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TECHNOLOGICAL AND ECONOMICAL ANALYSIS OF CURVED GLASS STRUCTURE

TEHNOLOŠKA I EKONOMSKA ANALIZA ZAKRIVLJENE STAKLENE KONSTRUKCIJE

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- curved and flat glass
- curved structures
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- materialization

Abstract

The main goal is to create links and an interactive relationship between the design process, materialization and realization of a curved glass structure. Based on established typology of curved building structure in terms of geometry, different hypothetical materialization models are created. The goal is to produce geometrically diverse, but optimally balanced design solutions of surface panelisation with respect to the original design idea, and in relation to surface transparency, simplicity of nodal connection, shaping technology, use of material and cost. The following criteria are established for analysis: shaping technique and material efficiency (technology criteria); hard costs/m^2 and total costs (economic criteria). The aim is to establish a methodological approach for realization of curved glass structure in order to select aesthetically satisfying and economically acceptable solutions.

Ključne reči
- zakrivljeno i ravno staklo
- zakrivljene konstrukcije
- tehnologija
- materijalizacija

Izvod

Glavni cilj ovog istraživanja je stvaranje veza i interaktivnog odnosa između procesa projektovanja, materijalizacije i realizacije zakrivljene staklene konstrukcije. Na osnovu utvrđene tipologije u pogledu geometrije, kreirani su različiti hipotetički modeli materijalizacije. Cilj je da se proizvedu geometrijski raznolika ali optimalna rešenja panelizacije površine u odnosu na originalnu dizajnersku ideju i transparentnost površine, jednostavnost čvornog spoja, tehnologiju oblikovanja, upotrebu materijala i troškove. Za analizu su uspostavljeni kriterijumi: tehnika oblikovanja i efikasnost materijala (tehnološki kriterijumi); troškovi/m^2 i ukupni troškovi (ekonomski kriterijumi). Cilj je da se utvrdi metodološki pristup za realizaciju i odabir estetski zadovoljavajućih i ekonomski prihvatljivih rešenja.

INTRODUCTION

Increasing number of contemporary architectural designs of curvilinear transparent building envelopes has set new requirements for application of curved and flat glass as an element of geometrically complex architectural structures. Large glass surfaces in which some materials have almost disappeared /1/ (dematerialized structures) have been enabled by recent technological and practical improvements of glass production, specially curved glass. At first glance, the application of either curved or flat glass provides an exceptional freedom in design of modern wavy shapes, but a set of constraints arises when it comes to the aspect of design, manufacture, use, performance, and economy. Characteristics such as minimum and maximum glass element sizes, radius of possible curvature, available coatings, optical/visual quality, selection of glass strength - glass type, thermal performance, as well as glass standards and local regulations significantly affect the final glass product, but differ considerably in case of curved and flat glass.

Referring to the geometry of glass structure surfaces, today there are no limitations in the process of their modelling. The word 'free form', interpreted as an expression of freedom and dynamics of architectural expression, says it is possible to create new forms if architects and designers are familiar with the geometry of basic forms, as well as with all elements of geometry. However, there are problems in practical fabrication, because unlike the abstract geometrically complex forms, structural elements have physical characteristics that prevent the creation of any geometry, /2/. This is specially emphasized in the case of brittle glass and easily breakable material unable to be produced in all shapes and sizes. Therefore, the design of curved glass structure is a compromise between different needs: fulfilment of design performance requirements, simpler production method and cost savings. More often, the relation between shape and fabrication poses new challenges and requires more sophistication from the underlying geometry, /3/. Therefore, numerous architects have returned to being highly engaged in the fabrication process to ensure the design intent is carried through into the making /4/. The selection of glass structure technologies is frequently a compromise between the intent of the architect, fabrication, transport limitations and the project budget. Particularly, frequently different curved glass structure typologies are compared taking into account mostly geometrical properties and neglecting economic evaluation. Therefore, the necessity of a comprehensive method to calculate and compare economic and technological performance of different investment savings options for glass structures has arisen. In this work, the cost analysis method is applied to assess the overall economic and technology feasibility of different types of glass structure technologies. The aim of the research is to apply established methodology in order to optimize the choice of curved glass structure, which minimizes costs while complies with optimal level of design requirements.

RESEARCH PRACTICE

A comparison of ten different building glass structure designs and technologies is shown (of the same materialization) in a residence building case study in terms of cost analysis. Technological performance is evaluated following application of either flat glass or one of five types of curved glass production methods proposed by *Guidance for European Structural Design of Glass Components* /5/. The economic evaluation is carried out following the investment cost calculation. Costs of glass construction (taking into account materials and production) are acquired from real offer prices of two largest Serbian curved glass manufactures. Finally, the relationship between construction costs and shaping technique is evaluated to define the economic effectiveness of each adopted design model of the curved glass structure.

Case study (real-world model)

Real-world curved glass facade, proposed as a case study, is a smart and energy-efficient residence building 'Infinity', located in city centre of Belgrade. It is freely wave-shaped glass facade consisting of 238 geometrically different elements, as shown in Figs. 1 and 2. The glass elements are supported by load bearing steel structure behind the glass surface. According to the project team, the building design is inspired by water, which shapes the position, life, and soul of Belgrade.

Figure 1. Glass facade of residential building 'Infinity'.

The curved geometry is performed by curvilinear surface envelope produced by conversion of double-curve into ruled surfaces which are generated by linear interpolation between two curves, /6/. Non-standardized single curvature glass panels are produced with not very reasonable cost using all different concave and convex molds. This glass complexity is counterbalanced by the design of universal steel supporting system, compatible with glass geometry, contributing to the simplicity of detail. Dimensions of glass facade panels are 980 × 1.080 mm.

Figure 2. Interior of the glass facade from the 'Infinity' building.

Geometry of created hypothetical models

The advanced geometry and technical possibilities are the basis for development of freely developable surfaces. The fact is that the highest surface quality that can produce a perfectly smooth solution can be achieved using double curved panels. On the other side, the most cost efficient way to realize a curved surface with glass is to use planar panels. The basis for creation of different models is curved geometry of the real-world glass facade surface model by a commercially available modelling package, in this case, Rhinoceros 4D. The dimensions of the structure that fit to the existing building have been adopted for all models. Furthermore, the achieved surface curvature of all models is optimally balanced, respecting the similarity to the original model, i.e. the existing facade. Parameters of geometrical characteristics that vary by models refer to individual panels and include:

- panel shape (rectangular and triangular),
- curvature of the panel surface (flat, single- and double curved),
- shape of panel edge (all edges are flat, two straight and two curved edges, and all curved edges), and
- panel size (two adopted panel sizes in the case of rectangular and triangular panels).

For models, the most commonly used panel shapes of curved forms have been selected, including triangles and rectangles. Triangular shape of the panel allows simple modelling of the glass structure given that their surface is always flat, while rectangular panelisation creates nodes that are more structurally stable and allows application of curved glass.

The diversity of applied panels in terms of curvature implies flat, single, and double curved panels. Flat panels are with straight edges, which enable their easier matching, while in single curved panels (vertical and horizontal torsa) the two edges are flat and two are curved making their fitting more complex. Additionally, the panel type geometry

- ‘hypar’ (hyperbolic paraboloid) is introduced, of double curved surface, while the edges are straight since double curved surface is cut through asymptotic curves.

Two variants of the panel size are adopted. In case of quadrilateral panelisation, the first variant corresponds to dimensions of the panel of the existing facade. The second adopted panel size has one dominant dimension - height that fits storey height. As well, in case of triangular panelisation, the first variant implies equilateral triangles, while the other is created by triangular refracting surfaces.

According to previously defined parameters, the following models are proposed (Figs. 3 and 4) with the purpose to adapt feasibility of a specified geometry of glass panels to the appropriate technological process of curved glass manufacture.

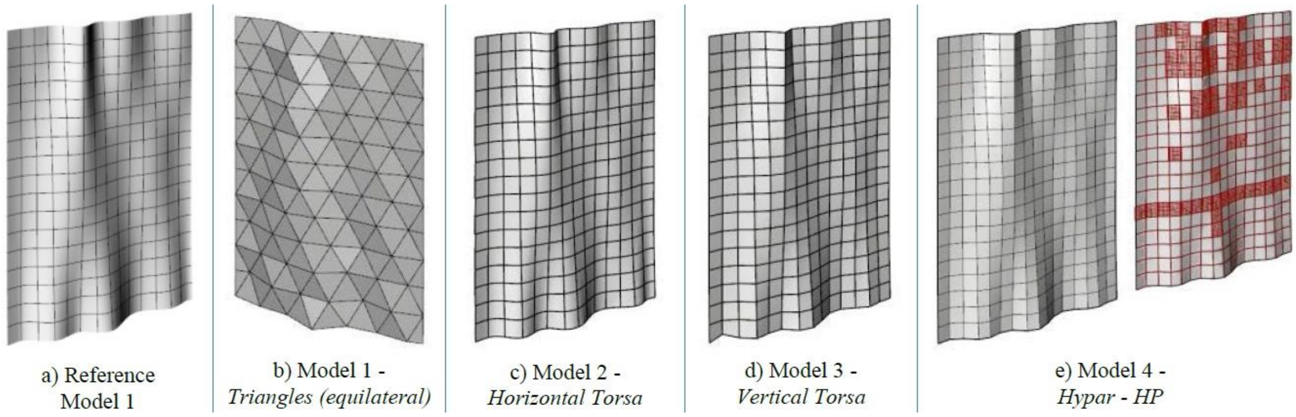

Figure 3. Models of geometrically complex forms of the glass envelope (small-size panelisation).

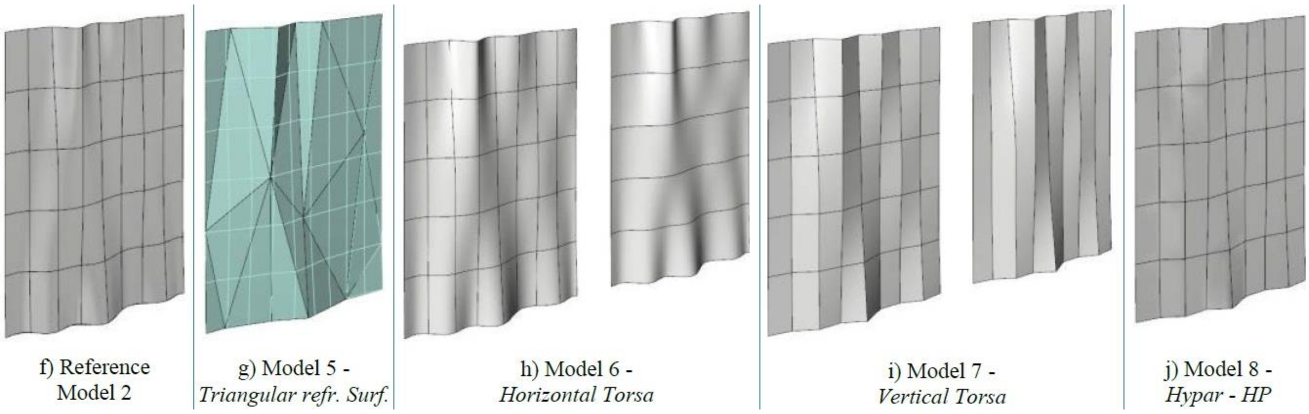

Figure 4. Models of geometrically complex forms of the glass envelope (large-size panelisation).

Table 1. Ten models of different glass structure geometries.

Model	Type of geometry	Panel size (cm)	Glass thickness (cm)	Structure surface (m^2)	Number of panels	Glass panel edges
Ref. Model 1	Freely-curved surface	94.4 × 111.4	6	270.20	238	curved edges
Model 1	Triangles (equilateral)	207 × 207 × 207	8	265.32	132 equ. /22 righ.	straight edges
Model 2	Horizontal Torsa	94.4 × 111.4	6	269.88	238	2 curved / 2 straight
Model3	Vertical Torsa	94.4 × 111.4	6	269.88	238	2 curved / 2 straight
Model 4	Hypar - HP	94.4 × 111.4	6	268.92	171 curv. / 67 flat	straight edges
Ref. Model 2	Freely-curved surface	166.4 × 382.6	10	270.20	40	curved edges
Model 5	Triangular refracting surf.	147.7 × 318.5	10	271.20	6 ent. /122 cut.	straight edges
Model 6	Horizontal Torsa	166.4 × 382.6	10	269.88	40	2 curved / 2 straight
Model 7	Vertical Torsa	166.4 × 382.6	10	269.88	40	2 curved / 2 straight
Model 8	Hypar - HP	166.4 × 382.6	10	268.92	40	straight edges

Geometrical features of ten models regarding glass panel dimensions and structure surface, number of panels, and type of panel edges are presented in Table 1.

Materialization

For materialization of adopted hypothetical models, the basic quality of glass - float glass, without coating and of appropriate thickness which directly depends on the geometry and panel, is selected. Three types of glazing, most commonly used depending on the place of application, are introduced according to the complexity of basic glazing element:

- single glazing using laminated glass for materialization of non-thermal structure, such as double facade in the case study. Laminated glass is selected meeting Serbian standards,

- double glazing - IGU option, using laminated glass panes and one single glass pane (separated by air) for cladding. Laminated glass is selected for the external glass, meeting Serbian standards,
- double glazing - IGU option, using two laminated glass panes separated by air for cladding. Laminated glass is selected for the external glass meeting Serbian standards, as well as for inner glass when necessary (special requirements arising from the use of facility).

EVALUATION METHOD

In order to evaluate the performances of different glass envelope technologies, the adopted methodology is broken down into the following steps related to technology and economic aspects and criteria for analysis:

Technological evaluation criteria:

a) curved glass shaping technique, and

b) material efficiency.

Economic evaluation criteria:

a) hard costs/m^2 for the structure, and

b) total investment costs for the entire glass structure.

Both groups of criteria are in direct correlation. Thus, a shaping technique that involves a less complex process (less time, labour and energy), implies a lower investment, both per m^2 and entire structure. As well, material waste, not related to the glass shaping technique, directly affects the cost.

Technological performance evaluation

The evaluation of technological characteristics for ten variants of the case study is carried out concerning the production method and material efficiency. For each model, the appropriate shaping technique is adopted in relation to panel geometry and availability of production methods in Serbia (Table 2). In case of single-curved panels in horizontal and vertical direction - Torsa models (Model 2, 3, 6, and 7), three possible shaping techniques are proposed. The first technique - thermal bending by mold, which is applied in case of real-world model, is available by only two curved glass manufacturers 'Konkav Konveks' and 'Pavle'. Another technique adopted to create single curved panels of small curvature is cold bending which is not known in Serbia, so far. The third adopted technique considered being suitable for Torsa geometry is thermal bending on the production line, but due to production availability by only one manufacturer ('Beokom') it is not possible to obtain necessary data for further analysis. The appropriate technique for twisted geometry of the Hypar models is cold bending due to small curvature and straight edges. According to the above the order of proposed techniques is selected (Table 2).

Material efficiency is the percentage of material used after cutting the elements within the standard glass pane (321 × 600 cm), as shown in the case of panel cutting in the form of equilateral triangles (Fig. 5).

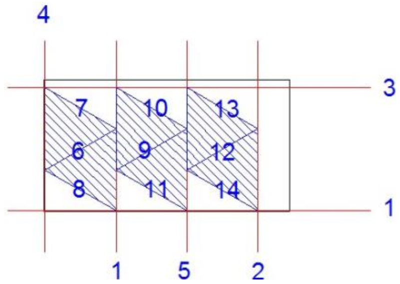

Figure 5. Panel cutting in form of equilateral triangles with 207 cm edge within the standard glass panel (321 × 600 cm).

Shaping techniques and material efficiency will be given a number between 1 and 5 in each of the mentioned categories. The used convention implies 1 for poor performance (shaping technique requires most labour, time, and energy; minimum material-efficiency) and 5 implies for excellent performance (additional shaping is not necessary; maximal material-efficiency).

An overview of the quantified estimate of different models of geometrically complex glass envelope in relation to the selected technological criteria is shown in Table 2.

Table 2. Quantified estimates of different models of curved glass structure based on selected technological criteria.

Model	Type of geometry	Selected curved glass shaping technique	Technological criteria		Overall quality by technological aspect
			Shaping technique	Material efficiency	
Ref. Model 1	Freely-curved surface	Thermal bending by mold	1	5	6
Model 1	Triangles (equilateral)	---	5	2.5	7.5
Model 2	Horizontal Torsa	1) Thermal bending by mold 2) Cold bending 3) Thermal bending on line	1 3 1.5	5 5 5	6 8 6.5
Model3	Vertical Torsa	1) Thermal bending by mold 2) Cold bending 3) Thermal bending on line	1 3 1.5	5 5 5	6 8 6.5
Model 4	Hypar - HP	Cold bending (geom. Optimization enabled small number of flat pan.)	4	5	9
Ref. Model 2	Freely-curved surface	Thermal bending by mold	1.5	1	2.5
Model 5	Triang. refracting surface	---	5	3.5	8.5
Model 6	Horizontal Torsa	1) Thermal bending by mold 2) Cold bending 3) Thermal bending on line	1.5 3.5 2	1 1 1	2.5 4.5 3
Model 7	Vertical Torsa	1) Thermal bending by mold 2) Cold bending 3) Thermal bending on line	1.5 3.5 2	1 1 1	2.5 4.5 3
Model 8	Hypar - HP	Cold bending	4	1	5

Based on the evaluation, some general considerations can be drawn from these results:

- In terms of production method, apart from the models with flat panels (Models 1 and 5), the best quality show Hypar models (Models 4 and 8), whose panels can be shaped by cold bending - a method that does not require manufacturing process. As well, Torsa models with single curved panels (Models 2, 3, 6, and 7) can be shaped in the same way.
- Regarding material efficiency, the best characteristics show models with rectangular panels of small-size panelisation (Ref. Model 1, Models 2, 3, and 4), using the largest part of the standard glass pane. Slightly worse features shows model Triangular refracting surface (Model 5), as well as model Triangles-equilateral (Model 1), which imply greater material wastage. The worst characteristics show models with rectangular panels of large-size panelisation (Ref. Model 2, Models 6, 7, and 8) since only one panel can be obtained from the standard glass pane due to its size.

The best overall quality of technological characteristics show Hypar model of small-size panelisation (Model 4) and model Triangular refracting surface (Model 5). As well, similarly are rated the models with single curved smaller panels (Models 2 and 3) which can also be shaped by cold bending.

In terms of production availability in Serbia, due to limited dimensions of the thermal bending furnace, the largest panels can not be produced. Large panels of Hypar geometry (Model 8), as well as single curved panels (Models 6 and 7) can be shaped by cold bending technique, since their geometry allows it (considering small curvature, at least two straight edges and forced deformation - deviation from the plane), /7-11/.

Economic evaluation

Economic evaluation is carried out following investment costs calculation. The starting point for the evaluation of economic aspects is the quantification of partial and total costs according to the individual constructions of the glass structure related to appropriate glass shaping technique that corresponds to glass panels geometry. The result is a determination of corresponding economic features of the structure, i.e. the ranking of hypothetical models. The evaluation can be used for the following considerations:

- To evaluate economic performance of an overall design of the glass structure (e.g. trade-off between aesthetical requirements and cost efficiency of technological process);
- To compare different solutions of glass shaping options for building structures;
- To assess the effect of possible cost savings, by cold bending techniques vs. hot bending, which in addition to more labour and time requires a necessary amount of primary energy for curved glass production.

Concerning costs, each created hypothetical model has been assigned an appropriate shaping technology and selected type of glazing. Basic characteristics of adopted criteria and thus method of evaluation include:

- Hard costs/m^2 of glass structure corresponding with the type of panelisation, sizes, and geometry of individual panels, as well as method of production and processing including curved glass forming techniques. The costs comprising the processing of flat glass (cutting and edge processing) and shaping of curved glass converted to m^2, without delivery and assembly costs. Generally, it could be taken into consideration that the assembly increases the cost by 20-30 %. In addition, the reason is that cold bending, assumed as part of assembly, has not been taken into consideration due to the inability to calculate costs (unknown technique in Serbia, so far).
- Creation of the Total investment costs proceeds according to the form of the envelope and its associated surface.

Hard costs/m^2 and total costs for various models of glass envelopes and selected glazing types, as well as ranking of models are shown in Figs. 6 and 7. All costs are in Euros and come from real offer prices of two individual manufacturers of glass constructions and materials (*Konkav Konveks* and *Pavle* - potential contractors).

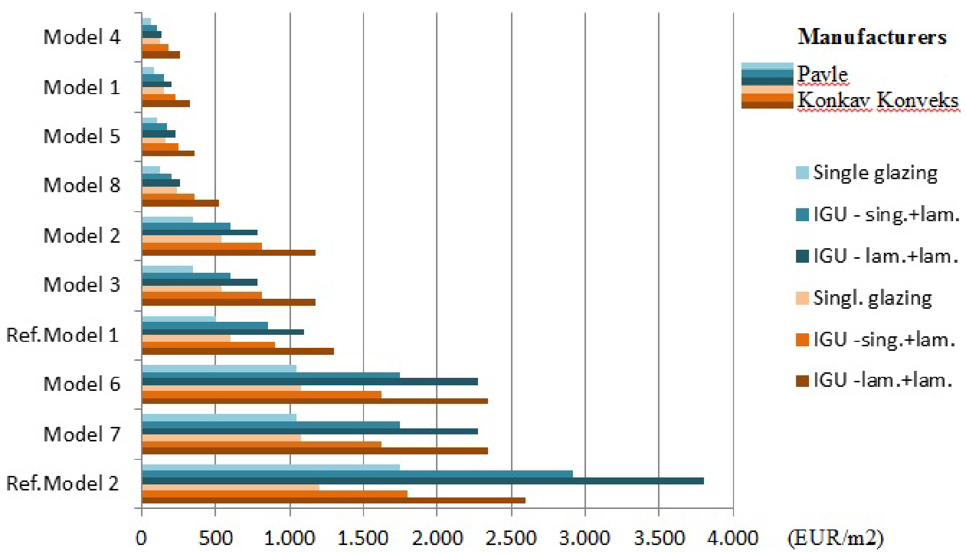

Figure 6. Ranking of various hypothetical models in relation to hard costs/m^2 for glass structure.

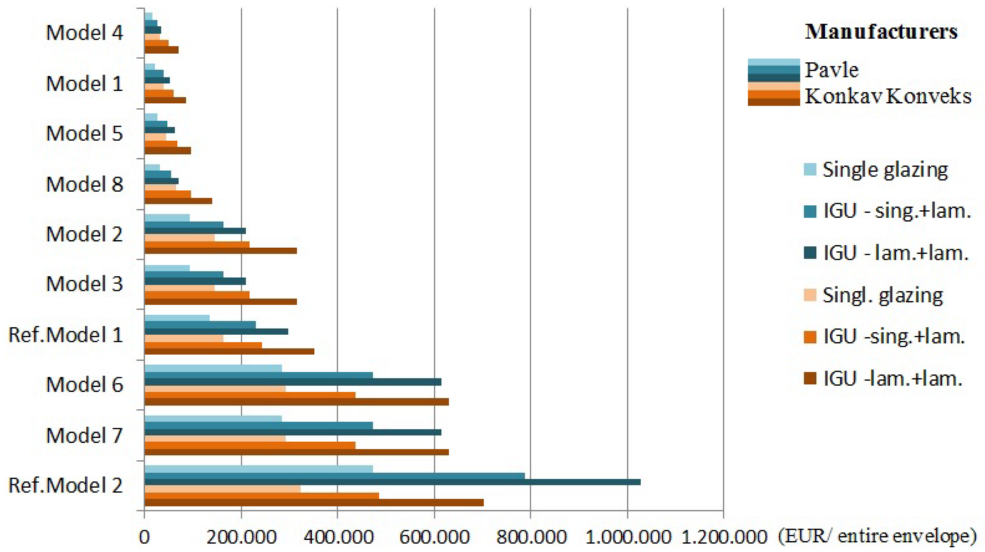

Figure 7. Ranking of various hypothetical models in relation to total investment costs for glass structures.

From this analysis, the following observation are made:

- The difference in the potential for cost savings by application of flat glass panels in the Triangle-equilateral (Model 1) compared to the Triangular refracting surfaces (Model 5) is negligible, even though Model 1 has greater material waste and number of panel cuts. Furthermore, it is noticed that significant savings can be achieved in flat glass panel application, while respecting the original form (more pronounced in Model 5) and that on average 69-81 % (in relation to single curved panels - Model 2 and 3) and 72-83 % (in relation to double curved panels - Ref. Model 1) in case of small-size panelisation, as well as on average 85-91 % (in relation to single curved panels - Models 6 and 7) and 86-95 % (in relation to double curved panels - Ref. Model 2) in case of large-size panelisation.
- As single curved panels are placed in horizontal and vertical direction in case of Models 2 and 3, as well as in Models 6 and 7, only the difference in costs regarding the size of panels is perceived. The significant difference between these models is noticed in respect to the perception of the envelope shape (part of a wider research). Concerning application of single curved panels in relation to double curved, on average 30 % reduction of costs could be achieved in case of small-size panelisation (Models 2 and 3 in relation to Ref. Model 1), while further, on average 40 % could be saved in case of large-size panelisation (Models 6 and 7 in relation to Ref. Model 2).
- Comparing in Table 2 and ranking in Figs. 6 and 7 the various hypothetical models of glass structures, it is evident that the best overall quality of technological and economical features shows the Hypar model of small-size panelisation (Model 4). This is due to the fact that the most important savings can be achieved by using cold bending technology for glass bending to hypar form (Models 4 and 8), on average 78-89 % (in relation to single curved panels - Models 2 and 3) and 80-90 % (in relation to double curved panels – Ref. Model 1) in case of small-size panelisation, i.e. on average 78-89 % (in relation to single curved panels - Models 6 and 7) and 80-93 % (in relation to double curved panels – Ref. Model 2) in case of large-size panelisation. In addition, by optimisation (approximation) of structure surface (Model 4) it is possible to achieve a certain number of flat panels (Fig. 3e). The highest savings, of almost 97 % is achieved by application of small cold bending panels (Model 4) in relation to the large double curved hot bending panels (Ref. Model 2).
- Potential for cost saving by cold bending of glass panels for the most economical 'Hypar' model (Model 4) compared to model with double curved hot bending panels in case of small-size panelisation (Ref. Model 1) is significant and amounts up to 88 %, while for the Hypar model of large-size panelisation (Model 8) compared to model with double curved hot bending panels (Ref. Model 2) amounts even up to 93 %. Furthermore, a significant difference in costs is noticed between the small-size and large-size panelisation, from nearly double (*Konkav Konveks*), up to more than triple (*Pavle*), both for single and double curved panels. Generally, there is a significant difference in costs between two manufacturers for curved glass processing. This is due to the fact that curved glass technologies are not yet widely used in construction practice.

CONCLUSION

A study of hypothetical models has shown that certain geometries of glass structures can be achieved in a simpler way by application of geometric principles in combination with good understanding of characteristics of glass and shaping techniques. These principles enable visual effects of double curved glass surfaces, but at the same time are sustainable in terms of design, technology and cost, implying the coherence between geometry, construction, and manufacture. The basic conclusions of the research are expressed in several ways:

- The principle of creating different (optimal) models of design and technology solutions for curved structures can be applied adequately in practice. Model variants of flat and curved glass panels are offered, following modern design guidelines based on defined typologies of glass panels according to geometry and curvature type, as well as different shaping technique. This enables further establishing the methodological approach to a problem of their realization.

- Curved glass shaping technique by cold bending, which has not been known in Serbia so far, is a solution that matches the physical characteristics of glass, while contributing to economical efficiency, preventing the visual problems of glass surface and enabling the use of most coatings and films. By cold bending it is possible to shape glass panels presented by the geometry of 'hypar' and 'torsa'. It is also possible to achieve savings in the manufacturing process up to 88 % in case of small-size panelisation and even up to 93 % in case of large-size panelisation (in Serbian conditions).
- The estimation of different visual and technological solutions and selection of aesthetically satisfying and economically acceptable option of curved glass structure is enabled by establishing the evaluation method.

Future research will include multi-criteria analysis for compromise ranking of alternative solutions in order to choose the optimal variant of curved glass structure. This method is suitable in case of multiple heterogeneous criteria (presented in the wider study), which are often mutually opposed, and a number of alternatives - variant solutions (presented in the paper). The goal of optimisation is to select the best variant solution in terms of adopted criteria and defined limits.

The methodology and results of evaluation of different hypothetical models of curved glass building structure presented in the research, can contribute to the development of curved glass application in practice and the design methodology of curved glass buildings.

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