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PERSONALISED FORMWORK – scientific approach for new solution variants

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Abstract. Application of personalised formwork is of most interest for architects and engineers now-a-days. Although a required demand when designing special constructions, there is little data and material solutions for this case. The cost and domain of application are of most importance in determining new solutions for concrete formworks. To contribute to these requests (a wider usage domain, productive material cost and maintenance), a personalised formwork concept is presented. The idea of reusing the formwork led to an elastic material – membrane (thermoset elastomers, synthetic rubber) with a punching tie-rod solution in order to obtain any architectural shape desired. This first solution was evaluated taking into account different membrane thicknesses. Several experimental tests denoted that the named chosen membrane variants are of low resistance for pouring a concrete architectural slab, so new solutions were discussed. Hence, a re-analysis of the PLM steps was achieved in order to find an answer for the encountered problem. By using creative methods, we obtained a second solution and put it to test. The attained results are used in order to establish the area of workability, to enlarge the tested domain and to assess the sustainability of a new type of personalised formwork

1 Introduction

The now-a-days architectural demands require new formwork solutions for concrete free shape structural elements. The need for special shapes was put to test in the early '40s (Fig. 1), but still, the current technical solutions for creating such concrete elements are limited and expensive. Hence, a solution is required for these types of structures.

The article discusses different equipment variants that can be reused as formwork and can satisfy different architectural shape. The first tested equipment is composed of pistons that act upon a membrane. Tests showed that this solution is limited: the membrane does not resist to concrete unless the piston density is increased, making this solution inconsistent for large dimensions. A thorough investigation on this formwork variant problem was carried out.

The article focuses on the PLM approach in order to obtain a new second solution for the demands.

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We will establish the functions that such equipment must satisfy, followed by technical solutions specification and finally certify through tests the attained new solution.

We conclude the article by evaluating the results in order establish the area of workability, to enlarge the tested domain and to assess the sustainability of the new equipment solution for a personalised formwork.

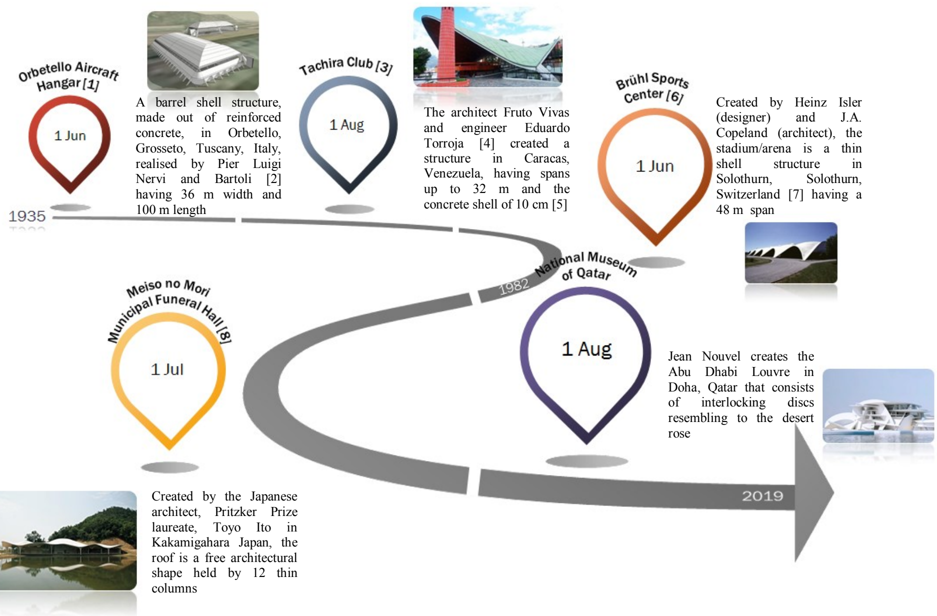


Fig. 1. Free architectural shapes – its beginnings and tendency

2 State of the art

After a reminder of the free architectural shapes, an analysis regarding the multitude of shapes encountered in those 3D structural elements was detailed (Fig. 2).

Knowing all these possible patterns, one can see the necessity of a personalised formwork type that can satisfy all of the above described shell types and the possible variants that each shape can led to.

During the years, the idea of creating a formwork for such shapes has fallen, in the last few decades, into place.

Besides the step by step assembly of traditional timber or steel formwork (Poggeler [16]), CNC milling solutions were used (Kolarevic [17]), fabric formwork or even 3D printing solutions.

From these appeared researches in order to simplify or to re-use the formwork: Troian et al.– the use of a deformation MDF base surface and an upper foam/silicone mould [18], Schipper et al.– prototype with two directional actuators acting upon a membrane [19], Beton Ballon [20] - inflatable mould, Boers [21] – pin-bed surface, van Rooy et al. – tensioned membrane mould [22] or vacuumatics solutions - Hulijben [23].

But when large scale elements such as roofs/ slabs are involved, the usage of such solution is not optimum neither from the material consumption point of view, assembly or cost.

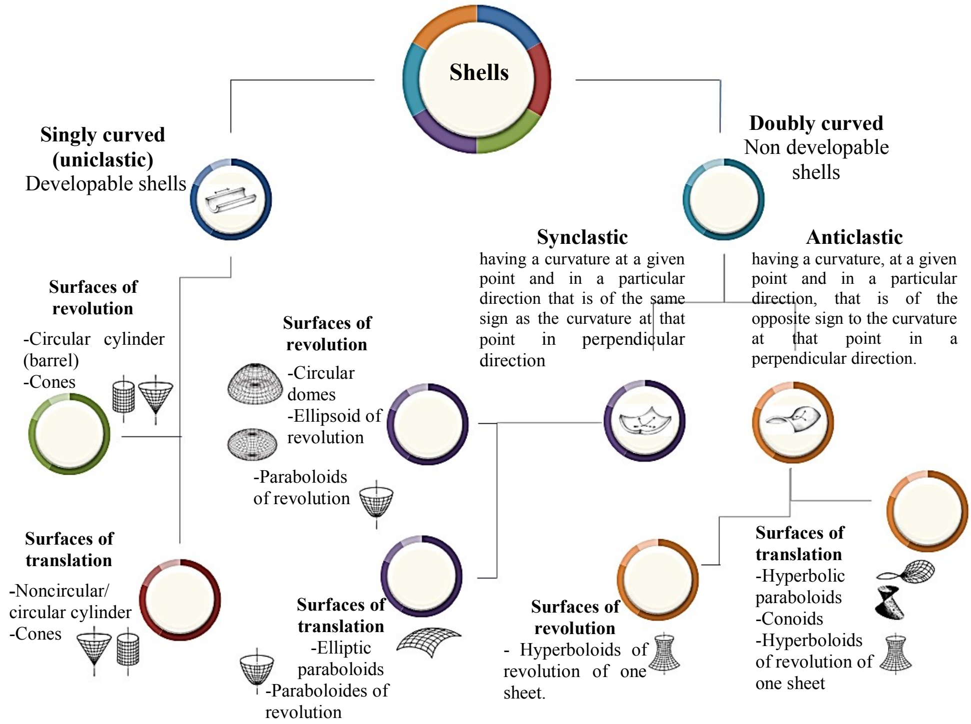


Fig. 2. Affinity diagram regarding structural shell types [11- 14]

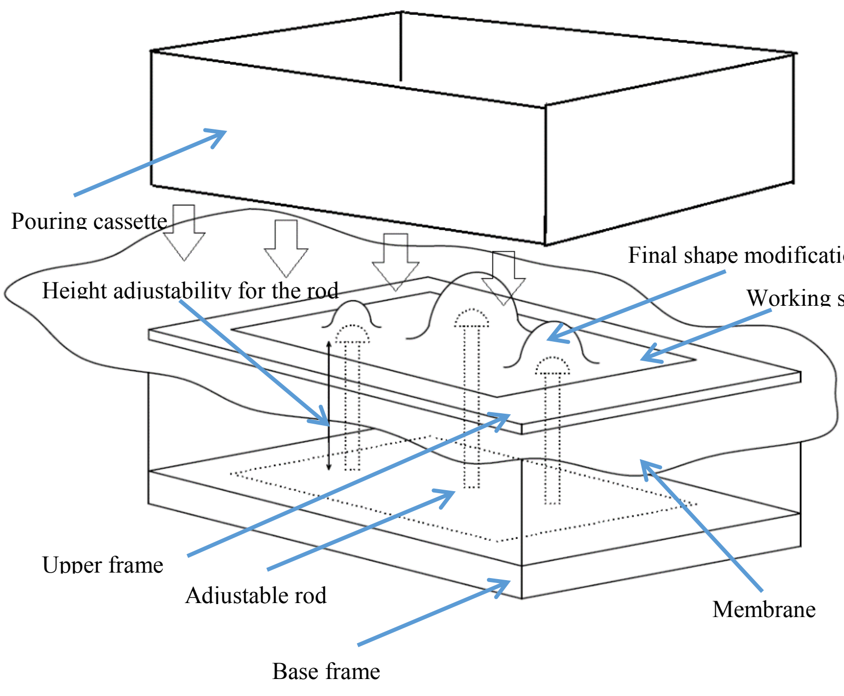


Fig. 3. Solution sketch for the tested variant

In our research (including this article) we try to find an answer for this situation by using a scientific approach.

Hence, multiple solutions for a personalised formwork were analysed. Previous experimental research [15] resulted in various equipment solutions.

Among them is the one represented bellow (Fig. 3): a personalised formwork composed of an elastic material – membrane (thermoset elastomers and synthetic rubber) and a series of punching tie-rods for curvature definition and support.

After several experimental tests, the solution proved to be invalid. At difference levels bigger than 230 mm, after the complex surface is attained, at concrete loading, excess deformations appear that chances the surface characteristics (note: a SBR rubber of 2 mm thickness was used and a single support rod – Fig. 4).

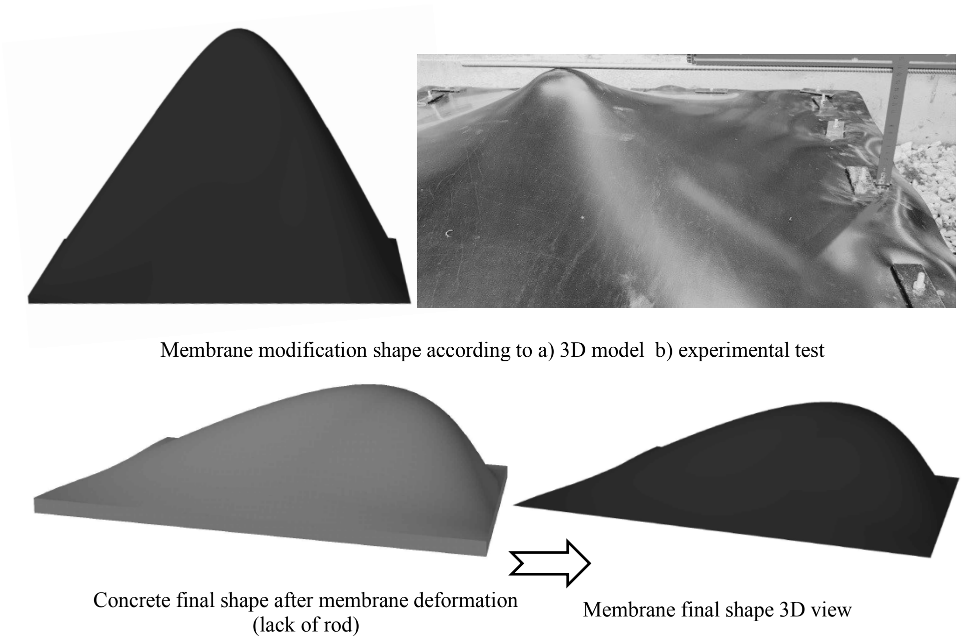


Fig. 4. Tests results for first variant solution – membrane failure deformation

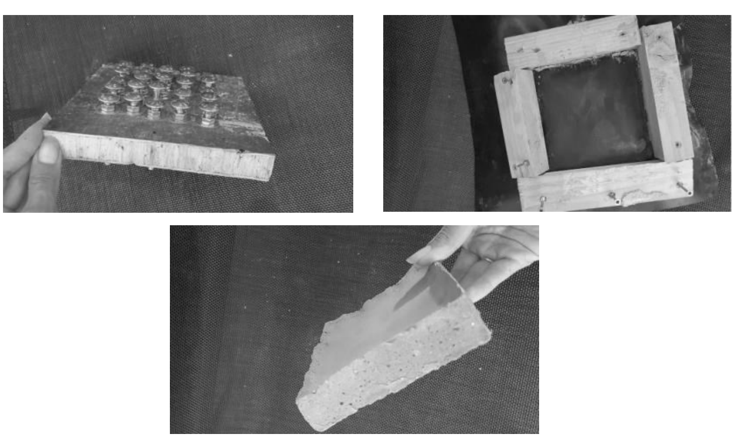


Fig. 5. Tests results when enlarging the piston density – membrane maintains shape

Although the shape preserves, when changing the piston density on the membrane (Fig. 5), this first solution equipment is ranged as inconsistent for large dimensions.

As a consequence, a thorough analysis, by using the PLM approach is necessary because it allows even in the solution design stage to satisfy the new functions obtained from the invalid tested variant (e.g. maintaining the deformed surface unchanged after concrete pouring) (Fig. 6).

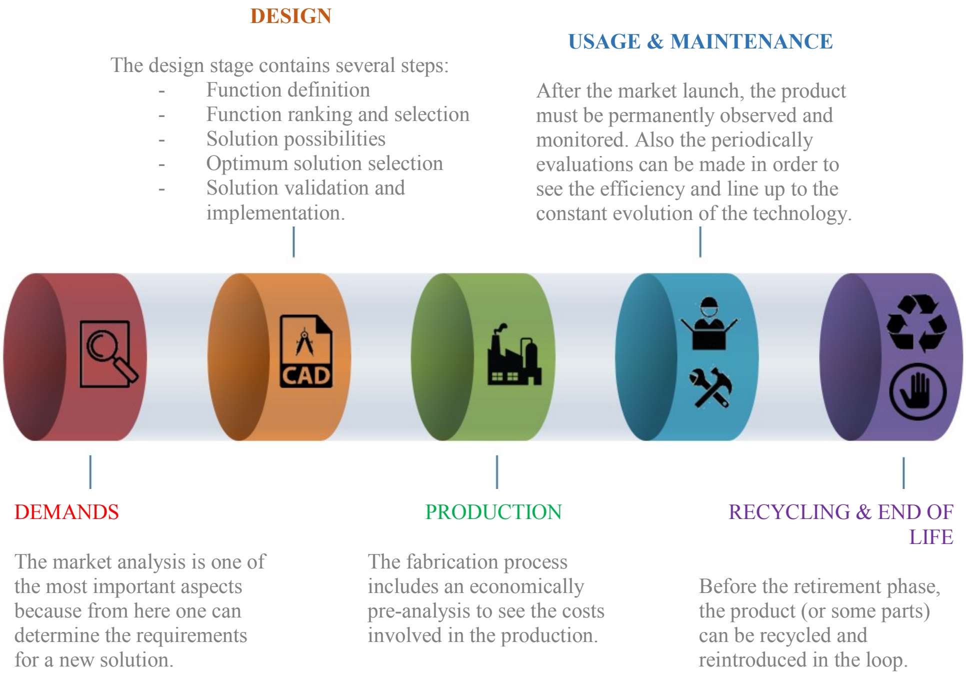


Fig. 6. Product Lifecycle Management steps

3 PLM approach

3.1 Function analysis

As noted, in the figure above, one of the PLM steps in obtaining an optimum solution for a personalised product is the demands and their analysis.

Because the experimental tests done on the equipment were invalid, the next step was to establish the reason for the test failure, finding a solution for the encountered problem and then determining the resulting requirements. Step two was defining their corresponding functions by using creative methods. Because most of them were complex ones, other focus sessions were made in order to obtain the basic (primary) ones (Table 1).

Another statement referring to the equipment's functions is that, because on the previous tests no other problems were encountered, the elaborate explored demands were the ones concerning shape moulding and fixing: formwork material types, obtaining methods for deformation, blockage and fall-back.

For the other ones, named also annex functions, intuitive or experimental based solutions were adopted.

Also, for this case study no reinforcement for the concrete element was considered. Future analysis will show the steel mounting approach and concrete depth assurance solutions.

Table 1. Function definition and dividing

Demand	Obtained function	Primary function dividing
obtaining shape diversity	to encase diverse surfaces	to obtain complex surfaces on x, y, z directions
		to pour a constant concrete layer according to shape
		to enclose the poured concrete
blockage shape system	to maintain position of the formwork	to fix formwork
		to block system
formwork dismantling	to strike formwork	to unblock system
		to remove fixing elements
		to remove mould
formwork resistance	to resist	to assure formwork strength
assuring reinforcement positioning	to mount steel reinforcement	to introduce bars
		to maintain optimum distance
formwork monitoring for crack, leaks, failure and temperature	to control	to verify formwork state
		to verify formwork position
		to measure temperature
assuring air removal from concrete	to diminish internal friction between particles	to vibrate concrete
ensuring manoeuvrability and easy mounting	to be handy	to assure moving

For these functions, in order to obtain new ideas, brainstorming sessions were formed. Building on the ideas of others or on previous solutions was a plus.

As previously mentioned, for the annex functions, the solutions assigned were based on intuition and test results (Fig. 7).

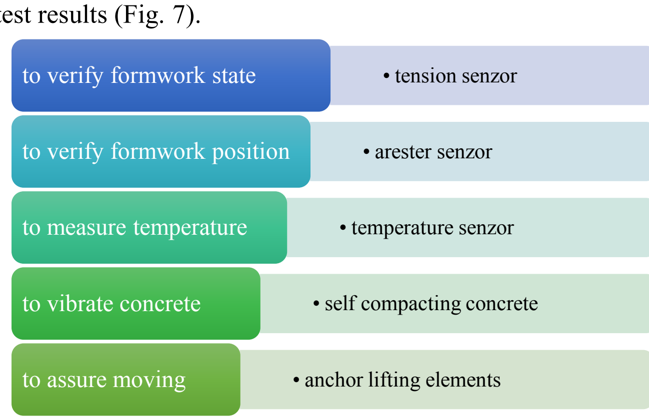


Fig. 7. Function solutions – annex function

The table below (Table 2) is a representation of the found solutions for each primary function regarding shape assurance.

Table 2. Functions' solution chart

Primary function	Possible assigned theoretical solution	Assigned technical solution
to obtain complex surfaces on x, y, z directions – F1	by pushing an elastic mould/ clay	umbrella type piston for different radius shapes and joint hinge
		point system formation
		elastic tubular element
	by using pressure – shape formation	liquid/ gas column pressure
	by pulling an elastic mould/ clay	point system pulling
	by cutting / removing parts from a material	clay modelling
	by adding parts to a material	spline interpolation forming
to pour a constant concrete layer according to shape – F2	pouring a quick setting material	pouring a quick time hardening concrete
	using double wall formwork	forming a symmetrical/ mirror formwork
	using an auxiliary pouring element with the exact thickness dimensions	horizontal personalised pouring machine
to enclose the poured concrete –F3	securing all margins together	use of a cassette
	securing separately each margin	using separate lateral secure sheet
	rise the formwork	establish end point and extend the extremities of the formwork (elastic/ clay)
to fix & remove formwork – F4	fixing/ remove elements under formwork	shape forming element with double role: shape formation and fixing
		base material as support
		wire/ lamella base support that respects the formwork shape
	fixing element in the concrete with recovery and remove all parts	telescopic pipe system
	fixing element in the concrete without recovery but removal of the auxiliary parts	wire/ lamella through pipe system that respects the formwork shape
		tension wire in the concrete
to block/ unblock system – F5	block/ unblock all fixing elements separately	• for pistons, point system, point pulling, elastic tube, spline interpolation and telescopic pipe system: with clamps, screws, latch, hydraulic, pneumatic systems • for clay modelling and base material support: air removal, entire necessary clay volume occupied • for wire/ lamella (exterior and interior): tension, clips

	block/ unblock a single element as a group	• for pistons, point system, elastic tube, point pulling, spline interpolation and telescopic pipe system: a table support, a remote • for clay modelling and base material support: air removal, entire necessary clay volume occupied • for wire/ lamella (exterior and interior): tension, clips
	block/ unblock a single element and the others like in a domino	• for pistons, point system, elastic tube, point pulling, spline interpolation and telescopic pipe system: a remote, acting upon first blocking/unblocking element • for clay modelling and base material support: not applicable • for wire/ lamella (exterior and interior): with successive clips
to remove mould – F6	remove with direct reuse (elastic case)	usage of an elastic material type (elastomer class)
	remove and remodel (clay case)	usage of a modelling material type (clay, wax)

The next step in the PLM analysis is the evaluation of the solutions. Hence, each technical solution was analysed to determine the best one taking into account different criteria. For this case, the QFD matrix was used (Fig.8a,b).

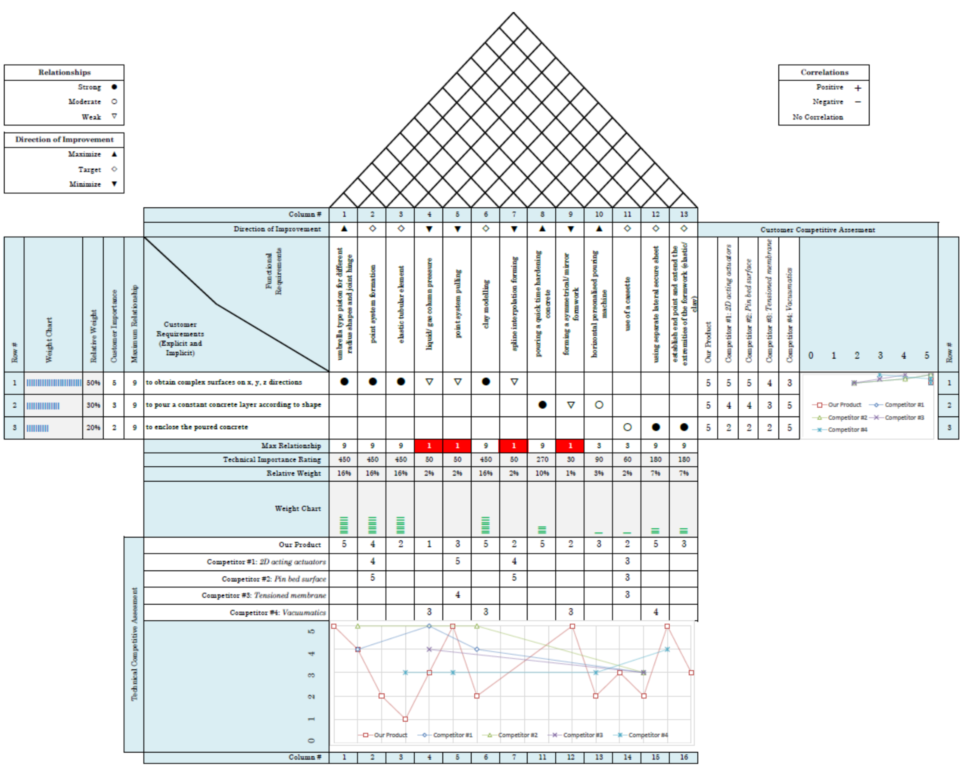


Fig. 8a. QFD matrix for solution evaluation (first three functions)

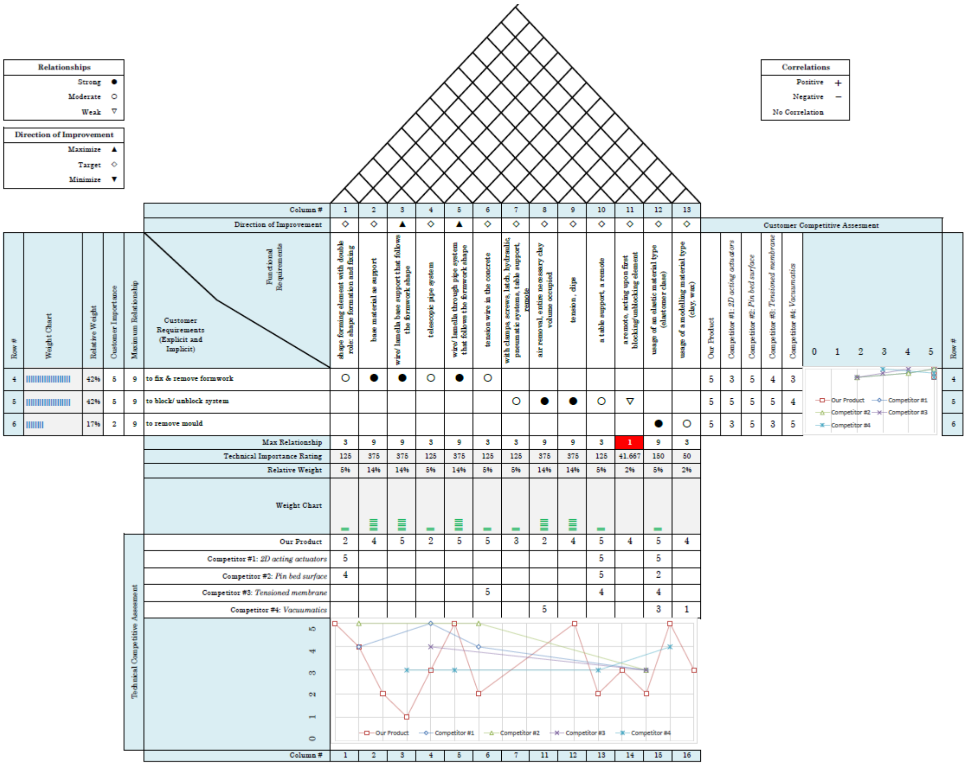
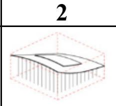
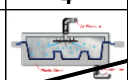
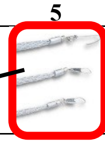
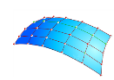
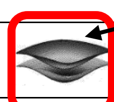
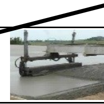
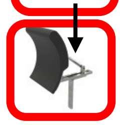


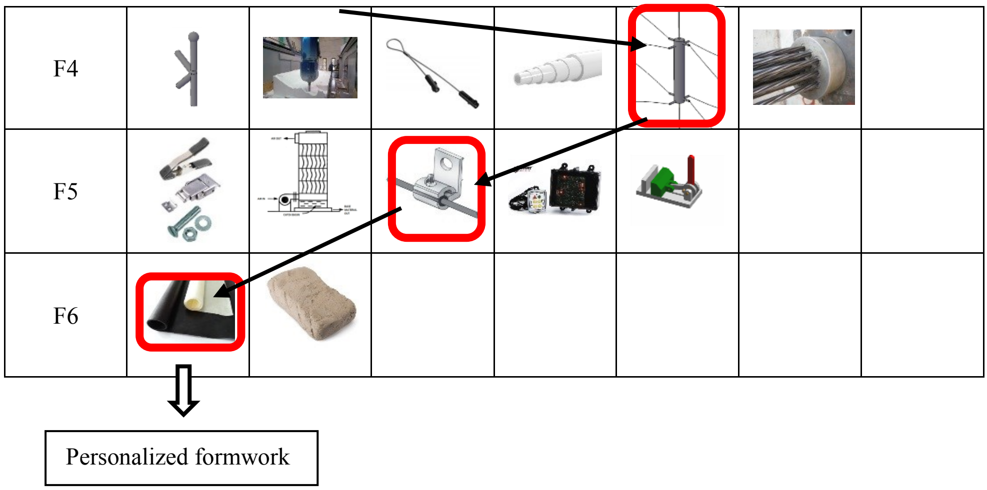
Fig. 8b. QFD matrix for solution evaluation (last three functions)

3.2 Possible solution

After a thorough analysis of all the possible solutions regarding the optimisation aspect, efficiency and costs, the possible was adopted solution and will be put up to tests. The morphological matrix shows in a suggestive manner the chosen variant (Fig. 8). Each solution was named as Solution 1-7 for each of the functions F1-6.

Table 2. Morphological matrix

Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7
F1							
F2							
F3							



As shown above, the personalised formwork is composed of an elastomeric material with cable pulling solution for shape formation and a spacer rod for thickness assurance. The wires assure the fixing of the membrane. Also, in the spacer, two perpendicular pipes are envisioned in order to strengthen the material. A section through the personalised formwork may clarify the resulting solution (Fig. 9).

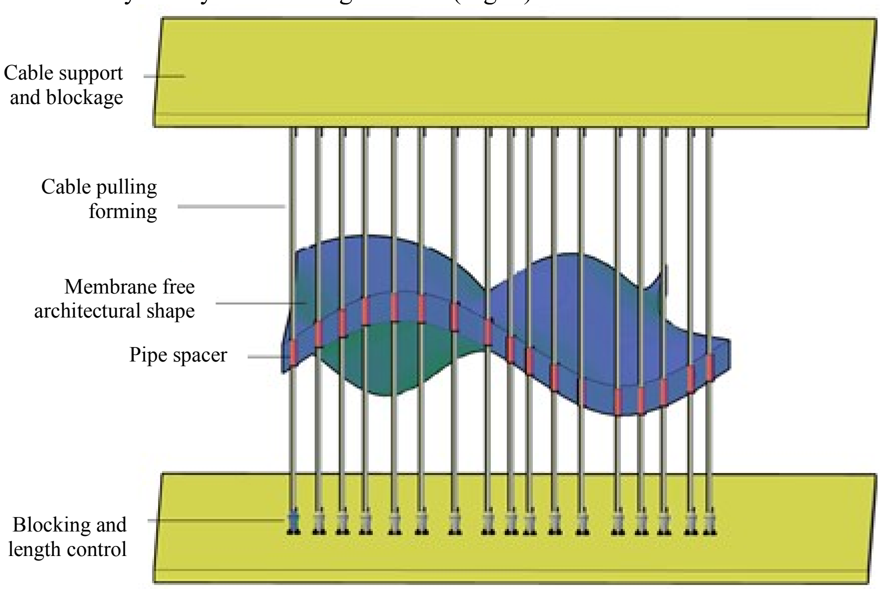


Fig. 9. Personalised formwork section

The next step in the PLM approach is to verify the solution by using F.E.M analysis and experimental testing.

3.3 Experimental testing

Because the solution needs to be validated, an experimental test must be conducted. For this step, the working stages were kept in mind in order to cover all the aspects within a pouring process (Fig. 10).

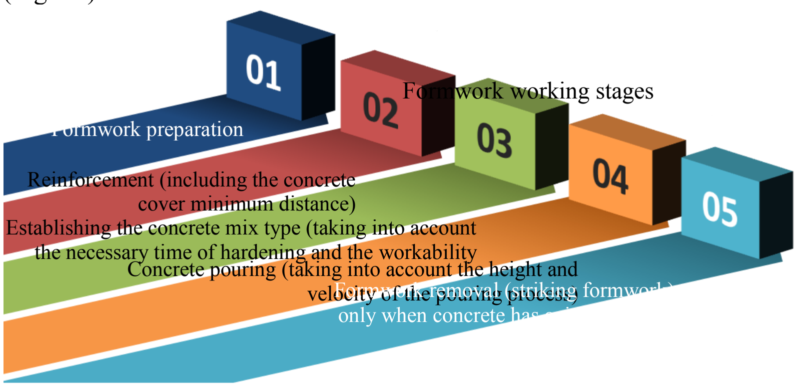


Fig. 10. Working stages for executing a structural element

Taking these steps into account, a virtual testing line for free architectural shape elements was featured (Fig. 11). The new solution for the personalised formwork is then put to test.

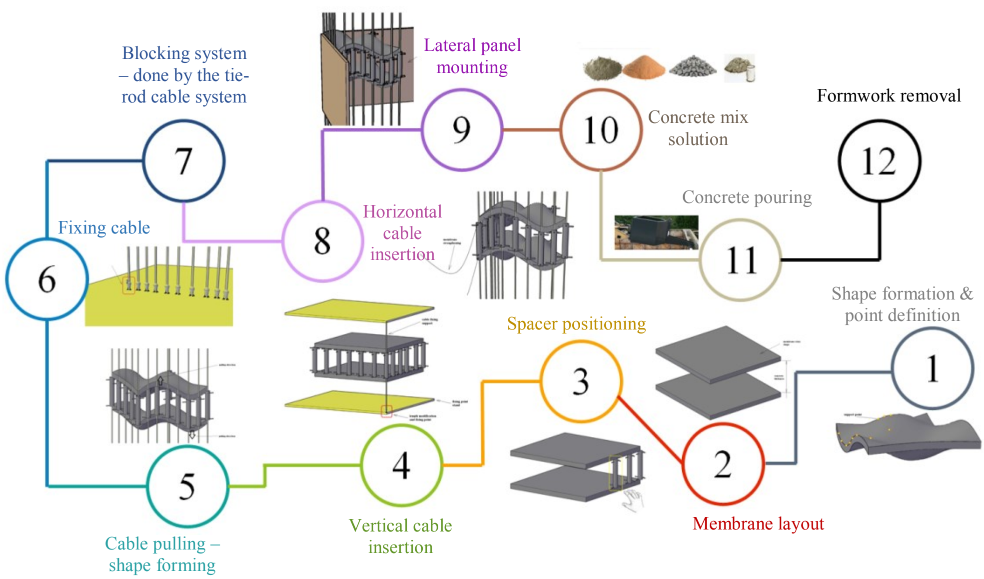


Fig. 11. Testing line membrane assembly and pouring steps

Note: The given shape is considered to be a free architectural shape for a roof. The final desired shape (Fig. 12) designed also in a CAD programme is of help in defining the points for the formwork. The control and fixing points of the nurb lines mark the spacer positioning.

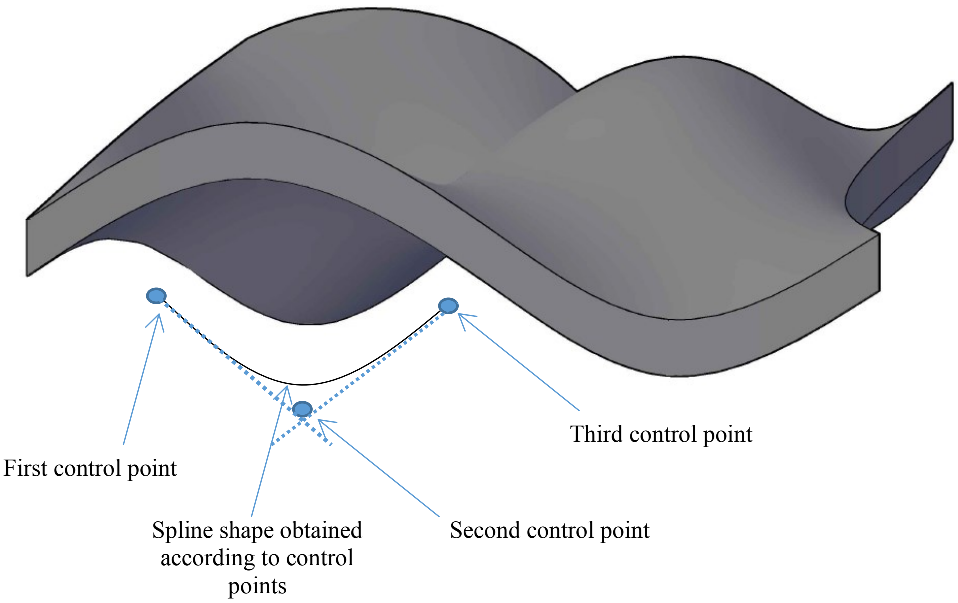


Fig. 12. Roof element (final/finite shape)

The same rubber types and thicknesses are used as previous tests [15]:

Table 3. Formwork material definition

Type/ Name	Thickness [mm]	Specific weight [gr/cm^3]
SBR	1	1.7 ± 0.05
SBR	2	1.7 ± 0.05
SBR	3	1.7 ± 0.05
NBR	1	1.5 ± 0.05
NBR	2	1.5 ± 0.05
EPDM	1	1.5 ± 0.05

5 Conclusions

After a thorough research regarding demands, functions and multiple solution variants, the obtained constructive solution is an option to be put to test.

By using the PLM approach, we could reanalyse the problem, find new resources and establish a new constructive variant that serves all the new requirements for the personalised formwork.

By validating a new solution we can establish the area of workability, enlarge it and assess the sustainability of a new type of personalised formwork.

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