FRANS MASEREEL CENTRUM KASTERLEE [BE]

Reciprocal frame roof structure

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Aerial view of the new pavilion during construction (© photography Vanhout Pro)

ABSTRACT

The Frans Masereel Centre roof structure is based on a centuries-old structural typology called reciprocal frame. Known from centuries to span over great distances with limited-length-timber-elements, this typology is generated by mutually self-supporting elements placed on a specific geometrical adjustment, and mainly developed through simple repetitive patterns. In the context of the extension of the Frans Masereel Centre, it has been adapted on an extruded truncated cone, offering a unique space, spreading through intimate rooms with various perspectives, giving no specific directions and evolving through the different spaces. This project was the opportunity to experiment the possibilities and limits of new technologies in the development of a millenary structural typology. During the whole design process, the different stakes – from the architectural orientations to the structural behaviour- were applied as various parameters of different geometrical optimisations and it was the opportunity to study a large panel of reciprocal frame possibilities. This annex presents the results of this study and their applications and will provide a critical look-back on the processes of optimisation of reciprocal frame structures, considering the efficiency of the tools, the choice of various parameters and different models and the application on a real scale project.

Keywords: Parametric design, genetic optimisation, reciprocal frame, timber structure

INTRODUCTION

The roof structure of the Frans Masereel Centre is based on a reciprocal frame. A reciprocating system uses relatively short members to build a structure with a span longer than that of its individual parts where each beam supports and is supported by other beams in the structure (Pawlyn [3]). The simple concept of a do-it-yourself structure was adapted to the complex volumetry of the project: an extruded truncated cone. Instead of an orthogonal, radial or hierarchical structure, the geometry is based on a modulus of 4 beams, called '4-nexorade', and organised in radial and ortho-radial lines on the cone.

Initially developed on several levels in a Cartesian space, this typology was projected on a cone, deforming the cells and giving specific orientations. The early definition of the inclined cone itself and its projection – equated with aesthetic and structural choices – was enhanced by local density distribution optimisation to adapt the modulus to the specific geometric support. Through these choices, various parameters emerged and were ruled successively through a genetic algorithm on different models according to aesthetic, structural and technical constraints. This project was the opportunity to test the scope of new technologies in the design of this century old typology. Through the whole design process, a large panel of variant constraints were applied as parameters of different geometrical optimisations and thus generated a large scope of reciprocal frame possibilities.

The evolution of the project led to the comprehension of a hybrid structural behaviour, between an interlocked network of beams and a shell. The production constraints with a complex geometry and a large number of unique pieces questioned the design process. This annex presents the results of the structural study for the Frans Masereel Centre and their applications. It provides a critical approach to optimisation processes of reciprocal frame structures, the realisation of complex shapes with unique pieces of wood, the efficiency of the tools, the choice of various parameters and different models.

1. DESIGN APPROACH

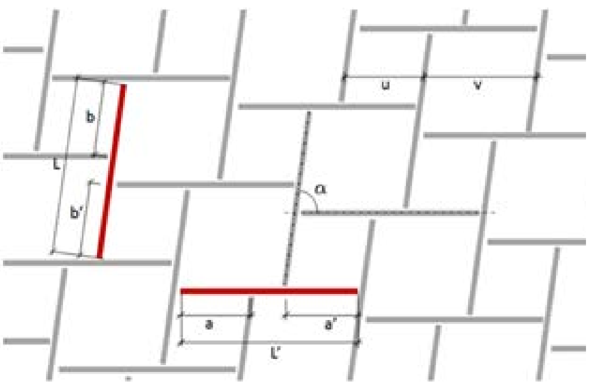
Preliminary developments – definition of the early parameters

During the competition the project was designed as a circular building a cone shape roof. Initial considerations for a concrete shell roof were rejected since it was too heavy and induced too much labour for the formwork. Typical Belgian houses have wood frame roof pitches, it was therefor decided to apply a wood structure. The roof is meant as non-directional uniform surface or grid and it had to adapt to the supporting conditions and placement of walls below. Although the spaces beneath are all unique, the common denominator and reference remains the roof. This meant that radial structures or structures with primary and secondary beams were rejected from the start. The small and self-providing local community further inspired us to suggest a structure that could be built by the people itself without the use of a big crane and using only massive wood (no laminated sections). Thus the choice fell on a nexorade structure which could answer to all these premises.

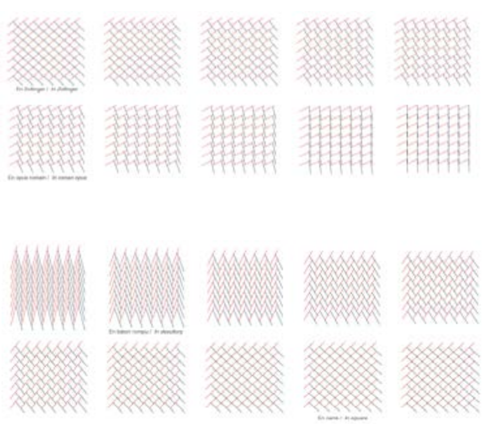
Once the competition won, several studies were pursued in order to finesse the geometry of the roof structure, based on early production hypothesis – notably the beam length – in order to place the equation between the aesthetic and structural stakes.

During the design phases it became clear that the structural load-bearing walls underneath this roof could still move due to programmatic or aesthetic changes. The initial idea of building a cone with equivalent structural quality everywhere enabled the architects to adapt relatively freely the place of the future load-bearing elements. Instead of building models emulating the architectural advances it was decided to make idealised and smaller tests for optimising individual parameters. Initial models thus were all set on a simple rectangular basis in order to observe the pure structural behaviour of the large variety of typologies without being disturbed by other constraints.

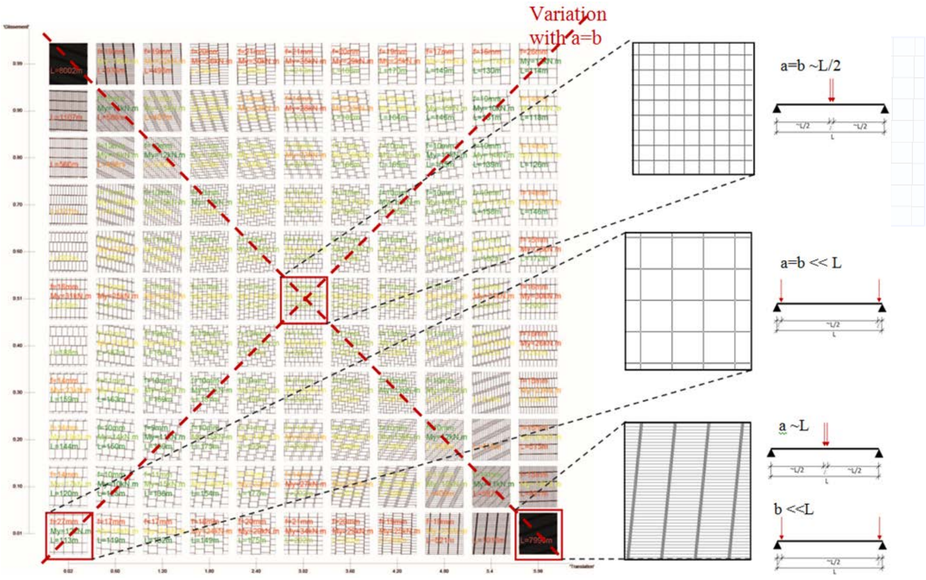
For a first test-series on this rectangular basis, all models were based on a 4-nexorades (Baverel, [1]). Two other rules were also adopted: all the beams should have the same length – between 2 and 6m – and have the same quality of supports for a similar orientation. Thus, one parameter ruling the support position was set for each direction (on the illustration below b=b' and a=a'- called X-shift and Y-shift). As a third degree of freedom for the algorithm, we decided that an additional parameter ruling the angles between the two directions should be defined (a). Thus three parameters were taken into account for the first studies (a, b, a). The algorithm was then allowed all possible variants within this range, from the typologies used by F.Zollinger where the beams support on their centre – generating rhombic cells, dimensions u~v~L/2 – to typologies where the beam are supporting in the proximity of their ends – generating differentiated rhombic cells, dimensions u<<L and v~L.



Choice of the early parameters - Records from Grasshopper



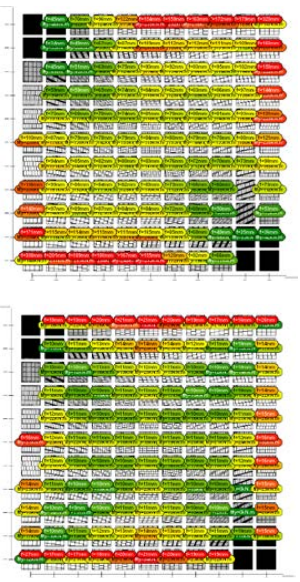
Panels of geometrical possibilities from the 3 parameters - Grasshopper



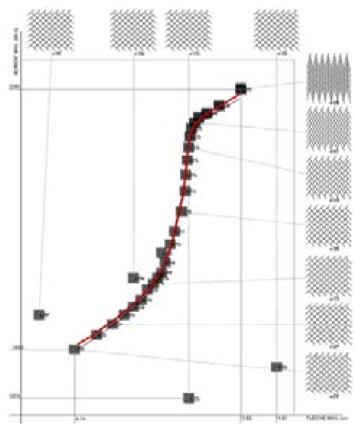
Maximum bending moment and deflection in function of the X-shift and Y-shift parameters, considering dead load and a surface load of 3,5 kN/m². *Data extracted from Grasshopper/Karamba3D model*

The first model was set as a fitness criteria to evaluate the X-shift and Y-shift parameters on the deflection and the maximum bending moment, considering a surface load of 3,5 kN/m² on a 12m-side square. From those studies, it appeared that the most efficient configuration corresponded to a maximal number of beams with a ~L and b <<L. Considering on top of this the dead weight of the beam, the optimised configuration shifted to a more regular one - around (a~L/3; b~L/3), depending on the dead weight/live load ratio.

A second variation was modelled, based on the angle parameters one variation only, considering the X-shift and Y-shift parameters as output data of the geometrical algorithm. As described in the graph below, the optimal angle considering the minimal deflection and bending moment was obtained for a 90° angle. As illustrated below, we noticed that a variation of the angle a from 90 to 60° would increase the maximum deflection by 39% and the maximal bending moment value by 33%.



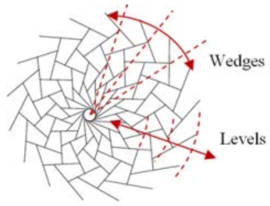
Maximum bending moment and deflection in function of the X-shift and Y-shift parameters, respectively represented here on abscissa and ordinate - *Top* : considering dead load ; *Bottom* :dead load with a additional surface load of 3,5kN/m² - *Data Grasshopper/Karamba3D model*



Maximum bending moment and deflection measured on the angle variation – *data extracted from Grasshopper/Karamba3D model*

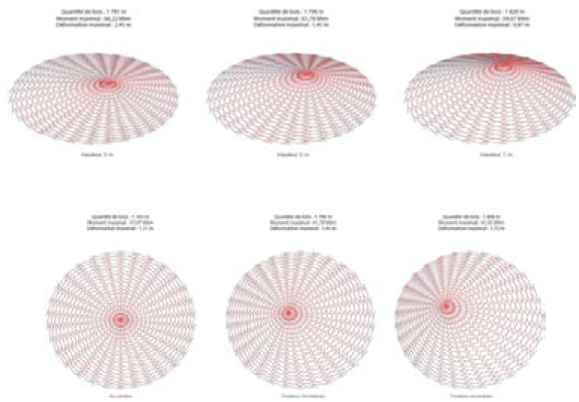
Conic model – from Cartesian to polar

As observed on the preliminary models, the boundary and load conditions proved decisive in the selection of the geometrical configuration. Thus, it was decided to observe the geometrical configuration on a truncated cone, closer to the geometry of the building, although still in development. The following models and researches were developed in direct collaboration with LIST & HNA in order to define the overall geometry of the roof.



Wedges and levels parameters

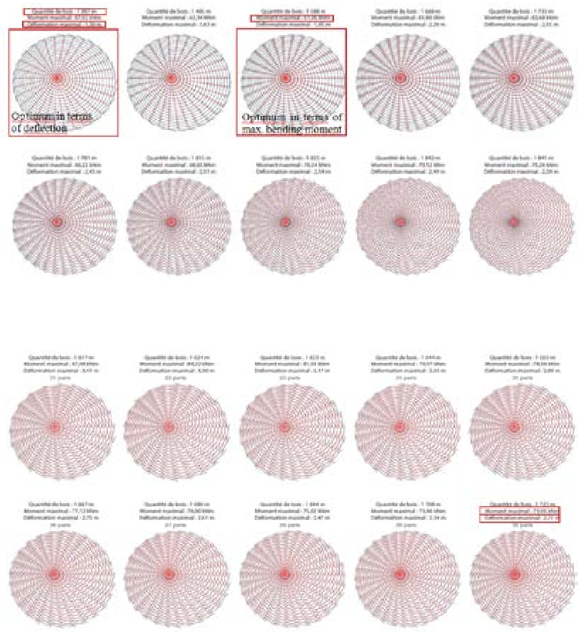
While projecting the 4-nexorade model on the cone, two additional parameters were taken into consideration: the number of wedges (corresponding to the number of radial elements) and the number of levels (corresponding to the number of ortho-radial cells), while keeping the restriction on the maximum beam length (6m which corresponded to the upper length of standard elements). In order to limit the number of parameters, one shifting parameter was set as fix in the following models – considering a=b. All the following models were made for a cone with a diameter of 29,6m and a height between 2,50m and 4,15m, with massive timber beams of 80x230mm section, the dead load and live load of 2 kN/m².



Variation on cone height and apex position *data extracted from Karamba3D*

A first series of analysis and exchanges with the architects were set up to point out the inherent parameters of the cone - height variation between 2 and 5m, apex position varying between 0 and 5m. The chosen option, close to the optimum, was found for a maximum height and a reduced eccentricity of the apex position.

As described above, a series of models comparing the shifting parameter were tested. This pointed out the importance of this parameter on the cone configuration, as a structural and aesthetic token. Within this range, the deflection varied by 18% and the maximum bending moment by 14%. Although the optimal configuration was observed for a reduced shifting parameter (a<<L where the beams are supporting close to their ends), a larger value was allowed for aesthetic reasons.



Top: Deflection and bending moment measured on a variation on the shifting - *Bottom*: and on the number of wedges - *data extracted from Karamba3D model*

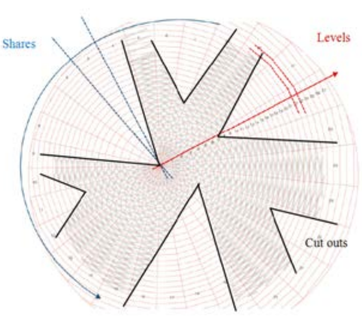
Whereas the two previous tests keep the amount of wedges and levels equal in each model, our next research kept the preliminary parameters equal but could add levels and wedges until the minimum length of the beam reached 1,5m and the maximum length

6m. Although the relative evolution of the timber quantity is quite small – 7%–, a variation of 20 to 40 levels lead to a decreasing of the max. deflection by 54% and of the max. bending moment by 24%. An optimum was observed for a maximum number of levels and wedges, maximising the timber quantity and minimising the beam length. For this reason it was chosen to adapt the model to the truncated cone.

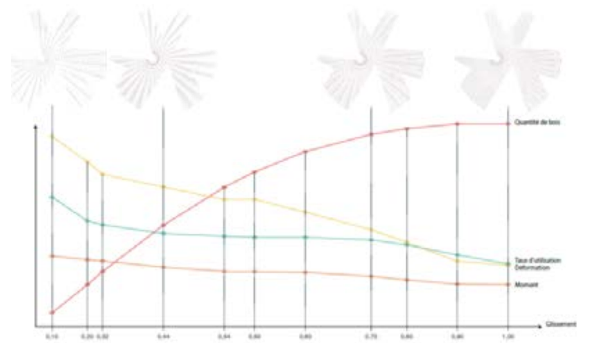
Truncated cone model - fine adaptation of the model

Since by now we had more precise indications on the cut-outs, we also tested our findings onto the chosen architectural form. We left the model with some degrees of freedom but of course much more restrained since we already had the chosen range from earlier research on the full cone. Due to a different type of configuration – support positions, spans, cells orientation- It appears a differentiation of local structural behaviour between each branch and the junction of them.

After an adaptation of the previous parameters and in order to optimise the structure, has been decided to optimise the level distribution. Although the share distribution - or a differentiation of the geometrical configuration in each branch - would have been an efficient parameter, it has been decided to keep it regular, as the roof should be continuous/regular/similar in the whole project.



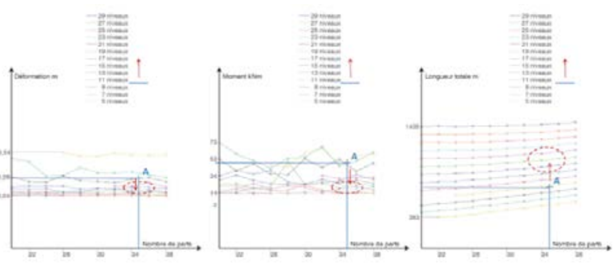
Schematic plan of the cells & cut out with regular distribution



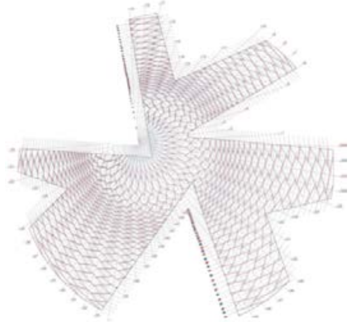
Deflection and bending moment measured on a variation on the shifting

The adaptation of the number of shells and levels leads was constrained with tolerances and border issues due to the position of the cut-outs. It remains results hardly legible because of the differentiation of behaviour of the branches within those stakes, as illustrated in figure 11.

In order to solve this issue, while keeping the roof uniformity, a modification of the level distribution has been performed. It remains from such a configuration a differentiation a variation on the orientation – from radial in the proximity of the apex to orthoradial in the branches- and a cell concentration in the long-span-areas.



Variation on the number of wedges and levels – *Grasshopper/Karamba3D model*



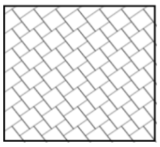
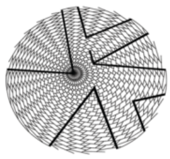
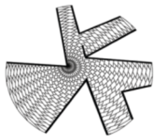
Plan view of the roof structure directly generated from karamba3D model

2. DESIGN ISSUES

Various parameters consideration

The early conception was made through three model types, from a rectangular projection to a truncated cone, expanding the parameters and the accuracy of the design. Although those models were parametric and not directly project related models, allowing the possibility of a large number of parameters and their control, important design choices were frozen with these models.

The result of this approach may not have generated the most efficient structural configuration, but is a result of successive choices and processes which were made with LIST & Hideyuki Nakayama. Therefore, it remains a compromise between aesthetic and structural solutions.

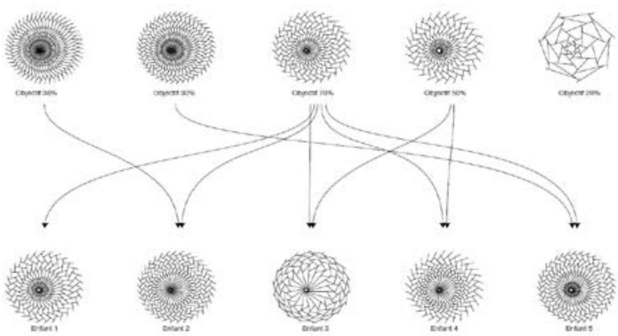
	1st model - rectangle	2nd model – cone	3rd model - truncated cone
Models			
Parameters	X&Y-shifts, rotation	Cone height, apex position, number of wedges and levels	Position of the cut-outs, local distribution of the previous parameters
Issues	Cells dimension and orientation on cartesian coordinates global structural behaviour	Cells dimension and orientation on polar coordinates, global structural behaviour	Position of the supports, local structural behaviour

Different models considered

As for the model's boundary conditions, different parameters were taken into account through different approaches. The previously described parameters (rotation and shifting) led to a thin local adaptation, resulting from an iterative process. According to architectural choices, other original parameters were frozen at an early phase, such as the global geometry, whereas the parametric tools would have allowed their variation, orientating the geometric evolution.

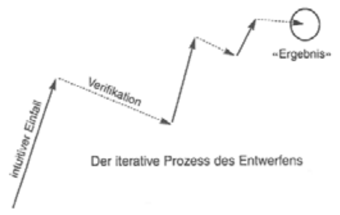
During the preliminary approach, simplified models were set up in order to apprehend the geometrical possibilities and the influence on the structure of the different parameters. The results of those models were extracted as a series of diagrams depending on the variation of one parameter within a predefined scope – resulting in one-dimension-diagrams. Those results were used to establish orders of magnitude of the structural behaviour (strains and deflections) and as a support of exchange with LIST and Hideyuki Nakayama.

Considering the interaction of the different parameters and taking into account multiple parameters(X-shift, Y-shift, rotation, level distribution) algorithms were developed in a second step. The researches of optimal configurations were performed using genetic algorithms such as Galapagos - single-objective evolutionary optimisation (Vierlinger [4]).



Genetic algorithm diagram applied on the level distribution

Although such a study, using genetic algorithm, was very efficient considering simplified models, it appears more complicated when used on more complex geometries such as a truncated cone, because of the model scale and configuration. As the ratio between the modulus (the 4-nexorade) and the dimension of the model is quite small (~1/30) border effects are very influential on precise local areas. Moreover, it requires a well-developed geometrical algorithm in order to rule the model tolerance (problems of identical node recognition, nodal release assignment, etc…) and to obtain significant results (graph of results avoiding peak due to local border effects).



The iterative process of the design (Hossdorf [2])

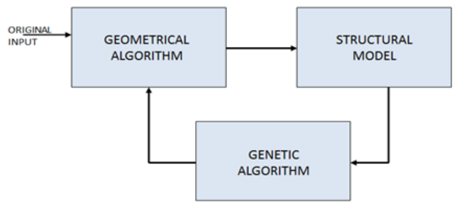


Diagram of the algorithm loop

Shell behaviour

Contrary to the original concept where each beam is supported on both ends and carries two others on its center, all the beams are interconnected in the sense that those connections can behave on both directions. According to the preliminary design of the beam connection details, pinned connections were taken into consideration in the structural model. Thus, the whole set of beams generates a network of beams, whose parameters define the density. In this set, the ratio between the average length of the beam – cell dimension - and the dimension of the model is approximately 1/30.

Considering the influence of the horizontal displacement of the beams locally and at the edges, it was decided, for economical and architectural reasons, to minimise the beam height and thus to block those displacements.

The comparison with a shell model pointed out the analogy with the roof structure behaviour –deflection and maximal constrains areas. The variations on the global cone geometry (height, position of apex, shell curvature) appeared to be more efficient than the changes of local parameters of the grid configuration. As observed in this comparison, the algorithms were performed to densify the critical areas.

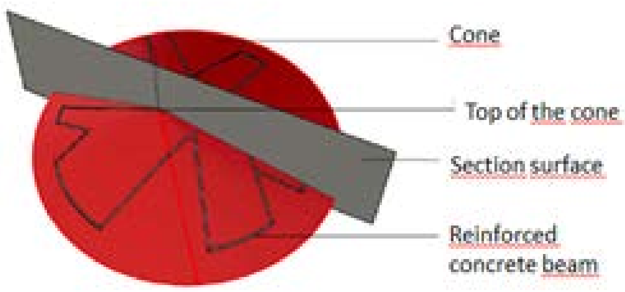
The global curvature of the roof was decided on the complete cone without cut-outs. The shell working is clear and positive. Because of the lack of curvature on parts of the branches and a certain lack on continuity, the behaviour of the roof structure is hybrid, between a shell and a grid of beams submitted to large bending moments. This behaviour evolves from the apex of the cone to the end of the branches, depending on the curvature and the position of the supports.

Genetic algorithm diagram applied on the level distribution

Construction issues

The very large variety of local geometrical configurations (ramification, beam orientation, surface curvature) generated an important range of different connection angles and types of forces (shear and normal). Taking into account the cost issues, a differentiation of the connections was performed, from tiled screw for low shear forces to simplex connectors for traction in the grain direction.

Although a differentiation on the level distribution was performed, researches were pursued to simplify the geometry and to limit the number of unique pieces. In order to guaranty similar cells on a same level, on a regular cone, the differentiation of the share distribution was not selected. Moreover, as the architects chose to maintain the reinforced concrete beams placed at the end of the branches on a similar height, the cone axis was lightly tilted by 3°.



Perspective and section of the cone tilt

As the covering of the beams is visible and should be adapted the geometry of the cone, the use of panels – and not laths – was chosen. Moreover, as the use of secondary structure was prohibited since the beginning of the project, the cells dimensions were an additional constraint for the geometrical configuration of the beams. This choice led to issues of tolerances of connections, due to the eccentricities of the beams, solved by deformation of the panel and use of smaller layout of the panels. A large quantity of different panels remained on each level. Those panels were not used in the wind bracing neither in the reinforcement of the rotational of the connections. Detail issues on connections and cladding are not explained here.

3. PARAMETRIC TOOLS ADAPTED ON A CENTURIES-OLD TYPOLOGY

Integration of large quantities of parameters

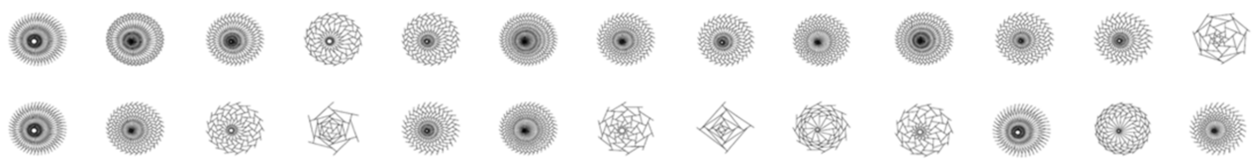
The main issue of such a project was the choice of the relevant variable parameters not the amount. During the conception process, such a large number of models with gradient complexity were developed for two reasons: to select the variable parameters and to generate material as base of discussion with LIST and Hideyuki Nakayama within the project deadlines.

Although we are currently able to set up optimisation algorithms using a large number of parameters, their development is time-consuming and often delivers limited or hardly legible results. Whereas the algorithm is able to efficiently calculate numerous possibilities far quicker than humans can, it is unsuited to point out other relevant parameters a human brain can promptly distinguish. Thus, such a development constitutes an iterative process to establish the relevance or the freezing of those parameters, by distinction of their leverage or their negligible influence, through the different phases whose input is constantly evolving.

This process needs a lot of architectural, structural and technical inputs. The parametric (re)search is a fantastic tool for a multiple optimisation but should always run parallel to other research. In order to inform the parametric we subdivided it in different themes which could each time be decided upon and fixed together. It does not undo the structural and architectural work but offers more options.

Large development of geometrical possibilities

Although this study was restricted from the beginning to several hypothesis and preliminary choices (as the use of 4-nexorades and the development on a unique modulus, for example) various possibilities have been generated and thus, demonstrate the large field of such a typology and further possibilities of development.



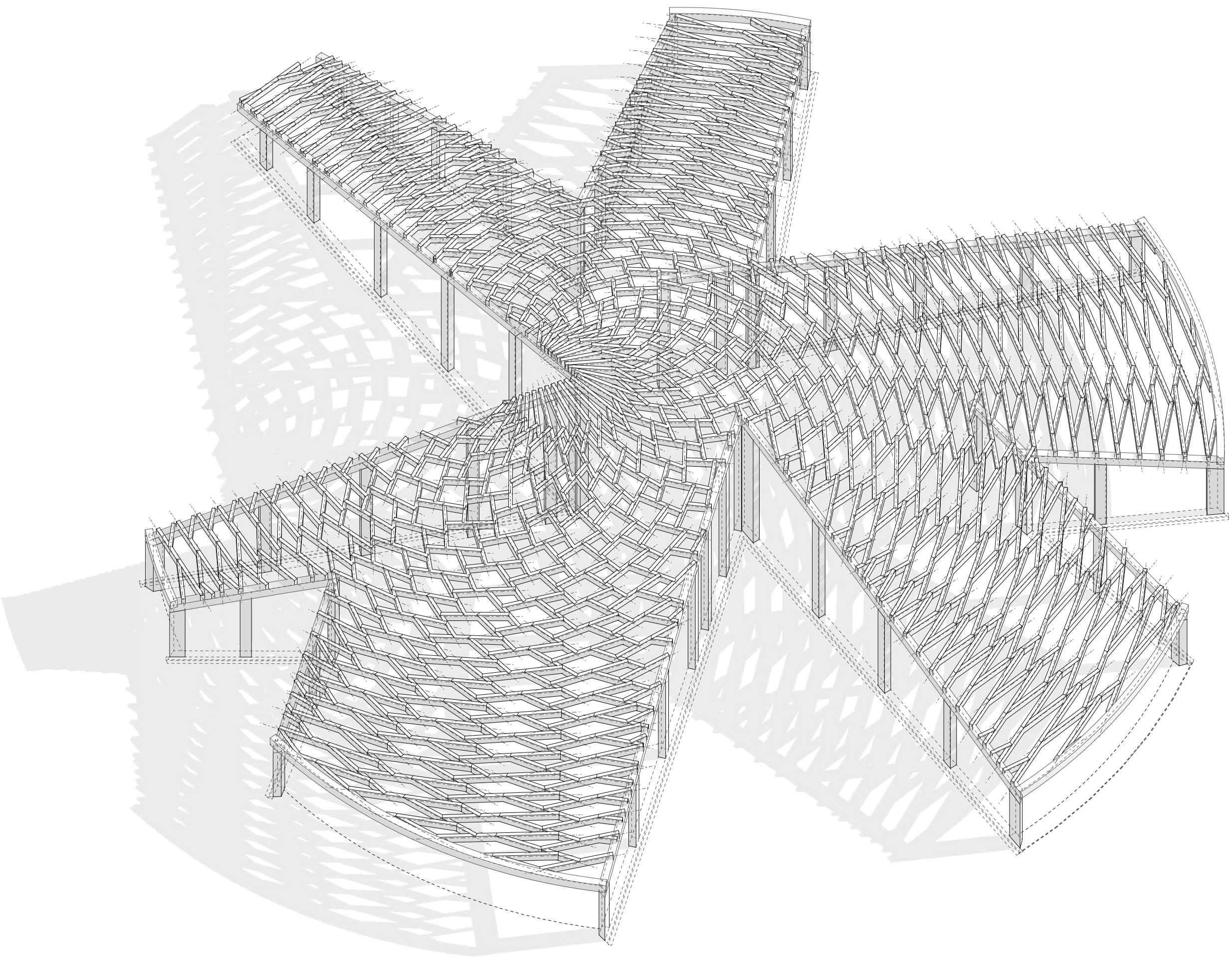
Panel of geometrical configurations of multilayer RF structures adapted on a cone

Conclusion

Besides the development of the project itself, this process was the opportunity to observe the possibilities of parametric tools such as the genetic algorithm, the parametric structural model (Karamba) with a large number of parameters and their local differentiations. Every parameter was thoroughly tested and agreed with the architect before going into the next phase. Those tools allowed us to discover a panel of reciprocal frame possibilities, from the ideal nexorade and cone of the Frans Masereel roof and their adaptation with the architect, within a control of their complexity.

References

[1] Baverel O. and Pugnale A., Reciprocal systems based on planar elements, in Structures and Architecture: New concepts, applications and challenges, Cruz P. (ed.), London: Taylor & Francis Group, 2013, 456-463.
[2] Hossdorf H., Das Erlebnis Ingenieur zu sein, Birkhäuser, 2003, 131.
[3] Pawlyn M., Biomimicry in architecture. London: Riba Publishing, 2011.
[4] Vierlinger R., Multi Objective Design Interface, MSc Thesis, University of Applied Arts Vienna, April 2013



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