)	PROS.	CONS.
Rhomboid	Office Building the XXX-en, by architect: bnb architect, B06 architectenbureau, 2010		- 2 repetitive edge panels	2 types of edge panels are created by splitting the modular rhomboidal panel into (i) a right-angled triangle and (ii) a trapezoid by the trim line which coincides with the edge of the building
	Beaugrenelle in Paris, by architect Valode et Pistre, 2014		- repetitive edge panel for horizontal trim, - no edge panel for "vertical trim"	
	Prada Aoyama Epicenter in Tokyo, by architect Herzog & de Meuron, 2003		One vertical façade edge panel is generally a triangular element obtained by cutting the regular rhomboid panel in half vertically. - repetitive edge panel	Panels, although regular in geometrical shape are different because of the use of flat or bent glass. Not all edge panels are identical. Inclined roof surface changes the geometry of the grid, thus a skewed rhomboid grid is produced, that requires additional shapes types of repetitive panels

TABLE 1 Repetitive oblique grids

5.2 POLYGONAL GRIDS - VORONOI TESSELLATIONS

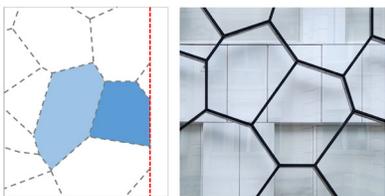
TYPE OF GRID	BUILDING NAME, ARCHITECT AND YEAR	PHOTO AND DIAGRAM	PROS.	CONS.
Voronoi tessellations	Parliament Francophone Bruxellois, by architect Skope/ Paradise Architecture/ COOPARCH-R.OU, 2014		Despite the illusion of immense complexity, the Voronoi tessellation is actually a repetitive pattern of convex polygons: 1 regular pentagon and 4 arbitrary convex polygons. Only 5 standard panels are required to cover the façade	To form edge panels, the 5 repetitive panels are trimmed by the horizontal and vertical trim lines of the façade. This trim operation generates numerous, non-repetitive unique panels. - many unique panels

TABLE 2 Polygonal grids

5.3 ARBITRARY OBLIQUE GRIDS (NO PERIODIC TILING)

Planar arbitrary oblique grids are less common because, due to the irregular arrangement of reference lines, instead of repetitive polygonal panels they require many irregular and non-repetitive panels. The application of arbitrary oblique grids means that every façade panel (including the edge panels) is described by a different polygon and has to be treated as a different façade element. Therefore, no specific edge panel strategy is developed as there are no repetitive panels – all panels have to be handled as edge panels. Nevertheless, some specific solutions for arbitrary grids exist and are discussed below:

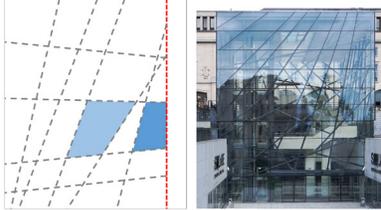
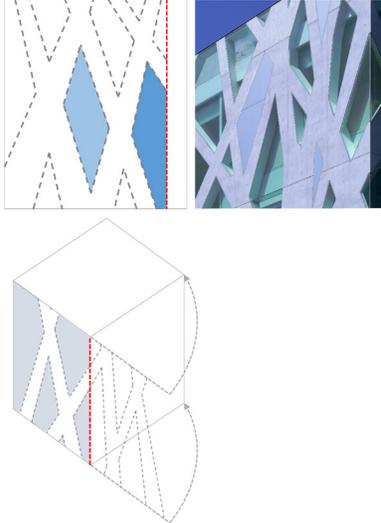
TYPE OF GRID	BUILDING NAME, ARCHITECT AND YEAR	DIAGRAM AND PHOTO	PROS.	CONS.
Arbitrary oblique grids (no periodic tiling)	Square Brussels Meeting Center, by architects A2rc Architects, 2009		The perpendicular façades are mirrored, which reduces the number of individual joints but still requires a lot of non-standard panels to be manufactured	Because of the irregular reference lines, the façade panels are highly arbitrary, and it is difficult to establish a substantial difference between façade panels and edge panels
	Tod's Omotesando Building, by architect Toyo Ito, 2004		The geometry of the oblique grid was originally taken from the Serpentine Pavilion, built in 2002 by Toyo Ito which "appeared to be an extremely complex random pattern" but in fact was "derived from an algorithm of a cube that expanded as it rotated". (The Serpentine Gallery Pavilion 2002, 2002)	Edge panels, which seem to be wrapped or folded around the corners of the building, create continuous irregular shapes. Façade produces a large number of untypical arbitrary panels that have to be handled independently

TABLE 3 Arbitrary oblique grids

6 DISCUSSION

The above chapters review different geometrical configurations of façade grids, with a special focus on edge panels. While edge panels in repetitive grids can be optimised to achieve a limited number of unique parts, arbitrary grids produce many atypical panels. Therefore, the reduction in the number of unique panels is a necessity, from an engineering perspective, in order to lower the cost, simplify the installation process and save time. The design process is also less complicated. In the

case of failure, repetitive panels are easier to replace because spare panels could be manufactured in advance and can be put in any location on the façade.

Edge panels are the understandable result of the use of the use of infinite repetitive oblique grids on finite façades. Their shape and differentiation/variety depend on how the building's façade grid and structural grid overlap. With respect to the practical and financial aspects of designing oblique façade grids, two issues are important:

Firstly, the number of unique edge panels should be reduced, and secondly, a strategy for designing edge panels should be adopted. The ways of reducing the number of unique edge panels were studied throughout the above chapter and the identified solutions are further discussed below.

Optimisation in the panel's design could include:

- A reduction in the number of unique edge panels;
- An aim to design panel shapes that are as rectangular as possible in order to limit potential glass-cutting wastes;
- An optimisation in the cutting method so as to rationally use the available material, and, in the case of non-glazed panels, the optional use of shape nesting.

6.1 REDUCING THE NUMBER OF UNIQUE EDGE PANELS

The number of unique edge panels results from the specific relationship between grid lines and the trim line. Over the course of this study, the following five conditions were identified as having an impact on the number of unique edge panels:

- **the trim line coincides with a repetitive grid line** – no edge panels are produced because the façade is trimmed by the so-called full module thus a repetitive modular panel is used as an edge panel;
- **the trim line serves as the line of symmetry of a repetitive panel** – if applicable – only one type edge panel is produced per trim line, e.g. in a rhomboid grid there is one edge panel for the vertical trim line, and one for the horizontal trim line;
- **the trim line is parallel to the repetitive grid line** – several edge panels are produced, but their number is limited because the edge panels are cut at the same angle as the grid line angle, and some degree of panel repetition is possible;
- **the trim line is an arbitrary line in relation to the repetitive grid line** – various edge panels are produced, which are not repetitive except in special situations. This is strictly due to geometry: there is a countable number of angles at which the trim line coming out of a grid node can pass through another node – because of the countable number of nodes – while the set of all possible angles is uncountable, it is a continuum. Therefore, for the majority of angles, the arbitrary trim line will not pass through a second node and, as a consequence, an unlimited number of various edge panels is produced;
- **the trim line and the grid lines are arbitrary** – various edge panels are produced which are not repetitive because of the random position of grid lines. All panels – including edge panels – are random polygons; the number of unique panels depends on the number of grid lines and their arrangement on the façade; some repetitiveness is possible only when identical bays are created.

First, three conditions have a decisively positive impact from the perspective of the façade optimisation, as the edge panels produced are either equal or repetitive. The latter two have a negative impact, unless a large number of untypical and non-repetitive panels is part of the initial design strategy, accepted by both the client and the designer of the façade.

In view of the above, the reduction in the number of unique edge panels – or the increase in the number of repetitive panels – is possible when there is a specific relation between the repetitive grid lines and the trim line:

- the trim line is also the symmetry line of the repetitive modular panel;
- the trim line is parallel to one of the repetitive grid lines;
- the trim line crosses two nodes of the repetitive grid; in selected cases, this repetitiveness requires a large number of nodes on the surface of the façade.

Such geometrical relations are illustrated in Fig. 6.

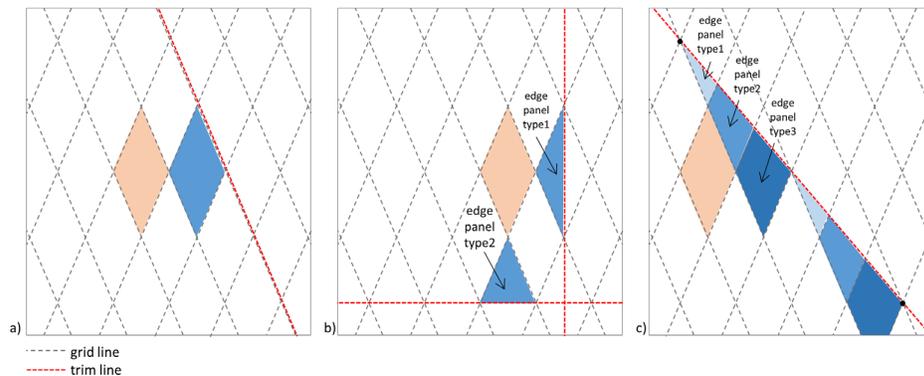


FIG. 6 The reduction in the number of unique edge panels is a specific relation between the repetitive grid lines and the trim line: a) trim line coincides with a grid line, b) trim line is a symmetry line of a panel, c) trim line intersects two nodes. Figure by author

6.2 TYPES OF EDGE PANELS

Based on the analysed case-studies and the geometrical analysis of repetitive and arbitrary grids, the following types of edge panels have been identified (see Fig 7):

- **unchanged panel** (minimal strategy) – where (i) the oblique geometry is compensated by a non-glazed panel e.g. stone or steel-sheet cladding or by a solid plastered or masonry wall; or (ii) where the edge panels are simply not required because the façade grid is trimmed with one of the grid lines. This approach completely eliminates the need to produce glazed edge panels. Examples of this strategy are the Mode-Gakuen Spiral Towers in Nagoya (by architects Nikken Sekkei, Makoto Wakabayashi);
- **trimmed panel** (subtractive strategy) – where standard repetitive glazed panels are trimmed in accordance with the façade geometry, usually by the edge/corner of the building. If the repetitive grid is trimmed with a trim line that is parallel to one of the grid lines, a limited number of repetitive edge panels might be produced; if the line is arbitrary or curved – a larger number of non-repetitive panels might be required. This approach is the most popular;

- **extended panel** (also called added panel, or additive strategy) – where the repetitive panels are extended to the trim line, forming polygons of various shapes and numbers of sides. This approach is often used when an offset from the axial controlling lines is required to form the envelope around the building's corners. The lengthening of the base panel allows for the compensation of the modular panel geometry with a repetitive element – usually a polygon – adjacent to the repetitive panel (e.g. Okhel Synagogue building);
- **continuous panel** (folded strategy) – where the glazed façade panel is seemingly “folded” over the corner of the building. This approach produces two non-repetitive edge panels on adjoining/adjacent façades and clearly marks the envelope's continuity which is underlined by grid lines that run across multiple façades (e.g. TOD's Omotesando building);
- **3-dimensional panel** (3D strategy) – where the edge panel connects two façades in the third dimension, e.g. in rhomboidal grids. This approach produces a panel that serves as an edge panel for both façades; the panel is usually perpendicular to the bisector of the angle between the adjoining façades e.g. 45 degrees for perpendicular façades.

In the application of the abovementioned two last solutions, no trim line is defined. In the case of the continuous panel, a trim line becomes a fold line, while in the case of the 3-dimensional panel, the trim line does not exist.

In regular grids, the second strategy of trimming the modular repetitive panel provides a different number of edge panels depending on the relationship between the grid and trim lines. A similar condition applies to extended panels, where an edge panel is usually associated with an offset in the geometrical relationships between the façade and structural grids. By extending the base panel it is possible to make up for the extra distance which usually occurs in convex corners of the façade, while in the case of concave corners this trimming strategy is required when the repetitive façade grid is associated with the building's axial controlling lines.

In equilateral triangle grids, the edge panels have at least one right angle. More complicated non-rectangular planar façades may require a larger number of irregular edge elements, which may affect the number of panels in the design stage and the production process (see the case of Japan Tabaco in Genève). It is also necessary to design and manufacture a large number of non-standard panels if the brief requires ventilated openings, fire-escape doors, or installation transitions.

A limited number of panels facilitates the manufacturing process, decreases the number of potential mistakes, and allows for more flexibility in the construction process because the same panel can be mounted in many locations and at many orientations. Please note: because of the location of the low-E coating layer, some panels are not interchangeable. An increased number of unique panels translates to highly complicated design and manufacturing. These processes can be facilitated with the use of parametric software which manages large amounts of geometrical data both in the design and manufacturing stages. On-site assembly of façade modules – in the case of a modular prefabricated façade – requires a just-in-time delivery of the façade modules or glass panels because the mounting sequence is crucial. If a single element is missing the entire operation can be slowed down or halted. Despite these limitations, the advancement in technology makes it possible to build more and more complicated façade grids.

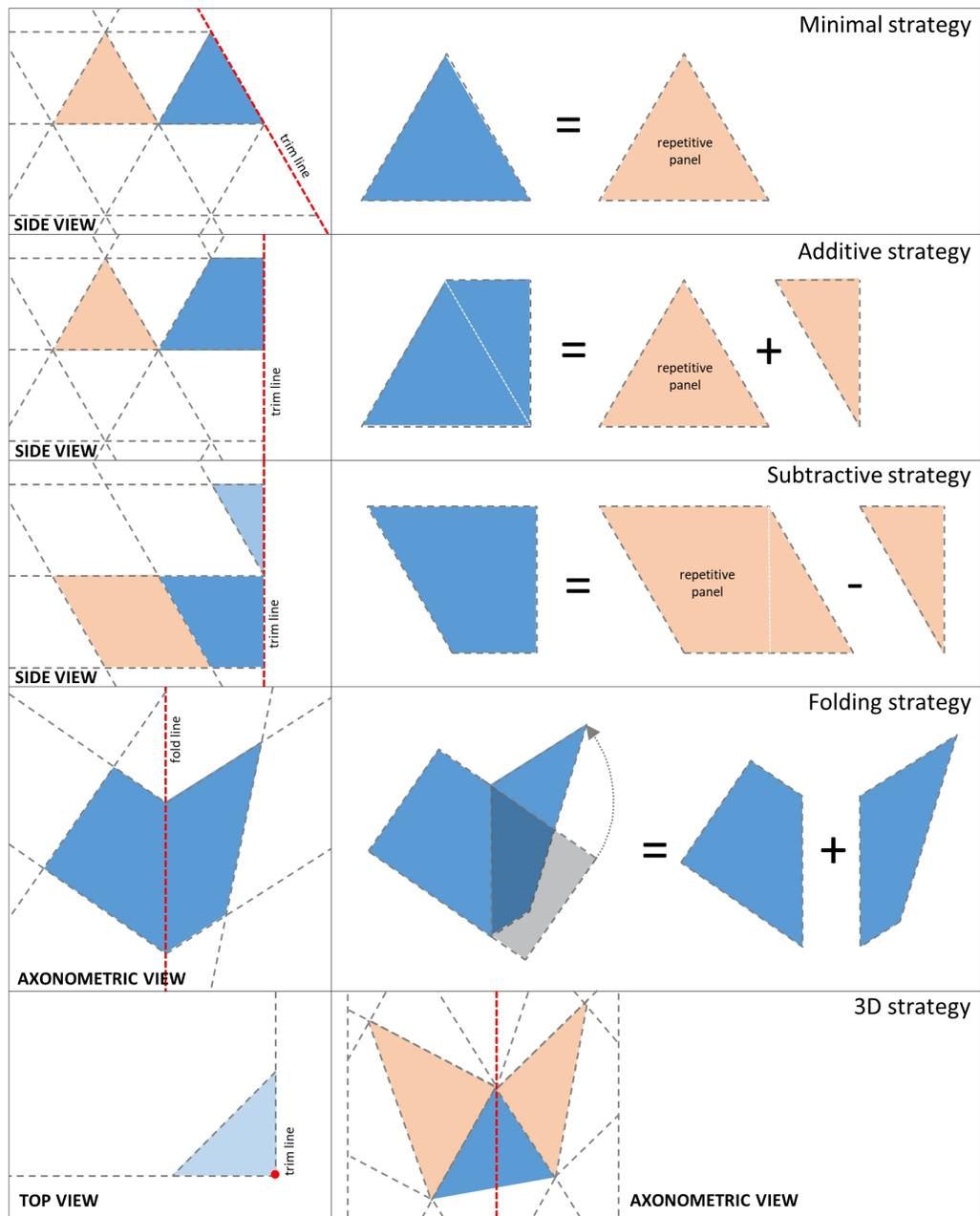


FIG. 7 Different edge panel strategies. From top to bottom: minimal, additive, subtractive, folding, and 3D

Summary

The subject of this paper was to analyse oblique grids used in planar light-transmitting façades. This study presents various approaches to edge panel design and evaluates their capacity to reduce the number of unique panels. In repetitive oblique grids, edge panels are usually developed by cutting the repetitive panel in half horizontally or vertically. Some geometrical transformations of repetitive grids – e.g. skew – horizontal node movement – require more unique panels. In arbitrary grids – or when the trim line is oblique or curved – numerous non-repetitive panels are produced. The presented case study revealed various edge panel strategies which were then evaluated. Recommendations were made as to the methods of reducing the number of unique panels and a general review of possible design strategies was offered.

Acknowledgment

The presented paper was funded by the National Science Centre, Poland grant entitled: "New trends in architecture of transparent facades – formal experiments, technological innovations", ref. no. 2014/15/B/ST8/00191.

References

- Abruzzo, E., & Solomon, J.D. (2006). *Decoration*. Princeton: Architectural Press.
- Biography of Toyo Ito (2003). Retrieved from <http://www.pritzkerprize.com/2013/biography>
- Brzezicki, M. (2014). Redundant Transparency: The Building's Light-Permeable Disguise. *Journal of Architectural and Planning Research*, 31(4), 299-321.
- Eekhout, M. (2008). *Methodology for Product Development in Architecture*. Amsterdam: Delft University Press/IOS Press.
- Gonzalez Quintial, F., & Artiz-Elkarte, A. (2015). Freeform surfaces adaptation using developable strips and planar quadrilateral facets. *Journal of façade Design and Engineering*. 3. 59-70. 10.3233/FDE-150033.
- Goodman, J.E., & O'Rourke, J. (2004) *Handbook of Discrete and Computational Geometry*. 2nd ed. Boca Raton: Chapman & Hall/CRC, 2004. Web. Discrete mathematics and its applications; Discrete mathematics and its applications.
- Fundamentals of Visualizing Environmental Data (2015), Retrieved from http://evshelp.ctech.com/Content/workbooks/fundamentals_of_visualizing_environmental_data/gridding_and_dimensionality.html
- Herzog, T., Krippner, R., & Lang, W. (2008). *Façade construction manual*. Ba: Birkhäuser.
- JTI Headquarters / SOM. (2016). Retrieved from <http://www.archdaily.com/784628/jti-headquarters-som>
- Knaack, U., Auer, T., Klein, T., & Bilow, M. (2014). *Façades: Principles of Construction*. (Second and revised edition). Basel: De Gruyter.
doi:10.1515/97830308211457
- Parlement Francophone Bruxellois/SKOPE. (2014). Retrieved from <http://www.archdaily.com/524725/parlement-franco-phone-bruxellois-skope>
- Pell, B., Hild, A., Jacob, S., & Zaera, A. (2010). *The Articulate Surface: Ornament and Technology in Contemporary Architecture* (3rd ed.). Ba: De Gruyter. <http://public.ebib.com/choice/publicfullrecord.aspx?p=1020455>
- Pottmann, H., & Bentley, D. (2007). *Architectural geometry* (1st ed. ed.). Exton, Pa.: Bentley Institute Press.
- Prada Aoyama Epicentre in Tokyo (2004). *Detail*, 10, 1131-1137.
- Rersson, R. (2013). *Flat Glass Technology*. New York: Springer.
- Rinaldi Marco, (2013). *Square Brussels Meeting Center by A2rc Architects*. Retrieved from <http://aasarchitecture.com/2013/04/square-brussels-meeting-center-by-a2rc-architects.html>
- Schittich, C., & Sauer, C. (2012). *Building simply two: Sustainable, cost-efficient, local* (In detail). Munich: Edition Detail.
- Seattle Central Library Curtain Wall Design*. (n.d.) Retrieved from <https://lmnarchitects.com/case-study/seattle-central-library-curtain-wall-design>
- The Serpentine Gallery Pavilion 2002 (2002). Retrieved from <http://www.serpentinegalleries.org/exhibitions-events/serpentine-gallery-pavilion-2002-toyo-ito-and-cecil-balmond-arup>
- Vollers, K.J. (2013). *Twist and build: Creating non-orthogonal architecture*. Rotterdam: nai010 publishers.