# Lightweight transformable structures: materialising the synergy between architectural and structural engineering

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## Abstract

As opposed to conventional, static structures, transformable structures possess a transformational capacity enabling them to efficiently respond to altered boundary conditions, such as climatic conditions, different locations, varying functional requirements, or emergency situations. Generally, this capacity is provided through built-in mobility (structural mechanisms) or by means of assembly/disassembly of its constitutive members (kit-of-parts systems). The former group demonstrates kinematic properties that allow them to rapidly respond to changing needs by folding, expanding, or by any other form of deployment. Generally they come in the form of lightweight deployable structures that can easily transform between different configurations. This makes them fit for temporary, mobile applications or for adding adaptable sub-structures to buildings. In what follows, the research performed at the Vrije Universiteit Brussel by the Transform Research Group, the Lightweight Structures Lab, and the Mechanics of Materials and Constructions research group (MeMC), all collaborating on lightweight deployable structures, is presented. Through six case studies, diverse possibilities of deployable structures in architectural and structural engineering are explored. Key aspects concerning the design, analysis and construction of mobile, as well as adaptable constructions, are explained. Finally, conclusions are drawn on the intricate relationship between the geometric configuration, the kinematic behaviour and

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the structural response of lightweight deployable structures.
*Keywords: lightweight deployable structures, mobile structures, parametric design, adaptable sub-structures, emergency sheltering.*

# 1 Introduction

Transformable structures can adapt their shape or function according to changing circumstances, to meet rapidly evolving needs, induced by a society that increasingly embraces the concept of sustainable design. This is further supported by the understanding that structures are not designed in an end state, but in a transition state, hence ‘transformable structures’. Based on how this transformation is realised, two groups of structures can be distinguished. Structures within a first group are designed as a demountable *kit-of-parts* system (cfr. Meccano® construction toy) with dry, reversible connections, usually intended for a gradual adaptation over time. The second group – which will be the focus of this paper – entails structures incorporating a *mechanism* (deployable/foldable), enabling them to rapidly transform between different states (e.g. a compact and an expanded state). This primarily results in lightweight deployable structures particularly fit for temporary or mobile applications or for adding adaptable layers to buildings.

Lightweight deployable structures cover a common area of interest of the Transform Research Group (TRANSFORM), the Lightweight Structures Lab (LSL), and the Mechanics of Materials and Constructions (MeMC) research group, all active within the Research Lab for Architectural Engineering (æ-lab) of the Vrije Universiteit Brussel. TRANSFORM studies the effect of designing, engineering and constructing in a transformable way, researching both aforementioned groups of transformable structures. When it comes to the second group, the vast experience of LSL on a wide range of innovative lightweight structures (such as membrane structures, kinematic form-active structures or pneumatic/Tensairity structures) has proven to be invaluable. MeMC has a vast experience in structural analysis and the design of steel and aluminium structures and has the necessary lab space and expertise to build full-scale prototypes and to test them. Through our combined research activities on the design and analysis of lightweight deployable structures and all appropriate subtopics related to the engineering of such systems we aim to expand the existing knowledge, develop new concepts and disseminate our findings.

It is the synergy between the three groups that gives rise to our common research activities, with a focus on lightweight deployable structures. This is presented through a selection of six diverse case studies executed by our researchers. These do not aim to cover the full spectrum of our research, but will demonstrate the main research topics, together with a number of relevant additional topics, including the design and analysis of the proposed systems, the development of digital design tools, model making and sustainable design. Finally, some conclusions are drawn on the current state-of-the-art of this research. To start off, a general introduction is given on lightweight deployable structures.

## 2 Lightweight deployable structures

Designing transformable structures entails a design approach in which time is explicitly included from the earliest stages of conception [1]. So, besides the three-dimensional space – well-known to engineers – the fourth dimension becomes a determining design parameter. The structure is transformable over time and can itself be described as being relocatable, reusable, demountable; its building components can be reconfigurable, removable, replaceable, etc. Temporary structures that have this transformational capacity, and are lightweight or easily removable, have a lower impact on the site. This makes them ecologically favourable.

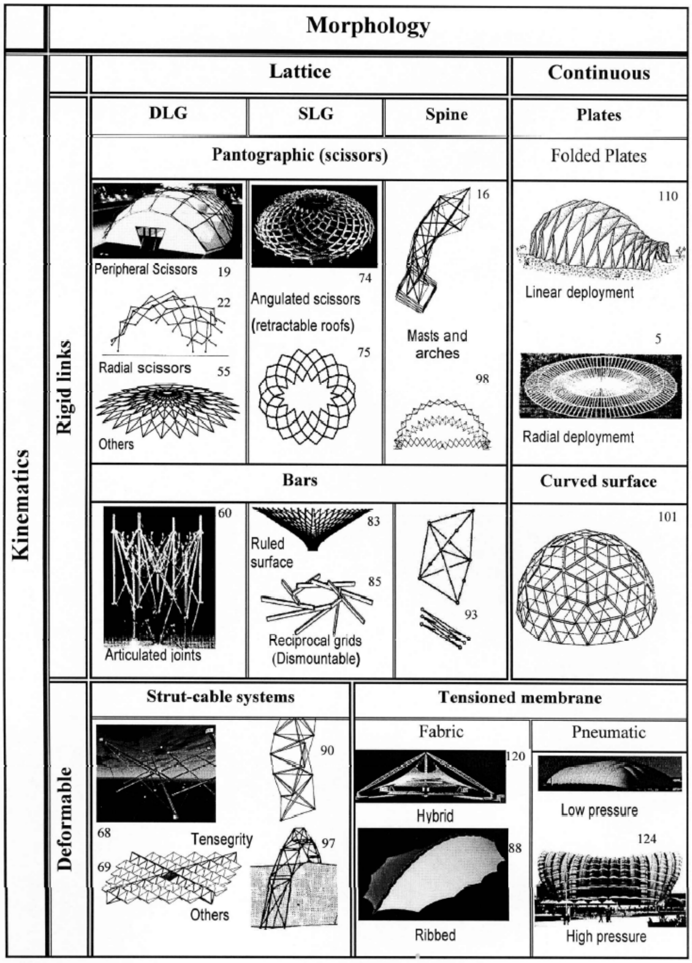

Figure 1: Classification of structural systems for deployable structures by their morphological and kinematic characteristics [3].

By introducing a mechanism, a structure is provided with one or more kinematic degrees of freedom (D.O.F.) and thus the capacity to transform from one state to another, i.e. from a compact configuration to an expanded configuration [2]. Generally, the process can be reversed and repeated.

Figure 1 shows a classification by Hanaor of the most common structural systems for deployable structures, based on their morphology and their kinematic behaviour [3]. Both structural mechanisms and demountable structures appear in the classification, as well as hybrid systems. Although some of these systems are more at home in the category ‘kit-of-parts systems’, the majority uses some sort of structural mechanism to provide the necessary transformation. The structural systems pictured in the classification are used for mobile applications as well as for larger, permanent structures such as retractable roofs [4]. These architectural engineering applications are described in more detail in the following paragraphs.

### 2.1 Mobile deployable structures

Generally, mobile deployable structures are capable of transforming from a small, closed or stowed configuration to a much larger, open or deployed configuration. In the fully deployed configuration they perform their architectural function. The most widespread applications are temporary lightweight structures such as emergency shelters for disaster relief, maintenance facilities, exhibition and recreational structures. These are typically small to medium scale applications whereby portability and ease and speed of erection are of utmost importance.

A wide range of structural systems have been used for mobile deployable structures such as scissor (or pantographic) structures [5] (see case studies 2, 3 and 5), deployable tensegrity [6], structural origami [7], foldable membrane structures [8] and Tensairity (see case study 6).

### 2.2 Adaptable building layers

For large sports facilities, retractable canopies are used to protect the grandstands from the sun, wind or rain. Sports arenas are static and permanent buildings, but by adding a retractable sub-structure, they are provided with the ability to react to changing circumstances, and to extend their use through all seasons (e.g. the retractable roof for Centre Court in Wimbledon). Similarly, buildings with large glazed surfaces (e.g. office towers) can greatly benefit from adaptable solar shading that controls the solar gains and thus simultaneously increases indoor comfort and decreases energy demand (see case study 4). The structural system used for the transformable sub-structures in permanent buildings can sometimes be quite different from the systems typically used for mobile applications. The biggest difference lies in the fact that there is a permanent structure that can act as a supporting and guiding structure for the transformable system.

## 3 Case studies

The diversity of current research topics within æ-lab on transformable structures based on mechanisms is demonstrated by the following selection of six case studies concerning recently finished or ongoing research. The first case study is about the development of a pedestrian bridge based on curved line folding, while the next two case studies are about the general design and analysis of deployable scissor structures and the power of digital design tools. The fourth case study presents the high-tech application of adaptable solar shading and the fifth one the low-tech application of transformable emergency sheltering and its socio-cultural aspects. Finally, the concept of deployable Tensairity is explained and valorised by building a full-scale prototype.

### 3.1 Case study 1: pedestrian bridge over the Zwalm River

For an architectural or structural engineer there is something truly mesmerising about the transformation from a flat piece of material with hardly any stiffness to a three-dimensional folded shape that can bear loads an act as a fully fledged and functional structure. This is exactly what N. De Temmerman (VUB), together with architect G. Pauwels (Dial-architects) accomplished with the design of a pedestrian- and bicycle bridge over the river Zwalm in Munkzwalm in Belgium. The idea has its roots in a principle called ‘curved line folding’, which means that a flat sheet of paper or another thin material is folded along curved fold lines, as opposed to ‘rigid origami’ where only straight lines are used. Folding along straight lines leads to a kinematic mechanism, whereas curved fold lines force the controlled introduction of ‘active bending’. This principle gives rise to interesting three-dimensional shapes with a surprisingly large stiffness.

The overall geometry of the bridge is derived from folding a flat piece of paper along two parabolically curved fold lines, thereby obtaining a convex bridge deck flanked by two concave side plates. The actual bridge is built from 10 mm thick *corten* plate steel (weathering steel) and can best be described as an open caisson construction, braced and stiffened by ribs on the inside. With a span of 10 m, an approximate width of 1.5 m and a total mass of 5000 kg this is truly a lightweight structure. What sets this design apart is the simple yet elegant design based on an abstract scientific principle and that all components have been cut from the same plate steel, assembled and welded, with no other elements added. Backed up by a vast amount of know-how and worldwide expertise, Victor Buyck Steel Construction (W. Hoeckman, G. Hoste, K. Van Hecke) acted as the contractor for the manufacturing of the bridge, resulting in a fine example of the synergy between architectural and structural engineering.

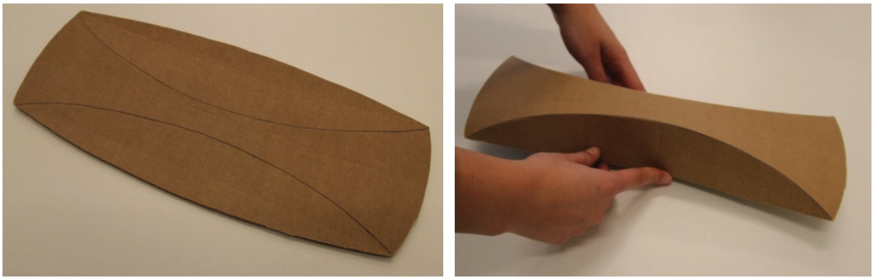

Figure 2: Scale model in cardboard demonstrating 'curved line folding' principle.

Figure 3: Designers G. Pauwels and N. De Temmerman standing on the lightweight curved bridge deck in corten steel (yet to become weathered).

Figure 4: The inside of the braced caisson construction (left) and a view of the slender fish belly bridge deck (right).

### 3.2 Case study 2: a generic design approach for angulated scissor structures

Scissor structures are a type of deployable structure consisting of hinged bars. Because they display a large deployment range, a reliable deployment and are fit for a broad range of applications, they form a particularly interesting sub-group [2]. A scissor unit is formed by interconnecting two bars by a revolute joint at the intermediate hinge point, which allows a relative rotation of the bars about an axis perpendicular to their common plane. The total structure is obtained by linking several of these units together at their end points using hinged connections. One can distinguish three basic types of scissor units depending on the proportions and shape of the bars: translational, polar and angulated scissor units.

In order to expand the geometrical possibilities offered by scissor structures and to propose innovative models, the angulated scissor unit was studied. This unit is characterised by having two identical kinked bars. Hoberman, who proposed the unit in 1990 [9], already demonstrated its capacity to generate more exotic shapes with his transformable hypar and helicoid [10]. TRANSFORM aims at exploring the full potential of the angulated scissor unit by developing a theory which unravels how to create an angulated scissor structure based on any arbitrary continuous surface. This opened the doors to a whole range of new geometries. The design method is based on two general steps:

(i) firstly, the base surface is translated into a quadrilateral mesh suitable as a base mesh for a scissor structure by discretising a network of principal curvature lines on the surface, and
(ii) secondly, the resulting mesh (i.e. principal mesh) is populated with angulated scissor units according to a number of predefined geometrical relationships which will assure a functioning mechanism.

A detailed explanation of this design method and some examples can be found in [11]. The theoretically endless new possibilities do however have a practical limitation, namely the ability to find a suitable network of principal curvature lines on the surface. A principal curvature line network is unique for any surface (except for a sphere and a plane) and might display large irregularities [12], which in turn can lead to ill-performing scissor structures. However several surfaces and surface families have already proven to be very suitable for application of these methods, such as the surfaces of revolution and the moulding surfaces [11].

The generic nature of the proposed design approach does not only make it applicable to a large number of surfaces and surface families, but also clears the path for its integration in a parametric design environment. Digital design tools are very useful to gain insight in the complex nature of these structures. They provide the means to quickly generate a large variety of line models of the scissor structures according to a number of user-defined parameters – giving direct visual feedback on the influence of each parameter – and to instantaneously simulate the corresponding deployment mechanism. Therefore they can significantly speed up the conceptual stages of the design process. Figure 5 demonstrates the working of such a design tool based on the proposed design method. It was developed in Grasshopper [13], a generative modelling plug-in for the computer-aided design package Rhinoceros® [14]. Aside from generating a myriad of different models and an instant analysis of its kinematic behaviour, the tool can be extended with other features benefiting the design process, such as a structural FE analysis (see case study 3) or the automatic generation of parts for a scale model (figure 6).

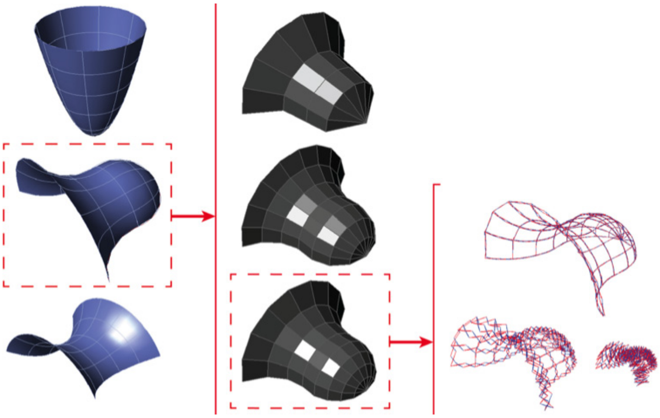

Figure 5: Main steps in a digital design tool for generating angulated scissor structures based on surfaces of revolution: (i) the base surface is designed; (ii) the base surface is discretised to obtain a principle mesh; (iii) the principal mesh is populated with scissor units and the deployment is simulated.

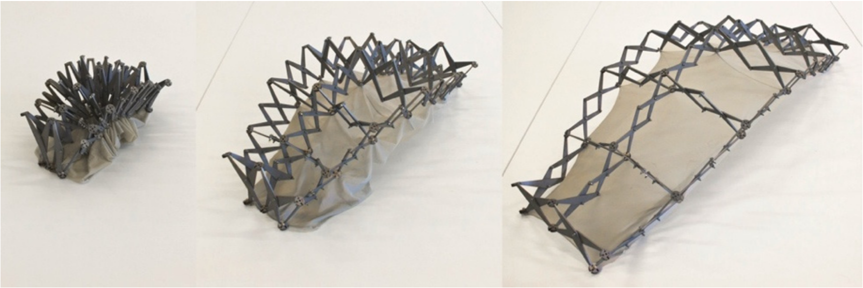

Figure 6: Physical scale model of an angulated scissor structure with membrane [11].

### 3.3 Case study 3: design through parametric finite element modelling

Despite the advantages scissor structures can offer, not many have successfully been realised. The design process is inherently complex: a scissor structure requires a thorough understanding of the specific two-and three-dimensional configurations that will give rise to both a fully deployable morphology and good structural properties. Due to this complex design process it is beneficial to evaluate these structures at a pre-design stage according to their structural performance.

By using a methodology of preliminary evaluation through parametric finite element (FE) modelling, the scissor structures could be geometrically and structurally optimised at an early stage (figure 7). This will enhance the overall design process, facilitate further detailed analysis and improve the performance of these structures, allowing the further development of various applications.

Karamba® – a commercially available parametric FE tool developed by Preisinger [15] – is employed in TRANSFORM research on deployable scissor structures. More specifically, Karamba® is an FE program embedded in the parametric geometric modelling environment Grasshopper (GH) (figure 8), also implemented in case study 1. With the use of these tools we can design and analyse deployable scissor structures in a single software environment which even more simplifies and speeds up the complex design process (figure 7).

An important aspect of Karamba® is its bi-directionality with respect to calculation data: the model response attained through physical simulation can be fed back into the geometric model. This allows setting up automated design loops that rationalise designs by taking into account structural data. For example, the geometrical height of a deployable scissor arch can be quickly determined to minimize deflection. Alternatively, the deflection can be investigated for different deployment stages of the arch. The absolute advantage is that the interaction between the geometrical and structural model is very fast. The designer can immediately understand the effects of geometrical parameters on the structural performance.

An aspect of this digital tool that adds to its speed of calculation is the fact that its capabilities are deliberately limited to those necessary in the early design phase: instead of e.g. employing isoparametric finite beam elements, hermitian elements are used. The latter are confined to linear elastic calculations of elements with straight axes. Yet the calculation of the element stiffness matrix can be done without the need for numeric integration and therefore very efficiently with respect to computation time. The reader is referred to Preisinger [15] for more information on Karamba®.

In this tool, scissor elements are modelled as one-dimensional beams connected by zero-length springs (representing the revolute hinges), which is an easy and effective method for a preliminary structural evaluation. The translational stiffness of the springs is set in such a way that connecting nodes share the same coordinates and only the springs' rotational stiffness about the axis perpendicular to the plane of the scissor unit is zero.

At an early design stage the focus is put on the structural performance of the scissor beams in the overall structure. Thus, the structural influence of the hinges can be ignored. This means that the non-zero stiffness values for the springs are set to a high value ($10^{11}$–$10^{13}$ kN(m)/m), though limited to avoid a badly conditioned stiffness-matrix which would lead to inaccurate numerical results in the FE calculations.

A preliminary investigation of this methodology has been conducted by the authors, in which the structural influence of different scissor configurations was determined [16].

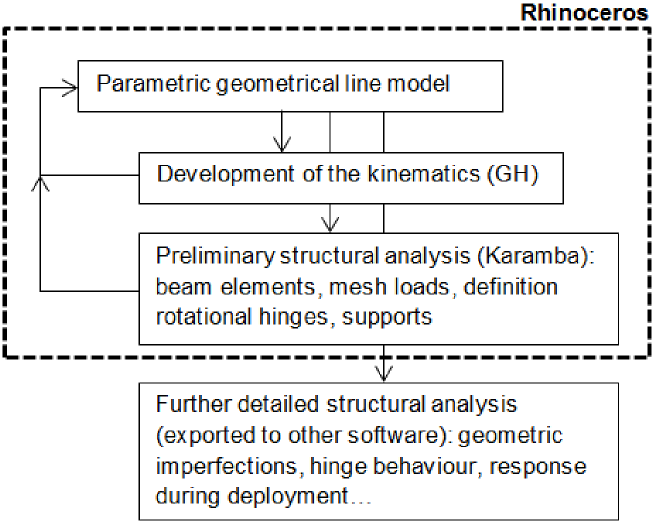

Figure 7: This flowchart illustrates how a parametric evaluation methodology for deployable scissor structures can benefit the overall design process: design improvements are made at an early stage through various iterations exclusively in the modelling environment of Rhinoceros®.

### 3.4 Case study 4: deployable structures and adaptive building envelopes

The building envelope acts as the interface between inside and outside and therefore has a significant influence on the indoor climate, comfort and energy use of a building. As most of the constraints acting upon the building envelope are time-dependent (weather conditions, the sun path, user preferences, noise, wind), the building envelope is increasingly considered as a dynamic structure, able to change its configuration, features or behaviour over time in response to changing conditions. Such building envelopes are known as adaptive (or responsive) building envelopes. In order to attain this kind of adaptability, deployable structures can be used, providing change in the building envelope through motion.

The folding process of deployable structures is particularly interesting for the active control of solar radiation and daylight. Recently, architects and engineers have been experimenting with the use of foldable structures as shading devices. A prime example is the “Dynamic Façade” project, better known as the Kiefer Technic Showroom located in Austria (figure 9, left). The metal panels can fold in various positions allowing occupants to adjust the light or temperature in a room. In this way, the façade changes continuously, creating a dynamic sculpture

[17]. Another example, the Abu Dhabi Investment Council (figure 9, right) consists of foldable shading elements based on an origami pattern. The solar shading elements can individually open and close in response to the movement of the sun throughout the course of the day [18].

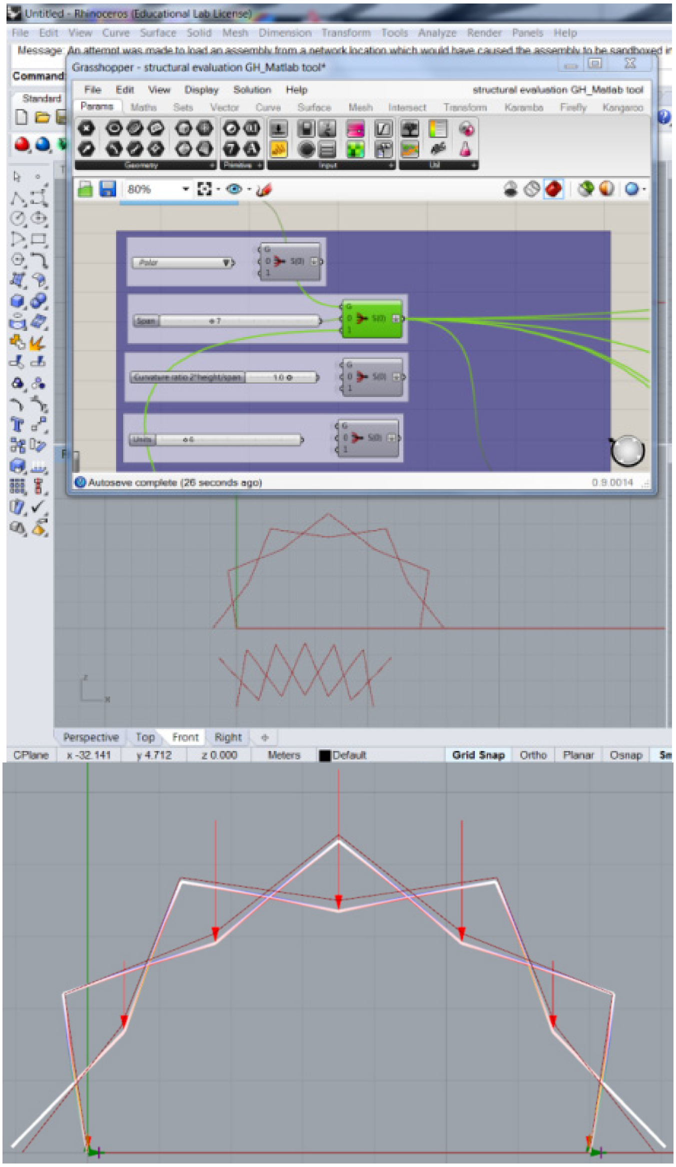

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Figure 8: The scissor geometry is parametrically defined in Grasshopper (left) and converted into a beam model and calculated with Karamba® (right).

Figure 9: The Kiefer Technic Showroom located in Austria [17] (left); Picture showing the installation of the dynamic shading elements of the Abu Dhabi Investment Council [18] (right).

Given these examples, there is a growing interest to study to what extent origami-based structures are appropriate for the use in adaptive building envelopes. Whereas the previous examples have proven the successful application of rigid-foldable plate structures as dynamic solar shading devices, the use of curved-line folding in this context remains unexplored. Moreover, by investigating the use of curved-line folding for the design of dynamic solar shading devices, new aesthetic opportunities for the design of building envelopes can be provided. As an example figure 10 shows the conceptual design of a façade with adaptive shading elements based on curved-line folding. Three different phases of the folding process are illustrated.

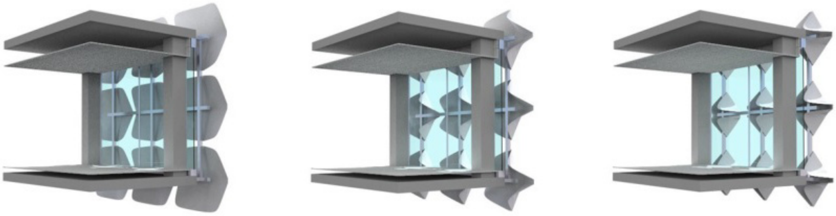

Figure 10: Conceptual design of a façade with adaptive shading elements based on curved-line folding.

The design and optimisation of a dynamic solar shading system is not an easy task. The diagram in figure 11 demonstrates that a whole series of parameters is involved in the design process: parameters defining the kinematic behaviour, parameters in relation to the morphology of the building and parameters influencing the energy flow through the façade. It is important to understand the relationship between these parameters and to study their effect on the performance of the shading devices, as explained in [19].

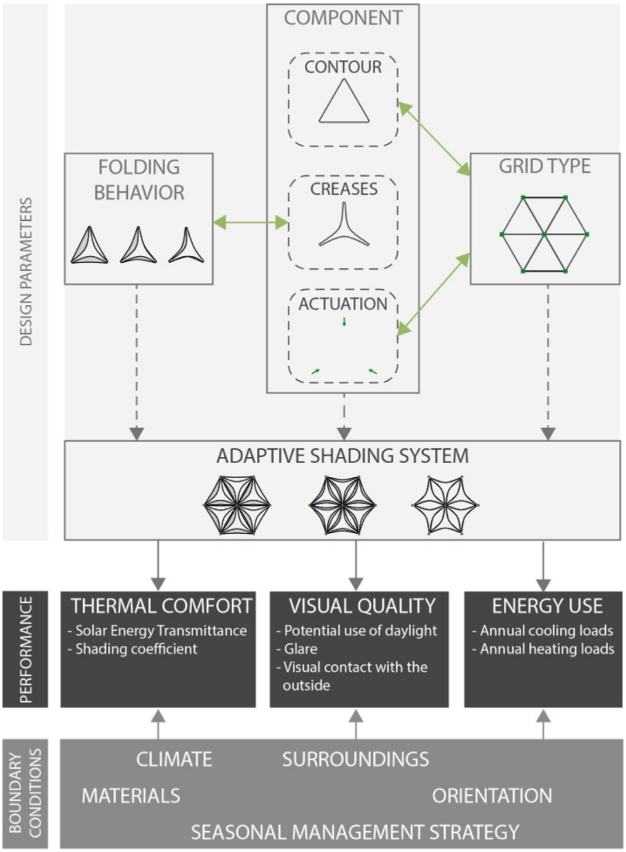

Figure 11: The diagram shows the relationship between all parameters to consider in the design of adaptive shading elements [19].

All things considered, it is clear that in order to improve the performance and the practical application of adaptive building envelopes, the development of a new generation of adequate transformable components is essential. Accordingly, (our) research on origami-based structures will play an important role in this process.

### 3.5 Case study 5: a design method for a deployable adaptable shelter based on multi-criteria optimisation

Disasters such as floods, earthquakes, volcano eruptions, famine and wars have occurred for ages and continue to do so. Knowing that a disaster occurs when a vulnerable community is hit by a hazard, and that the most vulnerable communities are struck the hardest, it can be stated that decreasing vulnerability is the key to enhancing a community's resilience. This resilience is best guaranteed by participatory and sustainable development processes involving the local community and all of the opportunities it has to offer, guided by a long-term vision. Rather than to impose a static short-term relief solution when a disaster strikes, both relief and development have to be addressed simultaneously in order to guarantee successful recovery using the socio-economic and cultural assets at hand to their full potential.

Shelter and housing are of utmost importance, as they play a crucial role in people's lives and in society: the loss of a home does not only constitute a physical deprivation, but can also cause a loss of individual and collective identity, orientation, security, privacy, thereby undermining many aspects of daily life, with a profound negative effect on the community. A home acts as a hub for a household's socio-cultural and economic interactions and thus can act as a catalyst for development.

There should be a link between relief and future development perspectives for those hit by disasters, if we want to offer a sustainable solution. Due to its multi-facetted character, housing has the potential to support and facilitate personal, social and economic recovery, i.e. to act as a catalyst for development. But in order to do so, the shelter solutions should be able to adequately fulfil their function in every stage of the relief and development process: from emergency, to rehabilitation to reconstruction.

Therefore, shelters cannot be static, but need to be adaptable in order to be able to evolve along with the changing context, hence act as transitional shelters. If a transitional shelter is designed as a kit-of-parts system, it can be disassembled into its constitutive components, which can then be rearranged and reused in a different configuration. Moreover, because of the open nature of the system, local materials and locally produced components can be introduced, thus involving the community and its human and material resources into the process. Transitional shelter intervention has a positive impact on communities and their development: communities take ownership of the concept by adapting it to their specific (socio-cultural) needs. This mutually interactive process for transitional shelters, stemming from a long-term vision, aims at effectively realising sustainable and participatory development.

Under the influence of prof. T. Tysmans (MeMC) and prof. R. F. Coelho (BATir, ULB, Belgium), this research is opting for a new design approach based on multi-criteria optimisation to combine the solutions of both the emergency phase (phase 1) and the development phase (phase 2) into one type of structure (figure 12). The aim is to provide a design tool that can be used by NGO's in order to design optimal deployable adaptable scissor shelters for the emergency phase. Furthermore, the elements of those shelters can be combined, after dismantling, in such a way that they result in several housing solutions for the development phase of the affected population. The design must take into account (i) the durability of materials and components over the permanent building's lifetime (fifty years), (ii) the possibility to integrate local building materials both for structural as for insulation purposes, and (iii) the significantly superior structural capacities that are required of its elements in the permanent state (larger spans, higher environmental loads, higher self-weight of building skin).

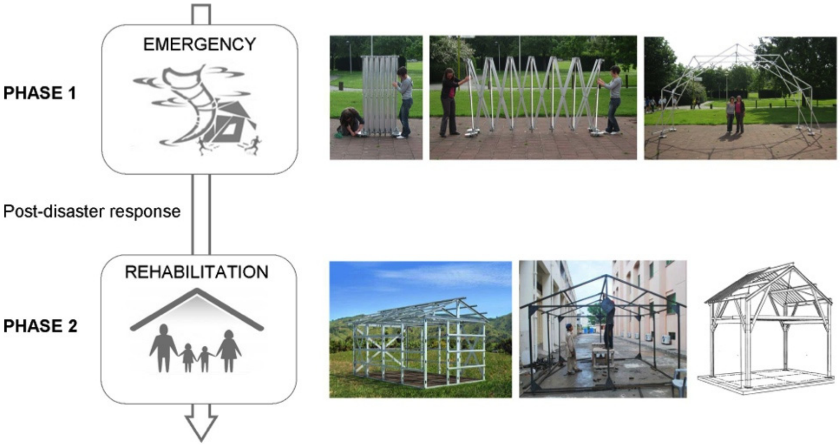

Figure 12: Scheme illustrating the proposed concept for a transitional shelter: in the first phase a scissor structure is used for a quick and easy deployment (photo: Alegria Mira L., Thrall A., De Temmerman N., prototype built at the VUB in MeMC lab); in the second phase the components are disassembled and reused for the housing of the local population (photo: [20]).

### 3.6 Case study 6: a full-scale prototype of a deployable Tensairity beam

Inflatable structures have been used by engineers and architects for several decades. These structures offer lightweight solutions and provide several unique features, such as collapsibility, translucency and a minimal transport and storage volume. In spite of these exceptional properties, one of the major drawbacks of inflatable structures is their limited load bearing capacity. This is overcome by combining the inflatable structure with cables and struts, which results in the structural principle called Tensairity.

Tensairity is a synergetic combination of struts, cables and an inflated membrane (by low pressurized air), as illustrated in figure 13. The tension and compression elements are physically separated by the air inflated beam, which – when inflated – pretensions the tension element and stabilizes the compression element against buckling.

A Tensairity structure has most of the properties of a simple air-inflated beam, but can bear several times more load [21]. This makes Tensairity structures very suitable for temporary and mobile applications, where lightweight solutions that can be compacted to a small volume are a requirement. However, the standard Tensairity structure cannot be compacted without being disassembled. By replacing the standard compression and tension element with a mechanism, a deployable Tensairity structure is achieved that needs – besides changing the internal pressure of the airbeam – no additional handlings to compact or erect the structure.

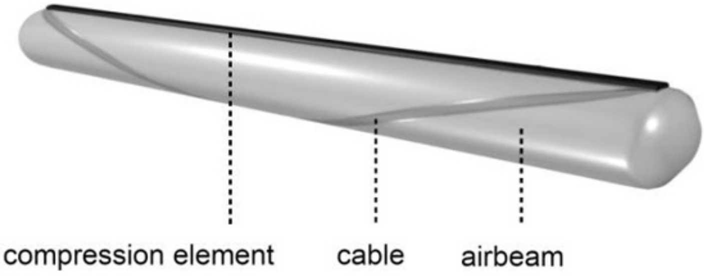

Figure 13: Basic cylindrical Tensairity beam [22].

This research is concerned with the development of a new type of deployable Tensairity beam. An earlier concept of a deployable Tensairity structure was developed in [23], and although it was promising, there were still issues to be solved and optimised. Within this study, a new proposal is made for a deployable Tensairity beam which is improved in terms of its structural and kinematic behaviour (figure 14). The system's load bearing capacities are ameliorated by changing the longitudinal shape from cylindrical to spindle, by decreasing the amount of hinges and segments and by positioning hinges on the compression side towards the middle. By means of a redesign of the configuration of the foldable truss, the kinematic behaviour is improved. The segments of upper and lower strut do not have to 'fold' into each other anymore. In addition, less hinges and less complicated joints are necessary. As a result, a more easily foldable proposal for the deployable Tensairity structure was obtained.

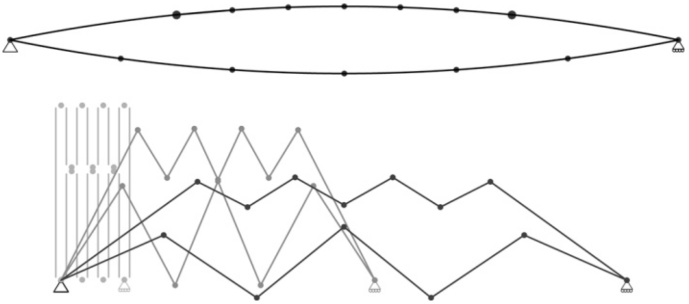

Figure 14: The mechanism of the deployable Tensairity beam [22].

Finally, a full-scale prototype (5 m span) of the deployable Tensairity beam has been designed and built, valorising the proposed concept (figure 15). Special attention was directed towards the hinge design and the attachment and positioning of the membrane to ensure an unimpeded deployment mechanism. An experimental investigation has been performed towards the structural behaviour of the full-scale prototype, which is presented in [22].

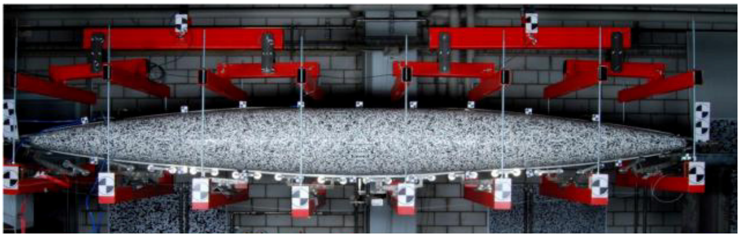

Figure 15: Prototype of the deployable Tensairity beam during experimental investigations [22].

With this research, the first step is taken towards a functional large-scale deployable Tensairity beam. However, many aspects in this research, such as the detailing and the gained insight, can also be applied to the development and research of other structures, such as Tensairity arches, cushions and grids. The application of the deployable technology on other scales or in other domains than civil engineering will bring forward new questions and knowledge and is certainly worth investigating.

## 4 Conclusion

This paper provided a selection of the research done on lightweight deployable structures at the Vrije Universiteit Brussel by TRANSFORM, the Lightweight Structures Lab, and the Mechanics of Materials and Constructions research group (MeMC), all active within or collaborating with æ-lab (Research Lab for Architectural Engineering). This selection serves as a demonstration of the variety of the research being performed and the methods being used to achieve our goals.

Within TRANSFORM, chaired by N. De Temmerman, the main focus lies on the transformation of structures, in order to provide them with a transformational capacity enabling them to adapt to changing circumstances. These changing circumstances can range from a sudden need (emergency), to climate conditions (sun, wind, rain, heat/cold), to altered functional requirements (transport, expansion, reuse), or any other boundary condition requiring a physical transformation. The transformation can take the form of deployment, in case of structural mechanisms providing a system with kinematic behaviour, or it can take the form of adding, reconfiguring, reusing components, as is the case with demountable kit-of-parts systems. The key aspect in the latter group is that the complete life cycle of the construction is taken into account, as an important step towards sustainable design and development. Even though this paper focused on the first system, both types of transformation are being researched in our group. In some cases even a hybrid system, combining the two systems is possible (as seen in case study 5 or in [24]).

The vast experience – spanning more than 25 years – of the Lightweight Structures Lab chaired by M. Mollaert, in the search for maximum lightness combined with an optimal structural performance results in substantial added value to the research of æ-lab. Through a wide range of research topics, the group contributes to the further development of ‘tensile surface structures’, ‘kinetic structures’, ‘graphic statics and form finding’. This currently translates in specific projects, investigating the design and implementation of pneumatic components in structural systems (see case study 6), the comfort assessment of spaces enclosed by translucent membranes, the design and calculation of new typologies for fabric structures, emergency shelters and the development of so-called ‘bending-active’ structures.

Added to that, the experience of MeMC is a huge asset in transferring an abstract concept to a full-scale realisation. Their expertise in the structural analysis of steel structures, their knowledge on materials for constructions, and their vast experience in developing and testing prototypes of innovative lightweight is of great value in the collaboration between ARCH (Architectural Engineering) and MeMC. Based around the legacy of W. P. De Wilde, young research leaders T. Tysmans and L. Pyl today continue the tradition of exploring the synergy between architectural and structural engineering. In another paper by Pyl *et al.*, you can read about how this synergy came about, and what successful collaborations it has yielded.

The possibilities of deployable structures are immense, but the challenges that they impose remain great. We aim to face these challenges and provide sustainable solutions for them. The capacities and behaviour of deployable scissor structures are being investigated on a structural level (Alegria Mira [24]) as well as from a geometrical and kinematical point of view (Roovers *et al.* [11]). They are being deployed in the field of emergency sheltering and disaster relief, where it is researched how their components can live on as structural elements to rebuild the local housing stock (A. Koumar). Responsive building skins are being developed using foldable origami structures, acting as the interface between inside and outside, therefore enabling to regulate e.g. airflow, solar shading in the façade of a building (Vergauwen *et al.* [19]). New concepts for foldable Tensairity are proposed, leading to lightweight, yet very high performing structural elements that can easily be transported and deployed (De Laet *et al.* [22]). In addition, exiting new fields are being explored such as deployability in bending active structures, thus expanding the boundaries of our research (S. Brancart).

The design and analysis of deployable structures is quite particular. The kinematic aspect lies at the very core of the concept and completely determines the process starting from the first stages of the design: one has to evaluate the final expanded configuration, in which the structure executes its architectural function; but the deployment phase, used to get to that point, is equally important [25, 26].

The design process of deployable structures inherently displays a high degree of complexity, found in the relationship between their geometry, their kinematic behaviour and their structural performance, sometimes combined with other design variables such as socio-cultural factors that need to be taken into account. Therefore, software tools have become indispensable during the design of deployable structures. Starting from the first steps, these tools can assist and speed up the design process and simultaneously provide insight to the designer. An interactive design environment can be integrated with analysis components, resulting in direct feedback on the design choices made. Despite this wide range of possibilities, one cannot underestimate the importance of physical (scale) models and prototypes, as they still have the potential of revealing overlooked design flaws and verifying the digital models.

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