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RESEARCH ARTICLE

APPLICATION OF DEPLOYABLE BAR STRUCTURES IN ARCHITECTURE: PROPOSAL FOR UNIVERSAL MULTIFUNCTIONAL MODULE

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Abstract

Deployable bar structures are made of lightweight materials, and that is one of the reason why they do not require high transportation costs, are easy to assemble (by unfolding) and disassemble (by folding) and are able to successfully respond to many requirements when in the shortest possible time it is necessary to provide architectural structures for various purposes. In this paper, the deployable bar structures are analyzed with the aim of forming a universal multifunctional space which could be used as a facility for temporary housing, healthcare, education and similar purposes. Due to the fact that geometric shape of a certain space significantly determines the function of that space, and the way it is used, detailed analyses of the geometric shapes of these structures have been conducted. Comparison of the forms explored so far with the existing architectural deployable bar structures has resulted in two distinct geometric forms: singly curved (barrel vault) and doubly curved (dome). It was concluded that the application of these forms in the form of freestanding modules provides limited opportunities for organizing functional content due to the specific locations of certain connections between elements, as well as the complicated design process. This is one of the reasons for rare application of these structures in architecture. The proposal of a multifunctional "Universal module 6" which consists of unified singly curved modules in combination with doubly curved and prismatic forms came as a result of the conducted analyses. Proposals for forming more complex architectural spaces of higher capacity provide a wider range of applications of these structures and opens new possibilities for their use.

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Introduction:-

Devastating natural and human induced disasters, like earthquakes, floods, and a large number of wars, which occur daily worldwide, are destroying homes and creating the need for temporary facilities as a shelter for the population that is left homeless. There has been a large need for temporary shelters that has emerged in the Balkans in recent months for accepting a large number of refugees in short-term. In these areas there is no developed infrastructure, as well as no temporary facilities which could successfully meet necessary requirements.

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Research (De Temmerman, 2007) and (Alegria Mira, 2014); have shown the advantages of application of deployable bar structures in emergency situations. Although the deployable bar structures are the subject of a large number of researches at most well-known universities in the world, the results of research projects usually remain in the stage of an idea or a physical model without concrete realization in architectural practice.

Geometry of deployable bar structures:

Geometry has been used since the beginnings of architectural vocation as a design tool for presentation purposes of the vision and concept of architectural structures. The geometric shape of a certain space significantly determines the function and the way it is used.

Francis D. K. Ching (2015) states that initial generators of any form are: point, line, plane, and volume. Easter Rivas Adrover (2017) in the geometric classification of deployable bar structures presents different manners and possibilities for forming geometric deployable bar structure forms, taking in consideration identical form generators, while displaying an overview of the application of different forms shaping generators.

According to (Ching, 2015), by combining geometric forms, it is possible to achieve different spatial relations (figure 1): space within a space, interlocking spaces, adjacent spaces and spaces linked by a common space. By putting geometric shapes in different types of organization, such as centralized, linear, radial, group and grid organization, different organizations of a specific space are achieved, but special attention is required for proportions, scale, and the use of that defined space.

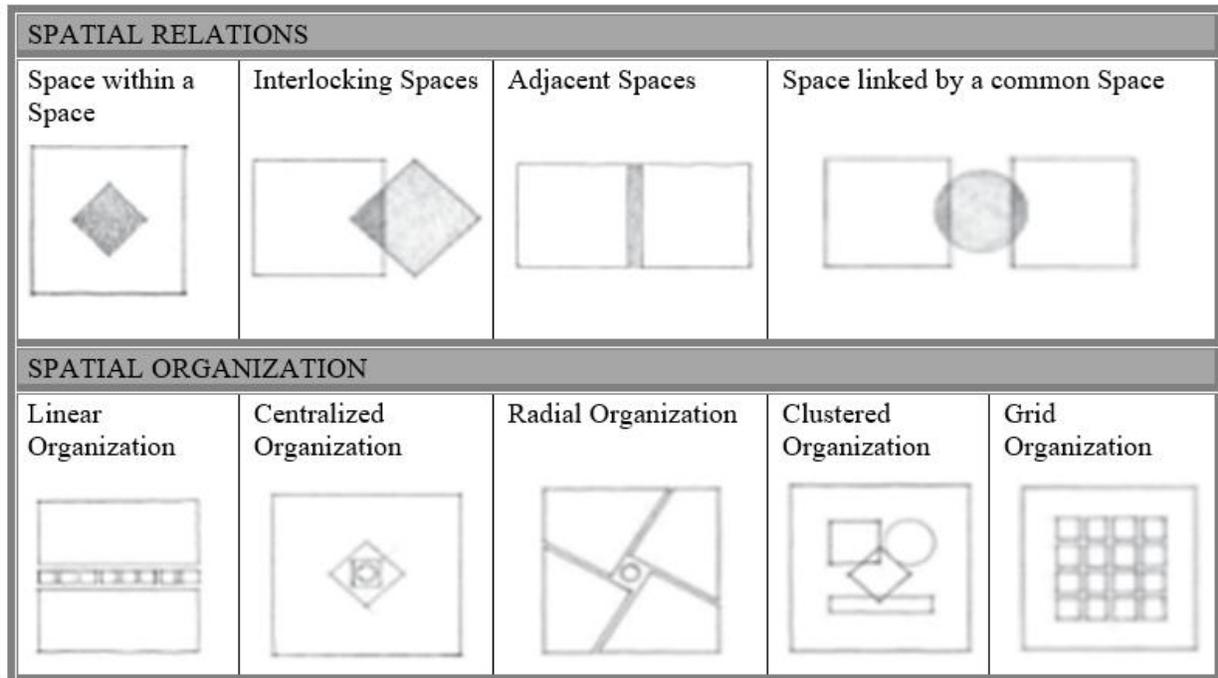


Figure 1:- Spatial relations and organization according to (Ching,2015).

In the design stage of architectural structures, simple geometric shapes are most often used, and by combining them, more complex architectural structures are achieved.

According to (Sala and Sastre, 2013) the correct choice of the geometric shape of the system is one of the most important steps in the process of designing transformable structures, and it significantly determines the possibilities of system transformation¹. Changing geometric forms of these structures which deviate from the classical, already explored forms, significantly increases the cost of the entire process of making deployable bar structures.

¹Applying certain geometric configurations makes it impossible to achieve the deployment of the system.

One of the main features of deployable bar structures is the position of bar elements and their joints that enable the transformation of the structure. The best-known example of these structures is scissor systems which can be assembled from translational, polar, or angular units. For different analyzes in the paper (Šljivić, 2019), modules composed of polar units are considered (Figure 2).



Figure 2:- Scissor structure made of polar units

By modifying the base bar element, additional transformability of the system is enabled. These possibilities are presented in the works of (Akgün, 2010), (Alegria Mira 2014), (El- Zanafy 2010), (Sala and Sastre 2013), (Rosenberg, 2010), (Lu, 2014), (Roovers and De Temmerman, 2015).

In 1993, Escrig and Valcárel have presented the classification of deployable bar structures, where singly and doubly curved geometric shapes stand out. The comparison of geometric forms shown in the classification of structures that were built so far, has resulted in the selection of typology of “barrel vault” and “dome” for further research in this paper (Figure 3,4).



Figure 3 :-Hoberman Geodesic Dome, Source: <http://www.hoberman.com/portfolio/expandinggeodesicdome>.

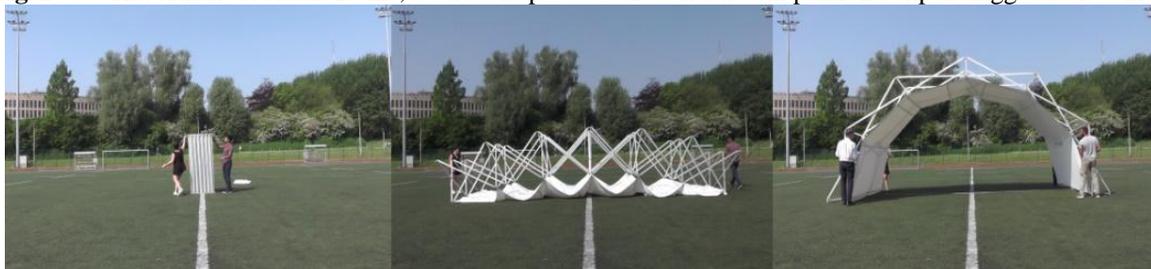
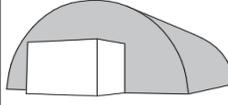
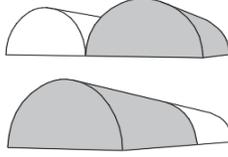
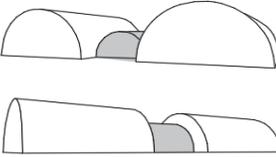
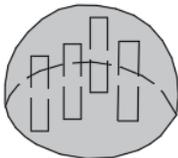
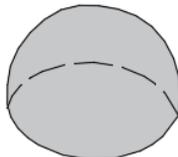
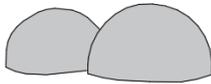


Figure 4:-FasTival; Source: http://www.konligo.com/docs/fastivaldossier_nl.pdf.

Formation of spatial relations and space organization of deployable modules of different geometric forms:

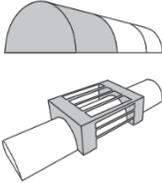
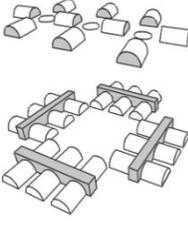
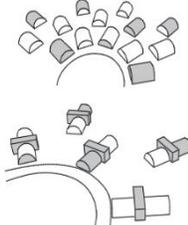
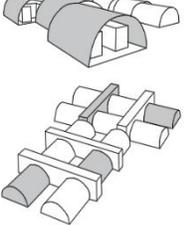
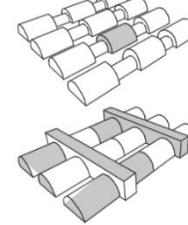
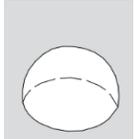
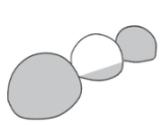
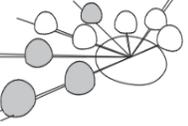
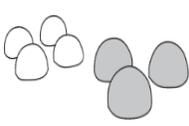
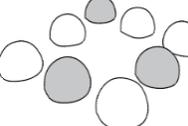
The potential of the previously mentioned forms as individual architectural structures is not sufficiently used because it does not provides possibility of organizing multifunctional spaces, which is one of the reasons why the application of these structures in architecture has not been realized in any significant way. Spatial analyses are done by setting chosen forms as unified modules for the cost efficiency of design and the fact the design is done only once. Analyses of selected geometric forms of deployable bar structures are done with the aim of finding their modular application, which by multiplication, or interconnection, meet previously presented the principles of spatial organization and spatial relations according to (Ching, 2015). Table 1 shows detailed conclusions of the conducted analysis of the deployable bar structures.

Table 1:- Spatial relations of universal modules.

SPATIAL RELATIONS				
Form-Module 	a) Space within a Space 	b) Interlocking Spaces 	c) Adjacent Spaces 	d) Space linked by a common Space 
DESCRIPTION	a)	It is possible to organize space within a space by combining different geometric forms. In such a space, deployable structure has the role of covering the space, and parameters such as height and span, significantly determine the possibility of the spatial organization. It is necessary to provide a greater height of the space so that all interior facilities could be organized without hindrance.		
	b)	Interlocking of spaces of the observed module with other elements and geometric forms is made possible only from the front and back side. Because of a specific position of load-bearing elements, it is difficult to laterally interlock spaces. By interlocking the observed geometric form with other forms, better spatial quality is achieved, which will enhance the characteristics of the singly curved deployable structure starting module.		
	c)	By joining two or more deployable modules it is possible to organize space only in the longitudinal direction because that way it is possible to achieve communication between them. It is not possible to interlock the structure and achieve the connections between modules in transverse direction. The disadvantage of adjacent spaces formed in the longitudinal direction is the creation of long spaces which have entrances and exits only from one side, while lateral sides are blocked.		
	d)	Modules are linked by a common space only in the longitudinal direction. By linking the modules with common space, the monotony of long linear structures is broken and new possibilities for creating different spatial functions are created. The geometric form of the space which connects the modules significantly affects the quality of the spatial organization.		
Form-Module 	a) Space within a Space 	b) Interlocking Spaces 	c) Adjacent Spaces 	d) Space linked by a common Space 
DESCRIPTION	a)	By using a deployable module of a doubly form it is possible to achieve the organization of space within a space. Deployable module has the role of only covering the space in this formation.		
	b)	A specific geometric shape of a deployable module of the doubly curved form makes it difficult to combine the structure with other geometric forms.		
	c,d)	The connecting of two deployable modules of the doubly curved form depends on the space which is provided as a connection with other forms and spaces, and its dimensions are conditioned by the proper usage.		

Modules were further analyzed by setting geometric forms according to proposed spatial organizations by (Ching, 2015), from which arise the advantages and disadvantages of the usage of geometric forms analysis of deployable structures.

Table 2:- Spatial organization of universal modules.

SPATIAL ORGANIZATION					
Form-Module	a) Linear Organization	b) Centralized Organization	c) Radial Organization	d) Clustered Organization	e) Grid Organization
					
DESCRIPTION	a)	In linear organization, modules are arranged in longitudinal direction because in this way interconnected spaces are formed. However, by adding appropriate spaces, which in architectural practice are often referred to as “joints”, it is possible to break the monotony of linear structures and make it possible to place entrances from different sides, which is the main advantage of this type of structure.			
	b)	Centralized organization of space is achieved by using individual modules which are organized around a center-point. Radial organization of space is achieved by using individual modules which can form many different structural configurations. However, as in the previous examples, the constraining factor is the limited lateral access to the modules. By adding certain spaces, the so-called “joints”, between two modules, it is possible to create more complex structures compared to the structures which consist of only one module which can host different functions and divide the space in specific parts. By shifting certain modules, it is possible to avoid the occurrence of other linear spaces that do not meet the basic functional requirements of a certain space.			
	c)				
	d)				
	e)				
Form-Module	a) Linear Organization	b) Centralized Organization	c) Radial Organization	d) Clustered Organization	e) Grid Organization
					
DESCRIPTION	a)	By combining the modules according to the principles of linear organization, long linear structures without proper function are created.			
	b)	By combining the modules according to the principles of centralized, radial, clustered and grid organization of space, freestanding forms of deployable modules are used, which means that in between the structures no warm connections are achieved. Previously made analyses of linear spatial organization have shown the disadvantages of interconnecting of modules and creating the structures which do not meet the basic functional exploitation requirements. However, the problem of organizing the space without providing a warm connection is emphasized in the case when the modules are used to form a more complex architectural composition.			
	c)				
	d)				
	e)				

The singly curved module stands out compared to doubly curved module because it provides a much greater number of advantages and possibilities of organization of spatial content. In order for the mentioned module to be used for the formation of different functional contents, the following parameters were also analyzed:

1. The proportions of the structure that are in direct relation to the proportions of basic bar elements of structure.
2. The illumination of specified type of structure, as well as the views from the building can be achieved only from the front and the rear of the module. However, the problem of illuminating the structure laterally needs to be treated specially by finding the appropriate finish for the structure which will enable the sunlight to enter.

3. A set of modules connected longitudinally creates long linear structures within which the circulation and flow of people are reduced compared to the other types of structures.

Analyzing the usage of singly and doubly curved forms of deployable structures for forming of multifunctional spaces consisting of more modules has resulted in the following conclusions:

1. Connecting the modules of deployable bar structures of singly curved forms in longitudinal and transverse direction does not allow the formation of multifunctional spaces.
2. Combining singly curved modules with other geometric forms allows for better organization of space.²
3. It is recommended to use doubly curved form (dome) for deployable free-standing structures, but it is necessary to do detailed research on the possibilities of achieving connection between singly and doubly curved modules.

“Universal module” proposal:

Previously explored freestanding forms of deployable structures are most often used as a temporary type objects with limited spans. In this sense, the introduction to a “Universal module” term is proposed, which has all the advantages of deployable structures such as easy transport, fast assembly and disassembly, more rational construction, with an additional advantage: multifunctionality of space.

The “universal module” is designed to meet basic architectural aspects such as: minimal spatial span, openings, sunlight provision, ventilation, as well as the feeling of comfort in architectural space. Combining a larger number of these modules provides the possibility of creating a space that is required for larger covered areas.

Analysis of function of multifunctional space:

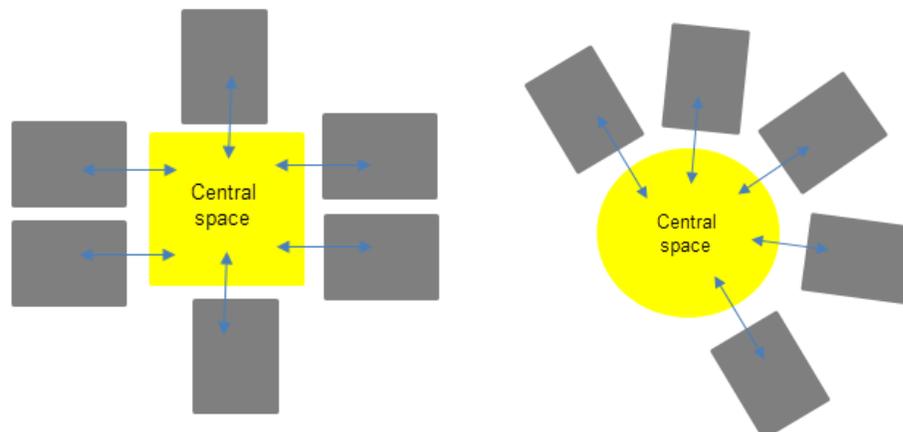


Figure 5:- Spatial analyses of different architectural space.

Based on spatial analyses of different architectural spaces, the concept of a space that does not depend on the purpose has emerged. This space represents a universal example of architectural structure divided into two zones: acentral space (larger) and an intimate, auxiliary space (smaller) (Figure 5).

When the “universal space” is used as a residential building, the central space represents a living room with accompanying facilities, while sleeping spaces are designed as more intimate spaces which can be connected to the living room. In educational facilities the central part is multifunctional, while classrooms and support rooms are physically separate spaces with a warm connection to the central space. In cultural buildings the central space represents the place of main events, while accompanying facilities are oriented towards that space. The organization of health care institution or an ER implies that the central space is a reception hall and intimate spaces are used as patient rooms and intervention.

In this way, in cases of different natural disasters, multifunctional “universal module” is applicable when it is necessary to create different architectural structures at given area as soon as possible.

²It is necessary to design a new cubic deployable structural form.

Geometric and spatial analyses of multifunctional modules:

Analyzing the form of “barrel vault” and its characteristics, it was concluded that the optimal span which can provide all of the previously mentioned functions is $S = 6.0 \text{ m}$.³ By defining the span, the height parameter $H = 3.0 \text{ m}$ is defined, which meets the basic functional requirements for a large number of architectural structures. The depth of the structure is defined based on the sunlight entrance range of 6.0 m . It is important to note that deployable bar structures are very delicate and that the use of smaller spans is more desirable.

The conclusions of the previously presented analyses have resulted in the consideration of the possibility of a radial organization of space using singly curved form as a universal module that is multiplied. Equilateral triangle, rectangle, pentagon and a hexagon are used for the floor plan base (Figure 6). The singly curved geometric structure follow the sides of the selected floor plan so that it forms a central space which requires the use of additional geometric forms and elements for covering. It is suggested to use doubly curved forms which will be joined with existing unified units and thus fill in the inner space marked in yellow (Figure 6).

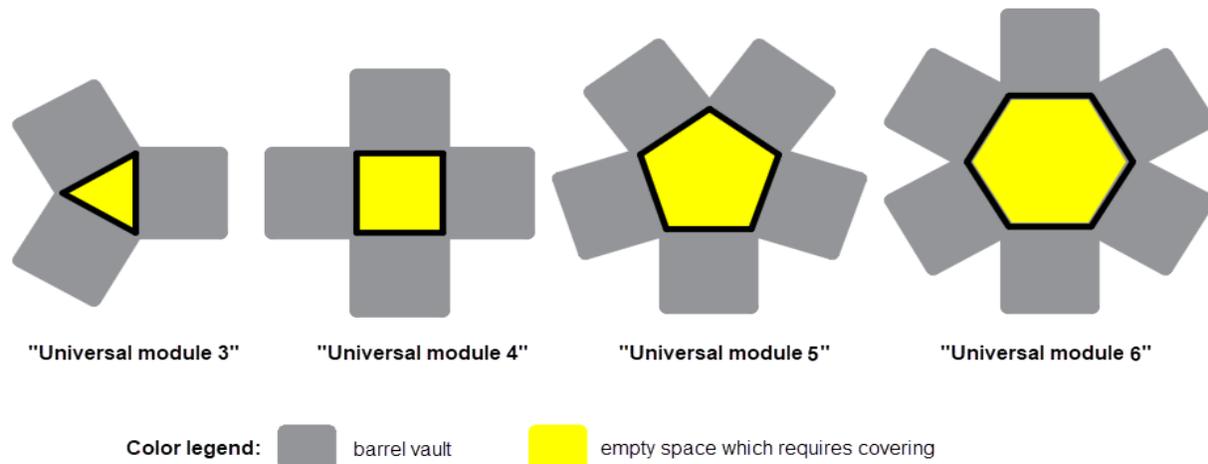


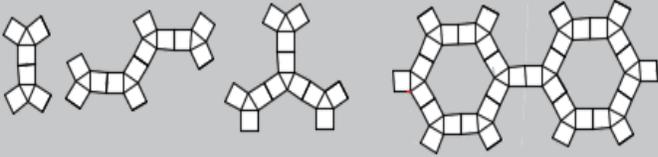
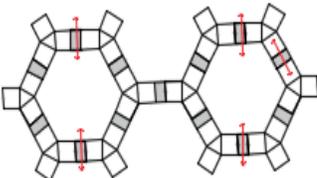
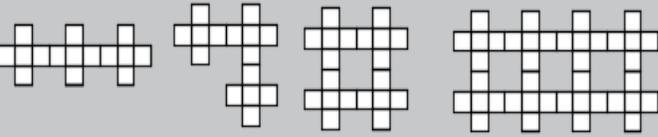
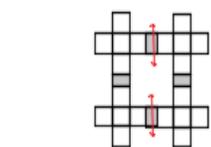
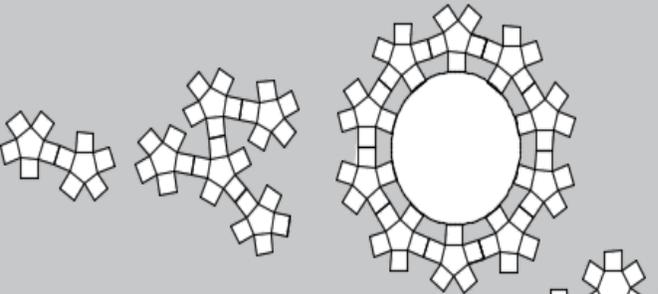
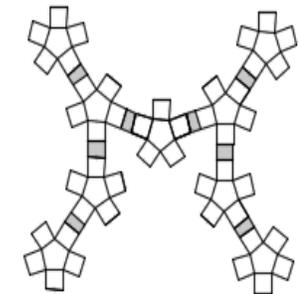
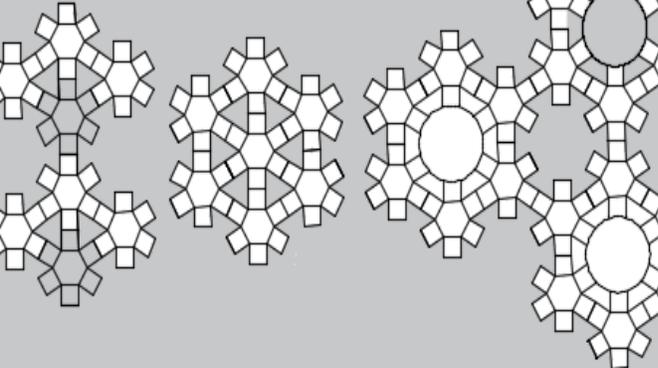
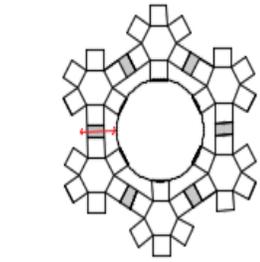
Figure 6:- Universal module“ proposal.

The floor plan variants shown in Table 3 were analyzed in the paper (Šljivić 2019) and represent the possibilities of combining identical modules and creating geometric forms for the composition of larger scale architectural structures.

It follows from Table 3 that the optimal modules are “Universal modules 3 and 6” composed using the base of a triangle and a hexagon. The hexagon offers a wide range of different solutions considering the possibility of connecting with identical forms. By correctly connecting six “universal modules 6”, a geometric form which creates a new central space is created, and it can be used as a common space. In further analysis it is necessary to explore in detail the ways of covering the central space and its connection to the modules. In Table 3 the use of additional geometric prismatic form is analyzed regarding the module usage possibilities.

³(Alegria Mira, 2010) and (De Temmerman,2007) have also selected the mentioned span for structure analyses in their works

Table 3:- Forming of spatial compositions using “universal modules” Source: (Šljivić, 2019).

FORMATION OF SPATIAL COMPOSITIONS USING UNIVERSAL MODULES			
GEOMETRIC FORMS OF MODULE			
BASE	MODULE		
			
			
			
			

The schematics of the model of combining “Universal modules 6” presented below (Figure 7) are of a conceptual character. By interconnecting the proposed modules, it is possible to achieve the warm connection between the spaces and to form arrangements with different contents by applying those modules.

The presented “Universal module 6” served as a basis for further analyses which were conducted with a goal to determine the optimal deployable bar structures span. The parameters of structural thickness and the number of units for structural spans from 6.0 to 12.0 m were analyzed. Detailed parametric analyses were done in the conceptual phase of design with the aim of gaining insight into the structural properties of the structure. The conducted analyses have resulted in the selection of optimal constellations of the number of units and of structural thickness, and more detailed analyses resulted in a proposal of a universal bar element for the formation of “Universal module 6”. After that, analyses were performed on models to find a new way of achieving the joint between bar elements. The proposal of the application of “universal modules” and “universal elements” for their formation will result in the more concrete use of these structures in architecture.

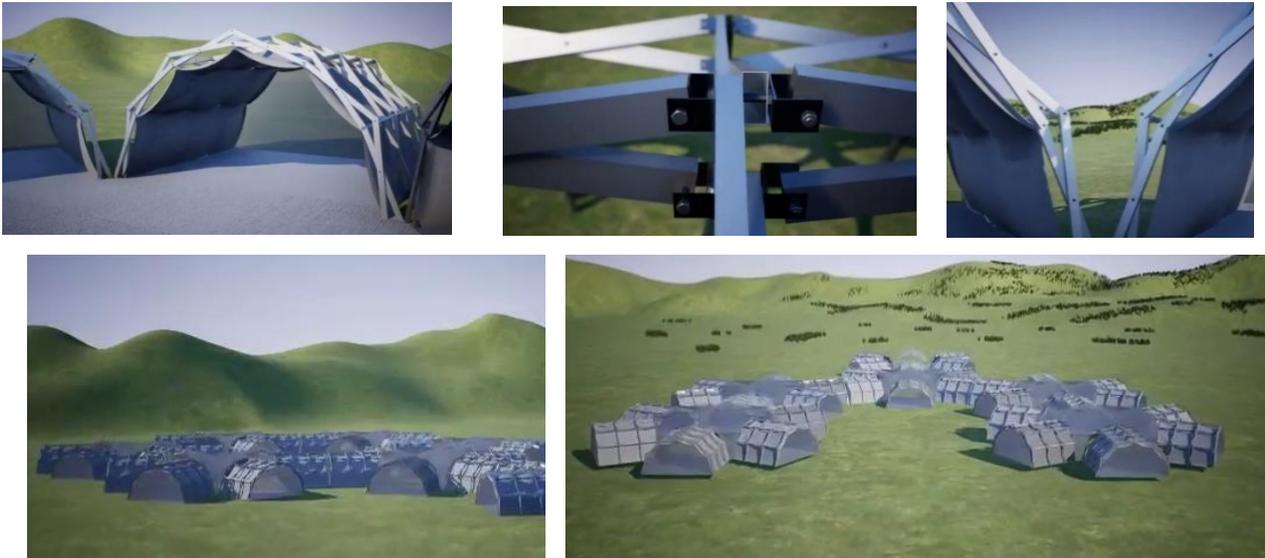


Figure 7:- An example of spatial organization with the application of “Universal module 6”.

Conclusion:-

There is often a need to provide a temporary shelter in the shortest possible timeframe for people who have lost their homes. Shelters are of a temporary character and are not built with a purpose for a longer stay. However, it is necessary that those shelters are lightweight with easy transport and storage options until the moment when the need for their usage emerges again.

In this paper, possible solutions for multifunctional temporary facilities built from deployable bar structures are explored. More detailed analyzes have separated singly curved forms as optimal for forming unified modules which create the “Universal module 6”. The application of the mentioned forms meets all architectural aspects and requirements of different spatial functions. Besides the application of these modules as temporary shelters in case of different weather disasters, they can be used for the organization of different sport events, as spaces for fairs and similar purposes. The usage and combining of analyzed geometric forms of deployable structures makes it possible to form architectural space of more complex geometric form which will provide a larger capacity and ensure the multifunctionality of proposed structures, which will significantly improve the application of these structures in architecture.

Focus of further research will be on finding the parameters which include defining unified elements and formation of the load-bearing structure inside pre-defined optimal geometric form and achieving different adaptabilities of the system.

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