

The CAD-tool 2.0 morphological scheme of non-orthogonal high-rises



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Dr. Karel Vollers

In the 1980s, as project leader for various architects (Gerssen, Kas Oosterhuis), Mr. Vollers worked on offices, hospitals and low-energy ultra-light housing. In the 1990s he worked for UN-Studio on the 300m span Erasmus bridge in Rotterdam.

A visit in 1986 to works of the Brazilian architect Oscar Niemeyer ignited a great interest in the architectural application of free curvatures. Dr. Vollers foresaw that computers would stimulate their usage in the industrialized world. In 2001 his commitment to systemized buildings resulted in a PhD cum laude at Delft University of Technology on the thesis 'Twist & Build, creating non-orthogonal architecture'.

He received the 2005 Dutch Aluminum Award, for the first industrial framing system for freely curved façades. The AA 100 Q Twist framing system, also featuring operable windows, was developed with Alcoa Architectural systems, Van Campen Bending and Tetterode Glas Voorthuizen.

With PhD graduate Daan Rietbergen he now develops adjustable moulds for glass and concrete panels.

"In consequence, twisted geometries with repetition of elements are applied not so much for economic gain as for semiotic connotation."

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. This paper proposes an easily accessible morphological scheme which, for example, enables data to be retrieved on the sustainable performance of the distinctive building shapes.

The shaping of most non-orthogonal high-rises is related to developments in modeling software. The morphological scheme is based on software manipulations to describe shaping, not on mathematical formulae. As software develops, new ways of generating shapes emerge. In consequence the shaping scheme gradually will be updated. The scheme is illustrated by examples of overall shaping and materialization trends.

Non-orthogonal high-rises

Iconic buildings express regional or national identity. They symbolise power and ambition. This built identity, created by mankind, is highly valued and of major importance in global communication.

To design outstanding buildings, architects move away from the standard. Shapes of simple geometry are increasingly varied to add expression. Designers get accustomed to applying complex geometries, and refine the shaping.

The sustainability credentials of high-rises is questionable, but for political, cultural and socio-economic reasons, they are built in large numbers, as boxes and as curved volumes. Curved volumes offer numerous potential advantages to designers and developers. A deviation from conventional high-rise shapes, which are generally extruded along their entire length or in broad segments, allows for greater story-by-story customization of floor plate geometry to its intended use.

Large construction budgets often appropriated for iconic projects in particular offer opportunities to experiment with new and innovative design techniques, and can result in published data and insight which reduces the risk of implementing these techniques in other projects, subsequently improving their

usefulness. Additionally, these techniques are in this context put to the test, as towers that truly earn iconic status have the potential to stand well beyond the design lifetime of modern buildings, underscoring the need for construction quality that yields durability and longevity. The growing market of non-standard, curved products stimulates application of strong curvatures. Iconic articulated buildings, in the mid-rise range of 60-100m, have started to fill the gap between slightly curved high-rises and strongly curved low-rise buildings.

Morphological scheme for high-rises

Integration of digital technologies into the various stages of building development is resulting in a variety of high-rise volumes with curving façades. Their geometrical complexity is increasing rapidly, and by implication the complexity of materialising. An easily accessible database, that distinguishes according to the overall shaping, will be useful when optimising build-up and performance of high-rises with curved façades. The author found no database nor morphological system matching the geometrical variety.

Mathematical descriptions that qualify façade surfaces as being anti-clastic/synclastic, single- or double-curved, do not describe

...tall timber

overall building shapes. Mathematical definitions of curved surfaces like hyperboloids, conoids, etc. are too difficult for most building participants to understand and do not sufficiently reflect the variations in building shapes.

A topology classification system designed by architects is described in Phylogenesis (FOA, 2003). It schematises surfaces - not building shapes. The scheme requires too much study to be generally used in the building industry.

In his book 'Skyscrapers-Skycities' (JEN, 1980), Charles Jencks classifies by form and expression. A grouping by metaphorical equation (in skyscraper, skyscraper or skycity) is elaborated with ambiguous and subjective names. He also lists the topics Morphology, Articulation of surface, Style, Activity, Technology, and Motivation. Only the Morphology section deals with geometric descriptions. It subdivides into Central, Longitudinal and Compound buildings.

The section Longitudinal classifies high-rises as a slab, stepped-, curved-, shaped-, amorphous- or complex slab. It covers high-rise shapes in general, but does not determine variations in buildings with curved façades.

Up-to-date high-rise project information is available on the CTBUH website www.ctbuh.org. Its database classifies according to geographical location, height, usage, etc. not to geometrical shape.

The morphological scheme proposed by the author deals with the overall shaping of volumes with curved façades. Compound buildings, i.e. those consisting of segments of different geometry types, are only briefly discussed.

Modeling software and high-rise shaping

High-rise shaping is largely related to the modeling tools that architects have available. Simple modeling procedures enable intuitive shaping of complex geometry designs. 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. Some focus on parametric modeling of the overall volume, others on morphogenetic structures, textures,

etc. The relative ease by which one can design allows rapid shape development and quick generation of digital data on components. The parameters can be manipulated numerically, and by adjusting points on the screen operated by mouse-clicks.

In the first generation of non-orthogonal building shapes, volumes were mostly geometrically described by manipulating straight lines or flat surfaces using the commands Copy, Move and Rotate (VOL, 2001). The process to describe non-orthogonal volumes involves handling large quantities of data.

In the second generation of non-orthogonal building volumes, solid modeling software was applied. In such software, shapes are described by relations between their composing elements. Scripting and parametric modeling procedures greatly eased drawing procedures and processing of data. Control of freely curved surfaces built of, for example, NURB curves is maintained by manipulating only a small number of points. In solid modelling software, volumes can be transformed by commands like Shear, Twist, Scale, Unite or Merge.

The third generation of non-orthogonal high-rises reflects the use of the before-mentioned tools, but a sequence of their use is hard to distinguish. By scripted procedures, new shapes are generated with increasing complexity in geometrical build-up. Designs often appear monolithic, with freely curved surfaces, textured by patterns of holes, ripples, etc. The complexity of their materialising is anticipated by second generation building geometries. Each was transformed with only a few tools.

An early version of the scheme grouped façade geometries by the chronological availability of a small selection of tools and software. Additionally, the popularity of twisted volumes led to incorporating features

“We’d been looking for ways in which we could replace concrete and steel construction wherever possible in an effort to reduce carbon dioxide emissions and reliance on fossil fuels.”

Andrew Waugh, director of Waugh Thistleton Architects, which teamed with structural engineer Techniker Ltd to design the world's tallest residential structure constructed entirely of timber and one of the tallest all-wood structures on the planet. From "Big Timber Hits London" Building Design and Construction, June 2009

of their superstructure. Growing use of other geometries inspired the classification of more high-rise shapes. To avoid ambiguity, the CAD-tool 2.0 morphological scheme, as the new version is named by this author, only distinguishes volumetric geometries.

Information exchange by graphics

The scheme is based on the observation that most high-rise geometries are primitive shapes, transformed by a limited number of manipulations. Mainly because of esthetics and building economy, the number of parameters used, generally, is less than 4. As an example, most twisted tower designs are generated by scaling a cube into proportion, and then twisting the volume. Most people can easily mentally visualise subsequent transformations. Computer commands thus replaced mathematical formulae to indicate the form build-up. Manipulations may be depicted by icons and these may be supplemented with numerical information. Such representation resembles the way software parameters are depicted on computer screens.

Nomenclature

To function optimally, the proposed scheme methodology and type names must find general acceptance. Hereto the scheme's names originate in widely used geometric descriptions of volumes (sphere, cylinder, cone) and in transforming commands (extrude, rotate, twist). Many command names resemble those in the tutorial book Architectural Geometry [ARC, 2007] and in modelling software of Generative Components and Rhino. ↻

With software evolving, for a similar command a different name may come into use. This changing of names is confusing, but sometimes it is necessary to connect to new insights into form generation or to use with updated software. As shaping diversifies with new tools, more typologies emerge and new names will enter the scheme.

Shapes can be generated in various ways and by use of a variety of commands. Such parallel options imply that a volume can be classified by various transforming commands. A sphere, for example, may be selected directly as a primitive shape, be made by rotating a half circle around an axis or be generated by scaling, in a modeling script, a circular plan as it is moved upward. By listing these commands in an order of importance, more unity in use of names is achieved. If a choice between listed commands is possible, then the preferred adjective for a primitive is the first from left. As other shaping procedures may come into use, other adjectives or a changed sequence may become more fitting.

If parameter values vary, for example the degree of twisting and scaling, or when a large series of transformations is applied, then the overall image often loses optical inner consistency. Most people will not understand how it was generated. If the sequence of manipulations is not obvious, or when the form does not fit into a category, then the volume is classified as a *Free shape*. (Names allotted by author are written in Italics).

Special categories, discriminating by function, composition or formal characteristic, supplement the scheme of overall shaping. These relate, for example, to wind energy or bio-climatic aspects. Specific features may also lead to adding descriptive adjectives to a shape name, such as *Arched* or

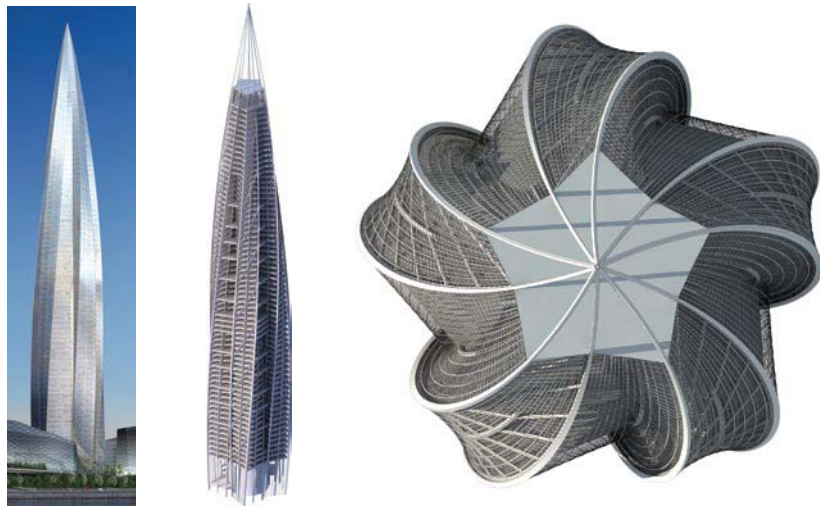


Figure 1a-c. Okhta Gazprom tower, planned in St. Petersburg, Russia (by RMJM); superstructure sideview; topview

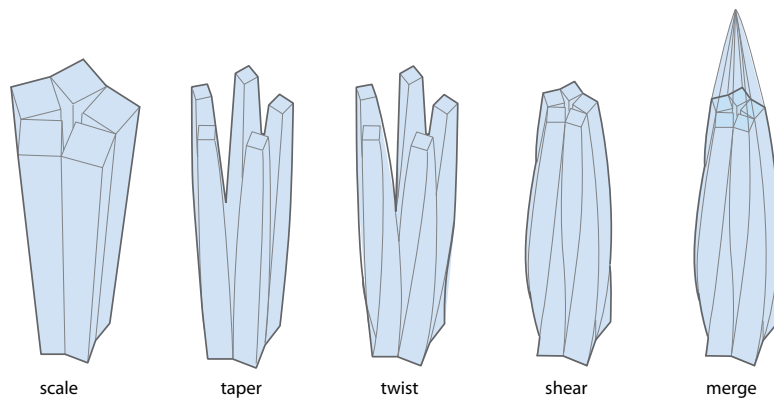


Figure 1d. Transforming sequence © Matthew Wilson, Vectorfield.org

Perforated.

do.

Example of generating a high-rise volume

The 396 m high Okhta Gazprom tower (see Figures 1a-c) is a *Compound of sliding tapered twisters* (the name will be explained later). The generating process of the building volume is exemplary for the use of modelling software. The overall volume does not twist, only the volume segments outside the cylindrical core

The volume can be generated in various ways. For example, start by positioning 5 cubes on the ground floor as a five-pointed star (see Figure 1d). Then scale the cubes upwards, tapering and twisting each volume around its individual central vertical axis. Next each axis is bent sideways while keeping the floors horizontal ('shearing') to make the volume's tops touch.

The model can also be scripted. Start this example by drawing the squares as a ground floor plan. Similar curved trajectories for the floor plans to follow are described, or constructed on the screen. The floor plans subsequently are scripted to get smaller and rotate while moving upward along the trajectories. The top was added later in the above sequence, to outline the geometry of the first drawings more clearly. It should have

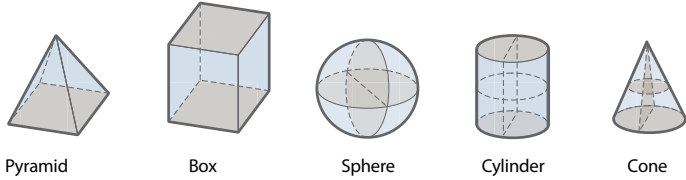
...Alan G. Davenport

“He would pack a model in a briefcase and have it by his side for an air journey. That did cause a number of up-raised eyebrows, even in those days.”

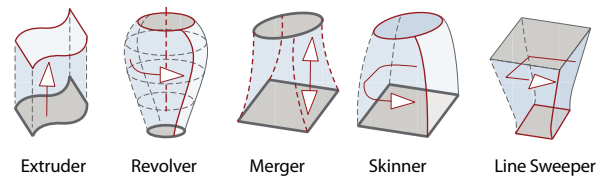
Peter King, Managing Director of the Alan G. Davenport Wind Engineering Group at the University of Western Ontario's BLWTL, in London, speaking about the life of recently deceased Alan G. Davenport. From "Wind Engineering Pioneer Alan G. Davenport Dies at 76", Engineering News Record, July 27th 2009

Main Categories:

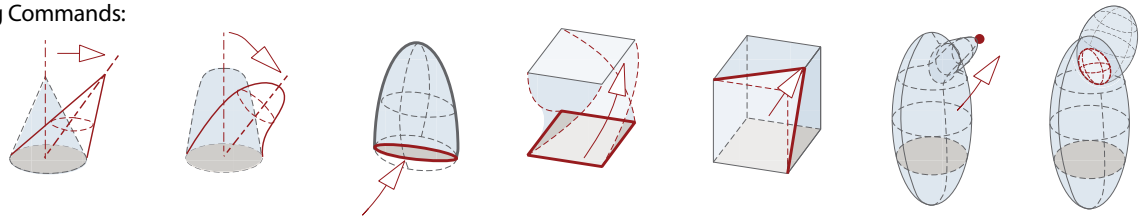
Primitives:



Generated Primitives:



Main Transforming Commands:

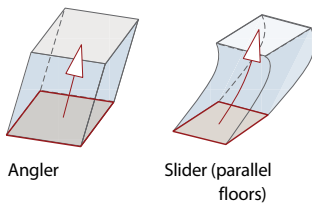


as Sub-Categories
above icons are a:

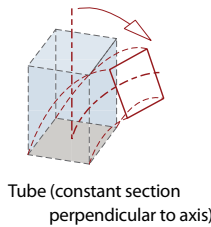
Sheared Cone Bent Revolver Scaled Revolver Twisted Box Line controlled Box Field controlled Revolver Boolean Revolver

Examples of Sub-Categories and Special Categories:

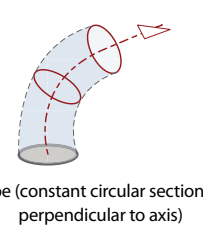
EXTRUDER Sub-Categories



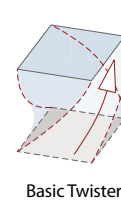
BENDER Sub-Category



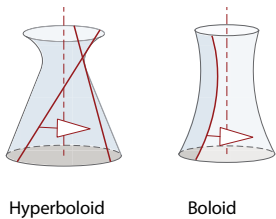
SWEEPER Sub-Category



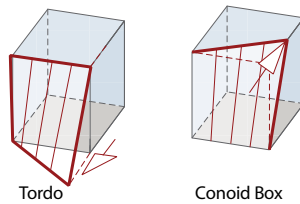
TWISTER Sub-Categories



REVOLVER Sub-Categories



LINE CONTROLLER Sub-Categories



Special Categories

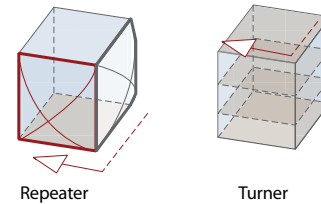


Figure 2. © Matthew Wilson, Vectorfield.org

been shown from the beginning, as an integral part with the lower volumes.

The CAD-tool 2.0 morphology scheme of non-orthogonal high-rises

Most articulated high-rises are variations of primitive shapes. The scheme (see Figure 2) is based on the transforming of such shapes. Primitive shapes and transforming commands in the scheme are limited to those that are most used, to obtain a concise overview.

In the scheme mentioned, software tools are concisely described in Appendix 1 and

illustrated with architectural examples in Appendix 2.

The *Main Categories* have 2 groups of volumes: Primitives and *Generated Primitives*. The Primitives only have limited variations in shape, because of the geometry of their origins. The *Generated Primitives*, like *Extruder*, *Revolver*, *Merger*, *Skinner*, add variation to the primitive shapes. They were generated by applying deforming commands with related names.

A Sphere, Cylinder and Cone can be made by rotating a generating line around an axis. They

are so often used that they are listed as separate primitives. As the standard is to scale the primitive Cube into the right proportions before further transforming, the name box is used for this already scaled shape. Less common primitives, like truncated cones, are left out. Such a primitive is classified by adding an adjective to the Sub-Category name, like *Bent truncated cone*.

Transformers are the commands (shear, bend, scale, etc.) that can be applied to transform the shapes in the *Main Categories*. ➤

Building volumes are named according to their shape in the Main categories, with the transforming command as adjective. An example would be a *Scaled twister*. If, after transforming, a primitive maintains its shape characteristics, then it is classified under that primitive's name. If not, then it is stored in the Sub-Category with the transformer adjective.

Buildings sharing a specific feature are grouped in the Special Categories. *Repeaters*, for example, have identical façades. *Turners* have at least 1 floor rotated.

Elaboration on the scheme

Transformers can also be seen as groups of volumes that apply a specific command. For example, the group *Twisters* contains the twisted boxes, twisted mergers, etc.

Some volume types are relatively easy to materialise and, therefore, grouped in sub-categories. Thus sheared, scaled or bent volumes are classified as *Extruders* when they feature repetition of floors. When a cylinder is scaled sideways, for example, its sections transform into ellipses. The scaling changes the cylinders' characteristics and it no longer is classified as the primitive *Cylinder* but becomes an *Extruder*. *Anglers* and *Sliders* are *Extruder* sub-categories. *Anglers* have an inclined straight axis along which the floors are repeated. This same axis in a *Slider* is curved.

The adjective *Basic* to a Transformer is used when it is a fundamental type of transforming with fixed parameters. A *Basic twister* has identical floors repeated upward with a constant rotation around a vertical axis. Its façades repeat on all of the floor levels. The *basic twister* is the first generation of the *twister*. In the second generation *twisters*, the parameters of floor plan contours, axis shape, axis inclination and/or rotation vary.

Hyperboloids are classified as a *Revolver* Sub-Category. They have a straight generating line that revolves around a rotation axis. The lines neither lie parallel nor intersect. *Tordos* and *Conoids* are classified as *Line Controller* Sub-Categories. They are created by moving contours, while ensuring that one or more of the transformed surfaces is a ruled surface (built from straight lines).

Evaluation

The use of parametric modeling software, stimulates application of non-standard elements. They approximate orthogonal flat products in price. The use of non-standard elements is visible in many non-rectangular high-rises; repetition of elements is losing importance now that freely curved shapes can be materialised rationally. In consequence, twisted geometries with repetition of elements are applied not so much for economic gain as for semiotic connotation.

Designers, clients and general public alike, are getting used to more complex geometries and their understanding of geometrical build-up grows. Use of transforming commands for building names requires basic knowledge of modelling procedures. One need not be able to work with the software tools. One needs only to mentally visualise the transforming principles: move, bend, twist, rotate, copy, mirror and know some primitive shapes like box, cylinder, cone. However, as modelling software develops, numerous specific commands are made and applied. Such commands are hard to discover, so the onlooker must be told about their existence. When the tools become more specific, less people will understand the geometrical build-up. Though this may limit the general application and acceptance of the morphological scheme, the use of specific commands is inherent to the generating process of the building volumes – and to the design tools architects are likely to apply.

A durable database classifying articulated high-rises will ease retrieval of information. Such a scheme should be kept up-to-date.

Using a keyword system will enable data retrieval on specific functioning, finishing or shaping variety. Linking various ways of the volume generation in a keyword-based database optimises the shape retracing.

Often it is difficult to distinguish the geometrical build-up and to retrace the transforming tools used. Storage of similar or alike shapes, under different names, undermines the database and confuses the user. This, together with the further development of parametric software, may necessitate using a higher level

of abstraction in a future scheme edition, for example by making it vector based. To be generally accepted, new descriptions probably must connect to the experiences in natural life. This will imply again the use of words like *twist*, *scale* and *rotate*. A new vocabulary may be developed on geometry but, when more abstract, it will take longer to be understood by the general public.

Projective geometry, making use of algorithms for the reconstruction of 3D objects from several images of that object, may be applicable to trace similar building geometries on a more global level.

Conclusion

Non-orthogonal buildings with curved façades can be morphologically organised in accordance with the computer manipulations used to draw them (see Appendixes 1+2). ■

Notes

FOA (2003). *Phylogensis*, Ed. M.Kubo, A. Ferre and FOA, Actar, Spain, ISBN 84-95951-47-9

JENCKS, C. (1980). *Skyscrapers-Skycities*, Academy Editions, London, ISBN 85670-679-5

VOLLERS, K.J. (2001). *Twist & Build, 010 Publishers*, Rotterdam, ISBN 90 6450 410 5

POTTMANN, H., ASPERL, A., HOFER, M., KILIAN, A., *Architectural Geometry*, Bentley Institute Press, 2007, ISBN 978-0-934493-04-5

AIELLO, C., (2008), *Skyscraper for the XXI Century*, eVolo Publishing, USA, ISBN 0-9816658-0-2

Appendix 1: Short Description of Software Commands as applied in the Scheme

Commands, are the names for the software tools used for generating or transforming building volumes. For example Shear, Twist, Scale, Unite or Merge.

The following describes, in short, the simplified various names and commands mentioned in the scheme.

Generated primitives are volumes, characterised by:

- Extruder, a closed line moved along a line.
- Revolver, a rotational volume, made by moving a 'generating line' around an axis
- Merger, having a fluent surface drawn between two closed lines, like a circle or a square. The type of generated surface varies with the software and basically is freely curved.
- Skinner, having a surface drawn by moving a specifically chosen line along two closed lines.
- Line sweeper. This volume is created by moving ('sweeping') a curved line along a base contour (a 'closed line') as rail-track. The curve can be scripted to during the 'sweep' change in shape, inclination, rotation, etc.
- Closed line sweeper. This volume is created by moving a closed line along a curve, the 'centre spine'. The closed line lies

perpendicular to the curve. The closed line can be scripted to during the sweep change in shape, inclination, rotation, etc.

Main Transforming Commands are the commands by which a volume shape can be changed. For example:

- Shear. When the floors are moved sideways in parallel, the manipulation is called shearing. The building volume, floor height and floor contours, when shearing, stay the same. A volume that was transformed with this command, is named a Shearder.
- Bend. By connecting an axis to the building model and then curving the axis, the volume can be transformed with it. When the original floor contours stay positioned perpendicular to the axis when it gets curved, a bent volume results with varying horizontal sections. Such volume is named a Bender. When the section perpendicular to the axis stays the same, the volume is named a Tube. If it varies, it is a Bender. When a tube section is a circle, it is named a Pipe.
- Scale. A volume can be scaled in the directions of the 3 axis or, for example, in relation to a chosen point.
- Twist. By twisting, a volume is twisted in relation to an axis connected to the

building. The rotation can vary, and the axis need not lie in the centre of the volume, nor be straight.

- Line Control. By this command, a line on a surface or surface contours can be moved and be changed in shape. The directly connected surfaces transform with the manipulation of the line.
- Field Control. By this command a selected part of a volume surface can be transformed. The surfaces connected to the moved part, transform too.
- Boolean operations allow for quick sculpting, for example adding (Unite) or deducting (Remove) parts resulting from intersections with other volumes.

Additional software operations to transform or create surfaces:

- Blend. By blending, a surface is made between surfaces. This is done along two lines: the 'touching curves' on the surfaces. By blending, a connecting surface of a fixed radius is made between two surfaces, replacing the contour line where they have met. Usually applied for rounding contours, this command transforms the volume drastically when the radius of the rounding is very large. ■

Appendix 2: Examples of Main-Categories and Sub-Categories

Sphere, Cylinder, Revolver, Shearder, Scaler

Sub-Categories: sphere segments, sheared revolvers

Cylinder (see Figure 3a), Cone and Sphere are primitive shapes. The Figure 3b is a Sphere segment. Rotational building models, Revolvers, are built by rotating a 'generating line' around a rotation axis. The generating line may be straight or may curve inwards, outwards or be complex-curved (see Figures 3cd).

Figure 3e Sheared revolver is optimised as to windage reduction in the prevailing wind

direction. By shearing, the floors are moved sideways. Figure 3f Scaled sphere has elliptical floors. It can be drawn by stretching a sphere over the vertical and a horizontal axis or by moving an elliptical floor upwards while scaling it.

Extruder

Sub-Categories: Anglers, Sliders, Tapered sliders, Slider assemblies

The floor contours of *Extruders* are identical and non-rotated. There are various sub-categories. *Anglers* have the floors piled under a fixed inclination. When piled under a

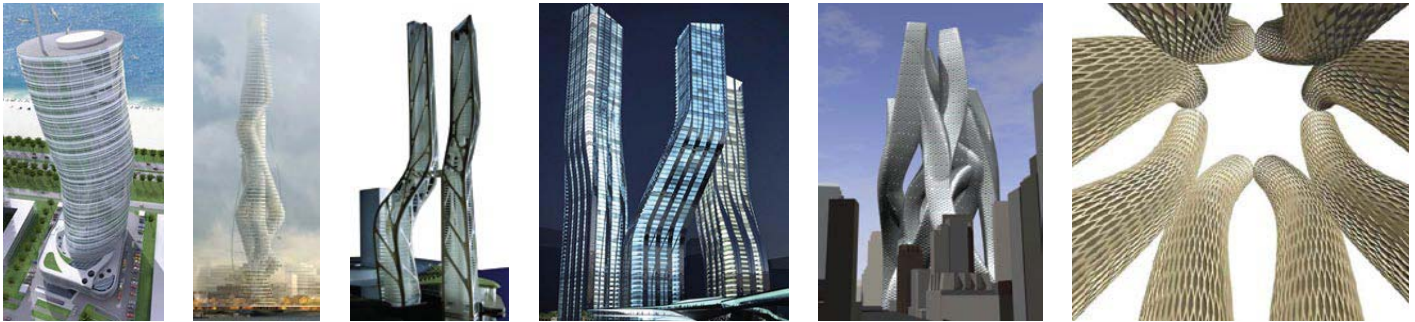
varying angle, the buildings are called *Sliders*. Often a slider is built as a stacking of straight segments (*angler segments*) leaning in different directions, with these parts fluently connected by bent segments (see Figures 4ab). Many high-rises taper to reduce windage at the top (*Tapered sliders*). Sliders can interconnect and form assemblies, to achieve a rigid structure, shorten traffic routes and provide alternative fire-escapes (see Figures 4cd). Figure 4ef slider assemblies interconnect, intersect and merge. When the floors of Sliders additionally rotate, they are *Sliding twisters*. ↗

Sphere, Cylinder, Revolver, Shearder, Scaler - Sub-Categories: sphere segments, sheared revolvers



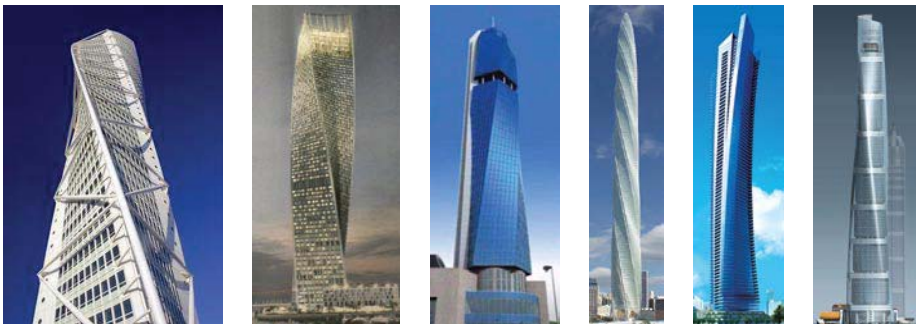
Figures 3a-f. Westhafen Tower, Frankfurt, 2005 (© Schneider&Schumacher); Fairgrounds redevelopment, Milan (© Libeskind); Swiss Re, London, 2003 (© Foster&Partners); Communication tower, Valencia (© T. Cortez); Torre Agbar, Barcelona, 2004 (© Nouvel); Green Bird (© Future Systems)

Extruder - Sub-Categories: Anglers, Sliders, Tapered sliders, Slider assemblies



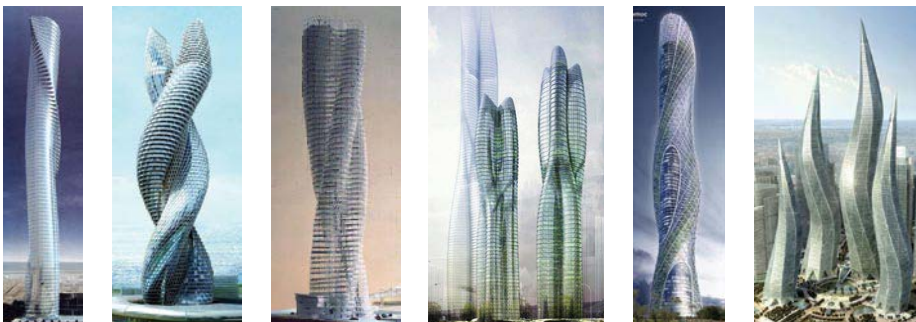
Figures 4a-f. Al Mutawaa tower, Dubai (© Soehne); Gazprom, Petersburg (© Herzog De Meuron); The Legs, Abu Dhabi (© Aedas); Dancing Towers, Dubai (© Hadid); Oblique World Trade Centre, New York (© NOx); World Trade Centre, New York (© FOA)

Twister - Sub-Category: basic – and tapered twisters **Line Controller** - Sub-Category: Tordo



Figures 5a-f. Turning Torso, Malmö, 2005 (© Calatrava); Infinity Tower, Dubai, -2011 (© SOM); Avaz Twist tower, Sarajevo, Bosnia-Herzegovina, 2008 (© ADS Studio); Chicago Spire, Chicago, on hold -2013 (© Calatrava); Ocean Heights One Residential tower, Dubai, -2010 (© Aedas); Shanghai tower, China, -2014 (© Gensler)

Twister - Sub-Categories: Sliding -, Helical -, Tapered-, Merging twisters



Figures 6a-f. Torre Castelló, Valencia (© Calatrava); Cobra Towers, Kuwait; Twisted Trees, Bin Hai Seaport City, China (© Lee Harris Pomeroy); World Business C., Busan, S. Korea (© UNStudio); Bicentenary Towers, Mexico City (© Vasquez & Wedeles); Dubai Towers, proposed (© TVS)

Twister

Sub-Category: basic – and tapered twisters

Line Controller

Sub-Category: Tordo

A basic twister has a constant horizontal rotation around a vertical axis and identical floors. Its façades repeat on all floor levels. The floors of Figure 5a basic twister hang rotated around a cylindrical core. The façade columns in Figure 5b incline in- and outwards, but are stepped sideways. The stepping and stiff connections to horizontal façade beams greatly reduce torque. Figure 5c compound twister has a twisting volume intersecting an orthogonal elevator shaft. Vertical recessed columns are positioned in a circle and the façades hang from protruding floors. Figure 5d tapered twister has inward curving transoms. This is unusual, as it implies a less efficient floor/façade ratio. Tapering decreases the repetition in upward direction. This is compensated by horizontal repetition. A tordo has an orthogonal superstructure and one or more twisted façades that do not share a rotational axis. The Figure 5e tordo can be drawn by curving some contours. All mullions connect to parallel flat walls. Not so in a twister: it's helical mullions lean sideways, and it's façades share the rotation axis. The 632 m high Shanghai tower, a tapered twister, will be organized as nine cylindrical buildings stacked atop each other, enclosed by the glass façade's inner layer. Between this and the twisted outer layer, nine indoor gardens, at different levels, will provide public space.

Twister - Sub-Categories: **Sliding - , Helical - , Tapered- , Merging twisters**

The axis of Figure 6a is slightly helical. The asymmetrical floors are piled vertically, not through the floor's centre of the partly circular contour, but through the gravitational centre. When floors move upwards along a curve, a *Slider* results. With additional rotation of the floors, it is a *Sliding twister*. A *Helical twister* has a helical rotation axis. Entangling volumes cover a range of organic connotations. The Cobra towers look like snakes with patterned skins (see Figures 6b). The *Intersected helical twisters* on Figure 6c have the elevators in the overlap. Circling an assembly of helical volumes in the

same direction, causes torque. The *Merged sliders* (see Figures 6d) merge from opposite directions and avoid this. One of the contrary twisting volumes of Figure 6e *Intersected twisters* occasionally is visible. The volumes rotate at different speeds. Figure 6f *Tapered sliding twisters* are shaped by individually scaling hexagonal based pyramids and rotating them around a 3D axis.

Sub-Category: **Basic Twister** - Sub-Categories: Stepped twisters, Hybrid twisters

As of this date, fluently curved/twisted glass panes have not been produced on a scale for high-rises. All façades are tessalated with flat panes. Just like the underside of a set of stairs, a twisted surface can be approximated by flat surfaces. The façades of *stepped twisters* are composed of flat segments (see Figure 7a). Torsion on the superstructure caused by inclining columns, is reduced by decreasing the protruding of wings. Often a twisted volume is simplified to a combination of cylindrical surfaces and stepped flat surfaces (see Figure 7c). *Hybrid twisters* have façades of various geometries, that fluently connect (see Figures 7bde), like cylindrical and twisted segments. Figure 7d *stepped hybrid twisters* features both aspects.

Merger, Boolean, Line Controller

Whereas *Mergers* are primitives, *Booleans* and *Controllers* are transformed primitives. The façade of the Figure 8a tower seems to transform from a circular base to a free curving roof contour, making the volume a Merger. But the façade can also be standardised to cylindrical segments, with flat parts in between. Uncertainty leads to classifying it a *Free shape*.

Booleans are volumes sculpted by deducting or adding volume segments that are described by intersections with other volumes. Their surfaces typically meet along clearly visible lines. Figure 8b *Free shape* has a canyon-like cut-out. It may be a *Line controller*, shaped by making orthogonal cut-outs from a box volume, and then transforming the surfaces by curving some contour lines. Compound volume Figure 8c is a *Compound of boolean extruders*, consisting of two overlapping

volumes. The volumes were extruded from the base contours upward, and had boolean operations parts removed. Figure 8d is a Boolean in which intersecting curves were drawn. These were used to make controlling around surface fields that subsequently were filled with glass and hole patterns.

Free Shape, Sweeper

Figure 9a *Free shape* probably was drawn with few manipulations, but it is not obvious which ones were used. It can be a *line sweeper* - a volume created by moving a curve along a base contour as rail-track. Or be a *scaled extruder* - made by first extruding a base contour upwards, then scaling it and adding a twist. Especially when the rotational axis is curved or the scaling varies and is excentric, determining the transforming process is difficult. Additional transformations will complicate retracing the shape build-up even more, especially for those not accustomed to drawing. Then the client, architect or contractor may have to supply the information for the database, by naming the commands used to generate the building volume, preferably in order of application. The Figure 9b volume, generated by applying various tools, is a Free shape. The Figure 9c volumes twist and taper. Especially when tops are cut off at an angle, and no patterns of repeating lines can be distinguished, then determining the geometry is difficult. They are classified as free shapes, as the façades are a mix of flat, single curved and (hyper-paraboloid) twisted segments. Both Figure 9d free shapers were designed by first optimising three stacked, different volumes to accommodate apartments, hotels and offices, respectively. Next is adapting the volume contours to visually fluently interconnect. Subjective fine tuning will make a shape only globally fit the morphology system.

Special-Category: **Compound volumes**

Sub-Categories: **Connectors, Blenders**

A *Compound volume* is a volume built by combining two or more complex shaped volumes. It differs from a Boolean, which is made by transforming a primitive shape, by for example adding or deducting (parts of) a ↻

Sub-Category: **Basic Twister** - Sub-Categories: Stepped twisters, Hybrid twisters



Figures 7a-e. Urban Totem, Mississauga, Canada (© Donner&Sorcinelli); Kuwait Trade Centre, 2009 (© NORR); Mode Gakuen Spiral tower, Nagoya, Japan, 2008 (© Nikken Sekkei); Torre Alicante and Torre Valencia, Valencia, Spain (© Calatrava); Sea Breeze tower, Dubai (© author)

Merger, Boolean, Line Controller



Figures 8a-d. Iris Crystal, Dubai, planned (© Aedas); Opus, Dubai, -2010 (© Hadid); Gazprom, Petersburg (© Studio Daniel Libeskind); Flagstore Luis Vuitton, Japan, (© UN-Studio)

Free Shape, Sweeper



Figures 9a-d. Desert tower, Peru (© Ferri); Hydropolis Dubai, proposed (© Hauser); PGCC, Penang, Malaysia, proposed (© Asymptote); Raffles City, Hangzhou, China, -1012 (© UNStudio)

Special-Category: **Compound volumes** Sub-Categories: **Connectors, Blenders**



Figures 10a-d. Farrer Road towers, Singapore, proposed (© Zaha Hadid); Urban Oasis, Singapore (© UNStudio); M. Schumacher tower, proposed Dubai (© L-A-V-A); SOCAR tower, Baku, Azerbaijan, proposed (© Heerim architects)

volume. Figure 10a shows a cluster of compound volumes, each composed of interconnected or overlapping segments. The recessed façade segments may have been made by intersecting outer volumes with an inner one, or by merging surfaces between lines drawn on the volumes. Figure 10b is probably generated by projecting curves onto a volume and demarcating fields with them. These subsequently were, for example, pulled outward with 'control lines' acting like magnets and were divided into horizontal bands. As the originating primitive shape is uncertain, this volume is classified as a Free shape. Figure 10c is a compound volume with lower segments sheared sideways or at least the façades there blended to the surrounding earth surface. Figure 10d is a compound of tapered sliding twisters.

Special-Category: **Punctuated towers**

Figures 11abd are Booleans. Figure 10a is a *Boolean sphere* with holes cut out where it overlaps with other spheres. Figure 11b is a blended *Boolean extruder*. The overall volume was shaped by deducting parts from a volume that was made by extruding a base contour upwards. Subsequently, the contours were blended: rounded off with a fixed curve. Figure 11c is a Free shape, as many transforming tools were applied to shape it. Figure 11d is a *Boolean box* with spherical holes.

Special-Category: **Slicers**

A *Slicer* appears to have a curving façade, this impression being created by balconies, louvers or other protruding elements. In Figure 12a the curving virtual outer surface is indicated by balcony contours meandering around an orthogonal glazed volume. The balconies of Figure 12b have recessed façades tessalated with flat segments. The smooth image on Figure 12d is achieved by the large number of thin sun-louvers. The Figure 12a-d volumes are molded by various transformations. As their geometry is not obvious, they are *Sliced free shapes*. Verticality of balustrades is less obvious on the high-rise Figure 12c than on the low-rise Figure 12e *Sliced twister*, where the overall look is not smoothly curved but stepped.

Special-Category: **Turners**

In 1924 the Russian constructivist Konstantin Melnikov designed the Pravda Leningradskaja office building. The floors were to hinge around a steel core, each rotating 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 designed by Rolf Disch in 1994.

Recently, architects have proposed various *Turners*: towers that can rotate as a whole, or in part(s). The top 5 of the 15 floors of the Rotating Residences (see Figure 13a) are to rotate individually. The Time Residences tower (see Figure 13b) is to rotate as a whole. The Da Vinci (see Figure 13c) floors are to individually rotate, allowing one apartment owner on each floor optimal sun-light and outward views. It is the first building designed to have floors programmed into a ballet-like scenario. The Dubai Renaissance (see Figure 13d) is a 300m high slab with a visual play on a transformed grid. The preliminary design idea was to rest the volume on a circular float so it could rotate and play a moving role on an urban scale, This was ultimately abandoned.

Special-Categories: **Bio-climatic towers, Wind energizers**

The boolean volume in Figure 14a has cylindrical façade segments. Bio-climatic performance is elaborated in all building geometries. Figures 14bd are Revolvers, Figure 14c is a twister. 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. In contrast, they 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. Often these are boloidal, to provide element repetition. Figure 14e is a *Boolean extruder*. High-rise wind-energizers can have wind generators of various kinds and on several levels: Lighthouse, Dubai (1 tower), WTC, Bahrain (2 towers), Atrium City Towers,

Dubai (3 towers). Volume configurations have been studied in Peter Land's Illinois Institute of Technology workshops.

Special-Categories: **Clusters**

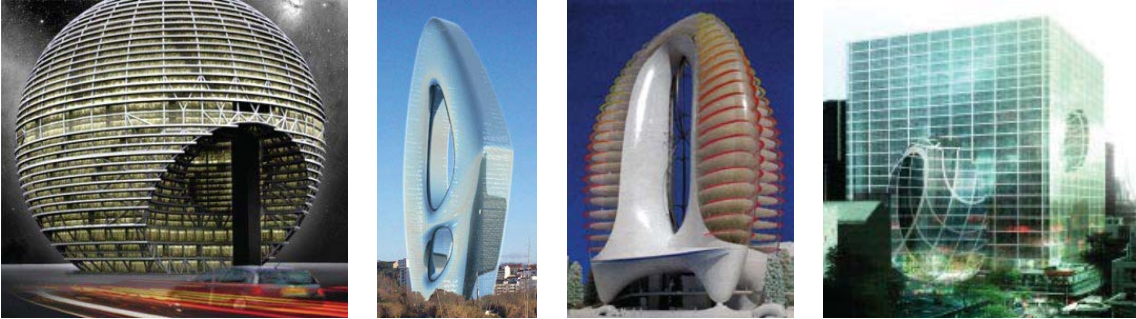
Usually the base and top of towers align with important urban elements like a road or canal. The *Twister twins* in Figure 15a twist approx. 90°. Sharing directions of top and/or base, unifies the towers. Many iconic buildings stand alone and mostly refer in a direction to themselves, i.e. their top takes up the directions of their own base, as indeed they are the most important urban element. A building rotation of 90° can bestow a crystalline beauty, like that of a cut jewel. Abbreviating from 90°, introduces natural associations and draws the attention away from the building. A singular iconic tower or an alignment of towers, pinpoints a project. If similarly transformed buildings encompass a setting, then an environment is created. Such towers need not be identical. With a limited number of parameters in the modeling, many variations can be made, like a *Slider cluster* (see Figure 15b) and a *Line Controller cluster* (see Figure 15c). Embedded formal harmony between buildings stems from sharing 'genes'.

Special-Category: **Façade patterns**

Avant-garde architects use modeling software to visualise new façade styling, geometries, textures and functioning. 3D printing is becoming economically feasible for the production of a large series of small building components. In time, it will allow grading materials (varying the materials' consistency and density), ease assemblage, add new functionalities (such as the capability to ventilate), etc.

In morphogenetic façade design, patterns are generated by scripting relations between components, to define their sizes and positioning. Building skins become 'populated' with windows or structural elements. Figure 16a *Boolean extruder* is an extruded volume with façades perforated by intersecting with cylinders. The hexagonal façade openings of Figure 16b vary also in size, but are flat. The Figure 16c box features a cubic lattice ㊦

Special-Category: **Punctuated towers**



Figures 11a-d. RAK Convention and Exhibition Centre, Ras al Khaimah, UAE, proposed (© OMA); Vertical Learning Centre, Portugal (© B. Silva); Bionic Tower (© Future Systems); Coolsingel Tower, Rotterdam, proposed (© OMA)

Special-Category: **Slicers**



Figures 12a-e. Aqua tower, Chicago, -2009 (© Studio Gang); Tower, Oslo, Norway (© MAD); Absolute World 1, Mississauga, Canada, -2010 (© MAD); Slinky Twins, Paris (© PCA); Nordhavn Residences, Copenhagen (© 3XN)

Special-Category: **Turners**



Figures 13a-d. Rotating Residences, Dubai, proposed (© Faisal Ali Moosa); Time Residences tower, Dubai, proposed (© Howells/Palmer&Turner); Da Vinci tower, Dubai / Moscow, proposed (© Fisher); Dubai Renaissance, proposed (© OMA)

Special-Categories: **Bio-climatic towers, Wind energizers**



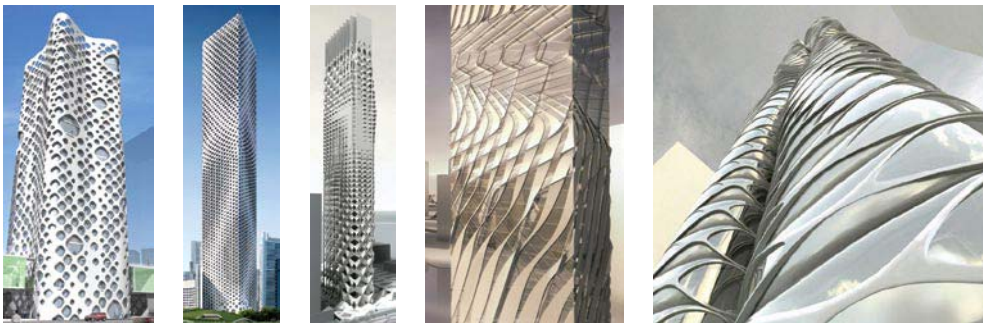
Figures 14a-e. EDDIT tower, Singapore, proposed (© Yeang); Commune towers 2026, Seoul (© Yeang); Sustainable tower, Dubai (© AlBaloushi); Innovatoren, Venlo NL (© McDonough + Arcadis); WTC, Manama, Bahrain, 2008 (© Atkins)

Special-Category: **Clusters**



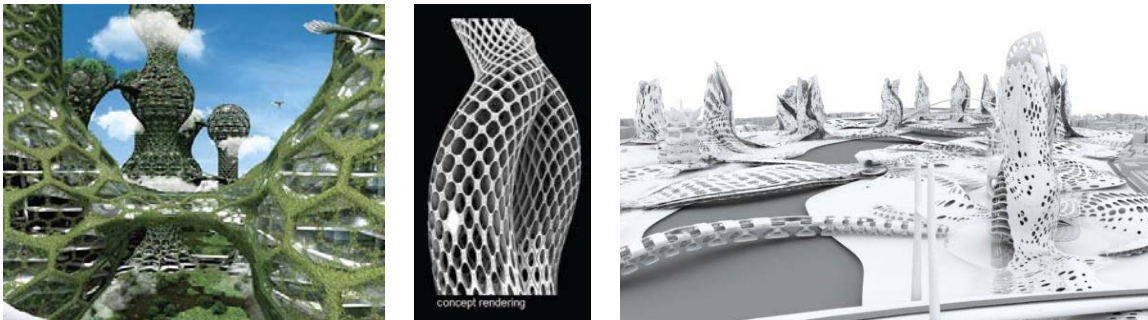
Figures 15a-c. Dubai Towers, Istanbul, proposed (© Inhouse Design); Caribbean, Keppel Bay, Singapore (© Libeskind); Dostyk Business Centre, Almaty, Kazakhstan (© NBBJ)

Special-Category: **Façade patterns**



Figures 16a-e. O-14 tower, Dubai, -2009 (© Reiser & Uemoto); Sino-Steel tower, Tianjin, China, -2012 (© MAD); Tower project (© Ali Rahim & Yeung); Residential Housing tower, Dubai and Commercial Office Tower, Dubai (© Rahim)

Special-Categories: **Structural façade patterns, Façade materials, Urban models**



Figures 17a-c. Commune towers 2026, Seoul (© Yeang); GC workshop study (© Neri Oxman); Urban plan, London (© AA workshop, London)

undergoing cycles of disintegration, migrating from order to chaos and back again. The façades of Figure 16d has folds in the glass (!) and other panels. The façades of compound volume Figure 16e are compilations of bulging elements of varying sizes.

Special-Categories: **Structural façade patterns, Façade materials, Urban models**

The gap between patterning and structural optimisation narrows in Figure 17a. 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 17b). Scripting procedures are applied to visualise and develop integrated functions (Figure 17c). Unexpected images can thus be generated, but they often require subjective visual finetuning. The response of future high-rises to the historical and social context,

urban fabric, new materialisation and added functions, is becoming visualised in the design entries for the Evolo Skyscraper Competitions. [AIEL, 2008] Their shaping as yet has not yet been classified. They can be listed in the Free shapers, or in special categories, like Structural façade patterns, Urban models. ■