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Morphological scheme of second-generation non-orthogonal high-rises

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Biography
In 1978 Karel J. Vollers (born in Redhill, UK 1951), obtained at Delft University of Technology his MSc degree in Architecture. As projectleader he worked for Dutch architect offices on technology inspired housing and office buildings (for Oosterhuis.nl, Neutelings&Roodbeen) and on the Erasmus bridge in Rotterdam (for UN-Studio). In 1992 he started his own practice ‘Vollers Architekten’ in Amsterdam. His focus on the architectural application of free curvatures in 2001 resulted in a PhD cum laude at Delft University of Technology on the thesis ‘Twist & Build, creating non-orthogonal architecture’.

Dr. Vollers lectured on materialising complex geometry architecture at internationally reknown Academies and Universities and currently is assistant-professor at the Chair of Product Development of the Faculty of Architecture in Delft. In 2005 the world-first industrially produced Alcoa-Twist framing system for freely curved façades was presented, that he designed and developed with the manufacturers. The system allows also for opening windows. He that year was awarded the Dutch Aluminum Price for Architecture. Dr Vollers recently made an adjustable mould for annealing freely curved glass at costs almost equal to those of cylindrical glass. In 2007, aided by governmental STW funding, he with a promovendus made a computer adjusted mould surface for producing 3D transformed panels of various materials. Dr. Vollers lectured at many congresses, especially on façade technology.
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Abstract
Non-orthogonal high-rise buildings are emerging with an increasing degree of geometrical variation. As yet no scheme categorises data on the basis of the overall geometries of such buildings. The author proposes an easily accessible morphological scheme which for example, enables data to be retrieved on sustainable performance of the distinctive building shapes.

The shaping of most non-orthogonal high-rises is related to developments in modeling software. The first generation of buildings was geometrically described by placing lines and floor surfaces into a 3-D composition using the software commands Move and Rotate and then generating façades through the (floor contour) lines. Data processing to describe non-orthogonal volumes was subsequently aided by software based on solid modeling. Now with second generation non-orthogonal façades, the drawing procedures and processing of data are further eased by scripting and by adopting parametric modeling procedures. In such software, shapes are described by relations between the composing elements. Their positioning is manipulated by only a few parameters.

The proposed morphological scheme is based on software manipulations to describe shaping, not on mathematical formulae. The scheme is illustrated by examples of overall shaping, façade geometries and materialization trends.

Keywords: façade, geometry, non-orthogonal, morphology, high-rise

Morphological scheme for high-rises
Integration of digital technologies into the various stages of building development results in a variety of high-rise volumes. Often the buildings have non-orthogonal façades to improve their performance, for example by minimising outer façade/floor surface ratio to decrease material usage/costs/energy consumption, or by optimising windflow to reduce windage or activate wind generators. The geometrical complexity of high-rises is increasing rapidly, and by implication the complexity of materialising their façades and superstructures.

An easily accessible database that distinguishes according to the overall shaping, will be useful when optimising build-up and performance of articulated high-rises. The author found no morphological system matching the geometrical variety of currently emerging articulated building volumes.

Mathematical descriptions that qualify façade surfaces as being anti-elastic/synclastic, single- or double-curved, do not describe overall building shapes. Mathematical definitions of curved shapes like hyperboloids, conoids, etc. are too difficult for most building participants to understand and do not sufficiently reflect the variations in building shapes.

Up-to-date high-rise project information is available on the website www.Skyscrapercity.com, at this moment the main website forum. Its database classifies according to geographical location (-ranging from continent to city), height, usage, etc. No database has been found that classifies according to the various non-orthogonal shapes.

A surface topology classification system designed by architects is described in Phylogenesis (FOA, 2003). It does not cover volumes. The system requires too much study to be generally used in the building industry.

Structural morphologies describe structures; these need not coincide with building shapes.

The morphological scheme proposed by the author deals with the overall shaping of volumes with curved façades. Combinations of different types of geometry are only briefly discussed. The various shapes names are inspired by the computer commands by which the volumes are generated. Conventional names for basic shapes like Cylinder, Cone and Ellipsoid are still used in the new scheme, being widely understood and easy to visualise.

Special categories with inventories of specific function or composition, supplement the scheme of overall shaping. These relate, for example, to wind energy or bio-climatic aspects. Also some formal characteristics are distinguished as separate categories, such as buildings with rotating floors. Specific information can be retrieved by a key-word-based data retrieval system. Shapes that do not match one of the proposed categories are filed temporarily with the Free shapes.
Modeling software and high-rise shaping

High-rise shaping is largely related to the modeling tools that architects have available. Some architects focus on parametric modeling of the overall volume, others on morphogenetic structures, textures, etc. Simple modeling procedures enable intuitive shaping of complex geometry designs, with real time representation. They also stimulate fine-tuning of the shapes. The parameters can be manipulated numerically, and by adjusting points on the screen operated by mouse-clicks. Little mathematical insight is required – but the consequences for structure, usable floor-space, etc. are considerable. Designers are assisted by software in handling such data. When a form is generated with only few shaping manipulations, then builders, building users and the general public can usually, with a little help, easily visualise how the shapes were composed. Computer commands then replaced mathematical formulae to indicate the form build-up.

In the first generation non-orthogonal building shapes, volumes were mostly geometrically described by manipulating straight lines or flat surfaces using the commands Copy, Move and Rotate. The command Scale was occasionally applied when designing tapered shapes, like conical buildings. The command Merge has only been used in small-scale designs.

The process to describe non-orthogonal volumes involved handling large quantities of data. This amount was decreased greatly by applying solid modeling software. In such programs volumes are sculpted by adding or deducting parts that are described by intersections with other volumes.

In the second generation non-orthogonal building volumes, the drawing procedures and processing of data are further eased by scripting or adopting parametric modeling procedures. In such software, shapes are described by relations between their composing elements. Control of freely curved surfaces built of for example, Nurb curves is maintained by manipulating only a small number of points. The relative ease by which one can now design in real time, allows rapid shape development and quick generation of digital data on components and their production. The programs also provide design data, such as on floor plan changes when a bulging building volume is bent sideways.

High-rise by definition has a prominent vertical direction. Building volumes with a repetition of floors are named *extruders* (Figure 1). The generic names proposed by author are written in Italics. Variations on the basic volume (an *ortho*) are introduced by inclining the axis along which identical floors are positioned upwards (an *angler*), and by bending the axis (a *slider*). Over time buildings were built with varying floor plans, for example, tapering like a pyramid. Subsequently rotational shapes were made around a vertical axis (*Rotors* like a Cylinder and Cone) and hybrid shapes that combine orthogonal volumes with rotational surfaces.

Using a computer when designing, helps to vary on the geometry. As the floors are multiplied upwards along the axis, a rotation can be added (a *twister*). When applying a constant rotation around a vertical axis, all floors are identical and the façades will also be repeated. A building with an orthogonal superstructure and one or more twisted façades is called a *Tordo*. Materialisation of Twister and Tordo has been elaborated on in previous papers (Vollers, 2005). *Free-shapers* and *Transformers* are the main groups of second generation volumes. Buildings in special functional categories will also be filed with the basic type in the morphological scheme.
**EXTRUDERS: Anglers, Sliders, Tapering sliders and Slider assemblies**

Extruders are buildings with basically the same floorplan over the entire height. An Ortho and a Cylinder are exceptionally regular extruders, having an orthogonal and circular plan respectively. Anglers are buildings with a repetition of floors, piled on top of each other under a fixed inclination. The floors can have straight or curving contours. When identical floors are stacked under a varying angle, the buildings are called sliders. Often a slider is built as a pile of straight segments leaning in different directions; these parts are fluently connected by bent segments (Figures 2ab). Separate sliders can be interconnected into ensembles, to achieve a more rigid structure, shorten traffic routes and/or provide alternative fire-escapes. Superstructure patterns in Figures 2cd suggest optimized force flow. Tapering sliders are also called benders. The slider assemblies on Figures 5ef interconnect, intersect and merge. When floors and façade structures repeat under a varying angle in an upward direction and with a rotation, then the volumes are sliding twisters.

**ROTORS: Globe segments, Bulging rotors, Cylinders, Squeezed rotors, Transformed rotors**

A Rotor is a building volume created by rotating a line around a vertical axis. When the line is vertical, the volume is a Cylinder (Figure 3c). When the line inclines, a Hyperboloid results. The line may also be curved. A semi-circle with its ends on the rotation axis when rotated, results in a Globe. The Globe segment of Figure 3a is triangulated with flat panels. Rotational building models can be made to bulge (a Bulging rotor) or squeeze (a Squeezed rotor) just by manipulating the curve that is rotated (Figures 3bd). The curvature of the line can also be more complex.

A transforming axis can be connected to the building model. When the axis then is being curved, the building transforms with it. (Figure 3e). This can result in different sections at the various levels. The tower on Figure 5f has elliptical horizontal floors. Such a form can be drawn with solid modeling software by first stretching a globe upwards and then squeezing this horizontally over 1 axis. It can also be drawn parametric, by moving an elliptical floor upward while scaling it, by relating it to a standing curved façade section line. The generic type name for the towers on Figures 5ef is Transformed rotors.
TWISTERS and TORDOS

A twister is a twisted building with façades repeated on all floor levels (Figure 4a). A tordo is a building with an orthogonal core and one or more twisted façades. The tordo in Figure 4b has a twisting superstructure in the façade with inclining columns and flat recessed glass façades. As the number of façades grows, the volume starts to resemble a cylinder, thus allowing for recessed vertical columns. The Mullions of the tordo in Figure 4c connect to orthogonally arranged structural walls. Figure 4d tordo has vertical columns positioned in a circle and twisted façades hanging from protruding floors. Stimulated by using parametric modeling software, high-rises increasingly are designed with flat unique sized non-rectangular elements. The Figure 4ef tapering twistiers probably were drawn parametrically. Tapering implies less repetition. This is compensated by making 6 façades and 4 wings respectively.

Sub-Categories: Sliding Twisters, Helical twistiers, Intersecting helical twistiers, Merging sliders, Tapered twistiers

Inspiration to transform the Torre Castelló axis into a slightly helical form (figure 5a), may have come from the engineering logic to pile asymmetrical floors vertically not through the centre of the circular segment of the floor, but through the gravitational centre of the floors. Entangling volumes cover a range of organic connotations. When floors are moved upwards along a 2D or 3D curve, they are sliders; if a rotation is added to the outer structure, a slider turns into a Sliding twistier. When the 3D rotation curve is a helix, it is a Helical twistier. The Cobra towers look like snakes, which in turn makes the patterned façades resemble snake skins (Figure 5b). The Intersecting helical twistiers on Figure 5c can have an inner vertical zone for elevator shafts. Circling an assembly of helical volumes in the same direction, causes torque in the superstructure. The Merging sliders (Figure 5d) merge from opposite directions. This avoids torque. If their superstructures twist, they are Merging twistiers.

The buildings on Figure 5e are Tapered twistiers. Buildings with a vertical axis are often crowned by a straight antenna. Buildings with a 2D curved or helical axis require a top that formally match. This can be a point (Figure 5e), ball, light, helical antenna, or completely differing shape, like a star or moonfigure. Mergers and Intersectors are special categories.

Fig. 4abcdef: Turning Torso, Malmö (by Calatrava); Infinity Tower, Dubai (by SOM); Ocean Heights One Residential tower, Dubai (by Aedes); Avaz Twist tower, Sarajevo, Bosnia-Herzegovina (by ADS Studio); Fordham Spire, Chicago (by Calatrava); Gazprom, Petersburg (by RMJM)

Fig. 5abcde: Torre Castelló, Valencia (by Calatrava); Cobra Towers, Kuwait; Twisted Trees tower, Bin Hai Seaport City, China (by Lee Harris Pomeroy); World Business Centre, Busan, South Korea (by UN-Studio); Dubai Towers, Dubai (by TVS)
Sub-categories: Stepped twisters, Stepped hybrid twisters

Materialising smooth twisted façades introduces torsion on the superstructure due to inclined columns. Fluently curved/twisted glass panes have not as yet been produced on a scale for high-rise. The former aspects are countered by simplifying the twisted structure to a cylinder, and embellishing the twisted or otherwise double-curved surfaces with flat panes. Twisted surfaces made by rotating and moving a horizontal straight line along a vertical twisting axis, connect easily to cylindrical surfaces that share that axis for their rotation. Just like the underside of a set of stairs, a twisted surface can be approximated by flat vertical and horizontal surfaces. All façades of stepped twisters are flat and stepped. This avoids having to produce twisted façade elements (Figure 6ae). Stepped hybrid twisters have cylindrical parts and some twisted surfaces replaced by stepped cut-outs, helically arranged with flat balustrades / façades and horizontal floors. (Figure 6bcd).

FREE SHAPERS

A free shape is made by applying manipulations to a simple object (a line, surface or volume). If too many parameters are varied, then the overall image can lose inner consistency and most people will not understand how it was generated. When the sequence of manipulations is not obvious, or when the form does not fit in one of the other type categories, the volume is a Free shaper. Adjectives may be applied, such as Arched, Perforated, Dented, etc., to distinguish their shape and connect to a keyword-based information retrieval system. Free shapers have several sub-categories, such as Mixers and Carvers. Mixers combine various types of curved surfaces. Carvers are volumes sculpted by deducting parts that are described by intersections with other parts.

In Figure 7a the main façades appear to be cylindrically curved. However, along the upper cut-out the front façade is pulled inwards, making it intriguing. Too many such adjustments would confuse. Figure 7b has a canyon-like cut-out of undetermined geometry. Its shaping juxtaposes the simple box-like overall shape. The façade of the tower on Figure 7c may have been drawn with just a few manipulations, but it is not obvious which they were.
Special category: Rotators

In 1924 the Russian constructivist Konstantin Melnikov designed the Pravda Leningradskaja office building. The floors of this steel structure were to hinge around a steel core and each was to rotate approx. 60°. In 1927, Buckminster Fuller proposed his Dymaxion House; the bungalow could follow the sun, pivoting around a mast. Later the principle was applied in various houses, like the 4-storey Heliotrop in Freiburg (Germany) designed by Rolf Disch in 1994. Rotators are towers that can rotate as a whole, or per floor. In the present millennium architects have proposed various towers with rotating apartments, like the Rotating tower, Torre Italiana and the Da Vinci tower by David Fisher. The first built will probably be the Rotating Residences (Figure 8a), the Time Residences tower (Figure 8b) or the Da Vinci tower (Figures 8cde). The top 5 of the 15 floors of the Rotating Residences are to rotate individually. The Time Residences tower is to rotate as a whole. The Da Vinci will have all floors individually rotating, allowing all owners optimal sun-light and varying outward views. It is the first to have all floors programmed into a ballet-like scenario.

Special Categories: Twister twins, Groups

Usually the base of twin towers lines up with an important urban direction (road or canal). The twister twins in Figure 9a twist approx. 90°. Their top direction refers mostly to that of the base. Sharing directions of top and bottom lines, unifies twins. The landmark Bahrain Financial Harbour development in Manama, Bahrain, includes a line-up of three twisted towers amid other (to be) iconic projects. A singular iconic tower or line-up of such towers, pinpoints the project. When similarly transformed buildings are grouped to encompass a setting, then an environment is created, not just a point or line of focus. Such towers need not be identical. With a limited number of parameters in a modeling script, many variations can be made, like a Slider group (Figure 9b) and a Transformer group (Figure 9c). The embedded formal harmony between the buildings stems from sharing the ‘genes’.

Articulated buildings have not yet been grouped in a composition that was optimised in shaping and positioning in regard to sustainable performance.
Special Category: Slicers

A Slicer is a building which appears to have a curving façade, this impression being created by balconies, louvers or other protruding elements. In Figure 10a the curving virtual outer surface is indicated by contours of meandering balconies around an orthogonal volume. Alternatively, curved (segments of) balconies may be repeated upwards, with a rotation (Figure 10b). Thus a virtual twisting outer surface results, not built up of straight lines, but of curves. Twisted surfaces built by repeating a curve, are curve-surfaces, just as ruled surfaces are built up of rules (=straight lines). The recessed façades of Figure 10b are embellished with flat segments. The smooth image on Figure 10c is achieved by the large number of thin sun-louvers. Verticality of balustrades is less obvious on a high-rise than on a low building like on Figure 10d, where the overall look of the façade is stepped rather than smoothly curved. When a building has floors vertically repeated with a horizontal rotation, it is a Sliced twister.

Special Categories: Bio-climatic towers, Wind energizers

The tower on Figure 11a has cylindrical façades and is, therefore, classified as a rotor. Bio-climatic performance is elaborated in basically all building types (Figures 11bcd). Whereas bio-climatic buildings usually function with low wind velocities and are open to the surrounding climate, Wind-energizers tunnel an accelerated windflow to activate generators. They in contrast usually have a closed climate system and smooth façades to ease windflow. façades around wind-apertures for optimal windflow have slight curvatures and rounded building corners. Boloid segments often provide element repetition and good windflow (Figure 11e).
Avant-garde architects experiment with modeling software and visualise new façade styling, geometries, textures and functioning. 3D printing is economically feasible for production of large series of small building components. In time it will allow grading materials (making varying material qualities within the monolithic product), ease assemblage, add new functionalities (such as the capability to breath), etc. The growing market for non-standard elements stimulates the application of stronger curvatures. Iconic articulated buildings in the mid-rise range of 60-100m will fill the gap between high-rises with slight curvatures and small landmarks with strong curvatures.

In morphogenetic façade design, patterns are generated by scripting relations between components and their sizes/positioning. Building skins become ‘populated’ with windows or structural elements (Figure 12ab). The SmartGeometry Group specialises in applying associative geometry with Generative Components software. One of their workshop studies was on helical surfaces populated with components which correspond to local stress (Figure 12c). The gap between patterning and structural optimisation narrows. The implications of such materialisation to shaping high-rise has yet to be defined.

Evaluation
A durable database for classifying articulated high-rises will ease retrieval of information concerning design and optimisation of their various performances. Such a scheme must be kept up-to-date, like the www.skyscrapercity.com website.

The proposed morphological scheme is based on types of overall shaping generated by the commands Move and Rotate. They are the first generation types. The second generation is generated with parametric modelling software. Most types thus created are filed as subcategories in the first generation scheme, but some are added to the scheme as separate basic types. Sub-categories and Special-categories follow from specific shaping aspects. A keyword system is to enable data retrieval on specific functioning, finishing or shaping variety. Especially the descriptions of the second generation volume types require further elaboration.

Conclusions
1. Non-orthogonal buildings can be morphologically organised in accordance with the computer manipulations used to draw them.
2. The way of shaping described in conclusion 1 is easy to visualise for most building participants.
3. The increase in application of non-standard elements in high-rise indicates that such elements approximate orthogonal flat panels in price.
4. As a consequence of conclusion 3, twisted geometries with repetition of elements will be applied not so much for economic gain and as for semiotic connotation.

Notes