Transformable structures in architectural engineering

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Abstract

This paper explores the possibilities of transformable structures in architectural and structural engineering. Key aspects concerning the design, analysis and construction of mobile, as well as adaptable constructions, are explained. The transformation of such structures, intended to meet changing requirements, is done by using mechanisms (deployable/foldable) or reconfigurable components (demountable kit-of-parts).

Transformable structures can adapt their shape or function according to changing circumstances, to meet rapidly evolving needs, induced by a society which – progressively – 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. The transformation of the structure is primarily done by either:

(i) incorporating a kinematic mechanism, enabling the structure to deploy from a compact configuration (e.g. for transport) to a larger, expanded state in which it can fulfil its architectural function (e.g. providing shelter) or,

(ii) by designing and realising the structure as a kit-of-parts system (cfr. Meccano construction toy) with dry, reversible connections between the constitutive components, enabling *design for disassembly*, whereby all components can be reconfigured, replaced or re-used.

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The former systems are primarily aimed at the field of temporary construction, in which lightweight, deployable structures are of great use, while the latter are primarily aimed at allowing a structure to be adapted gradually over time. The paper explores the possibilities and limits of both systems, including topics such as geometric design, kinematic behaviour, structural analysis, design- and analysis software and sustainable design. Conclusions are drawn on the current state-of-the-art and suggestions are made for future research.

This paper serves as an introduction to the other papers participating in the special session on ‘Transformable Structures’ at the HPSM 2012 Conference.
Keywords: transformable constructions, adaptable structures, mobile structures, deployable structures, kit-of-parts systems.

1 Introduction

The focus of the research activities of the Transformable Structures research group of the Vrije Universiteit Brussel lies on the design and analysis of these innovative structures and all appropriate subtopics related to the engineering of such systems in order to expand the knowledge, to develop new concepts and to disseminate our findings.

Transformable structures can adapt their shape or function according to changing circumstances, to meet rapidly evolving needs, induced by a society which 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’.

Figure 1: A transformable scissor structure dome based on the principle of the USC (Universal Scissor Component). Built at Imperial College in September 2011 during the SMG (Structural Morphology Group) International Seminar.

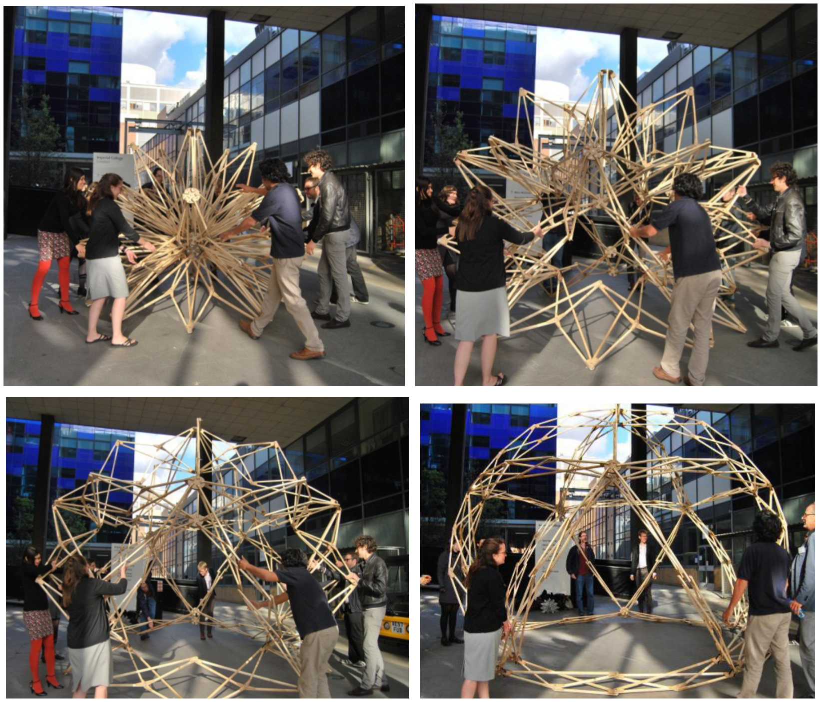

Figure 2: Four stages in the deployment of the icosahedral dome based on the USC. The structure is built from a single type of triangular component, but can take many shapes, just like a Meccano™. This prototype was used to test the assembly process and the deployment process.

This paper aims at concisely defining the scope of our research on transformable structures. The main research topics are mentioned, together with a number of relevant additional topics, including the design and analysis of the proposed systems, the application of software and model making, and sustainable design. Finally, some conclusions are drawn on the current state-of-the-art of this research.

2 Transformable structures

Designing transformable structures entails a design approach in which *time* is explicitly included from the earliest stages of conception [2]. So, besides the 3-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 which have this transformational capacity, and are lightweight or easily removable, have a lower impact on the site which makes them ecologically favourable.

Based on how this transformation is realised, two groups of structures can be distinguished. The transformation of the structure is primarily done by either incorporating a *mechanism* or by designing the structure as a *demountable kit-of-parts.*

2.1 Structural mechanisms

By incorporating a mechanism, the structure is provided with a certain mobility and can therefore deploy from a compact configuration (e.g. for transport) to a larger, expanded state in which it can fulfil its architectural function (e.g. providing shelter), as shown in Fig. 3.

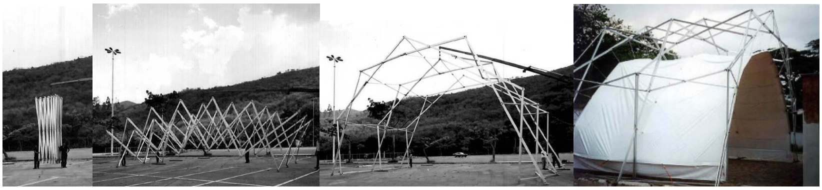

Figure 3: Mobile deployable bar structure (© Grupo Estran).

2.2 Demountable kit-of-parts

By designing and realising the structure as a kit-of-parts (cfr. Meccano toy construction system) with dry, reversible connections between the constitutive components, *design for disassembly* becomes possible, whereby all components can be reconfigured, replaced or re-used (Fig. 4). The following chapters will describe these systems in greater detail.

Figure 4: Example of a demountable kit-of-parts system (© Michael Lefeber).

3 Structural mechanisms

By introducing a mechanism, a structure is provided with one or more kinematic degrees of freedom (DOF) and thus the capacity to transform from one state to another, i.e. from a compact configuration to an expanded configuration [3]. Generally, the process can be reversed and repeated.

In architecture, typical applications are mobile deployable structures or retractable roofs. Figure 5 shows a classification of the most common structural systems for deployable structures, based on their morphology and their kinematic behaviour [4]. 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 and larger, as well as for larger, permanent structures such as retractable roofs [5].

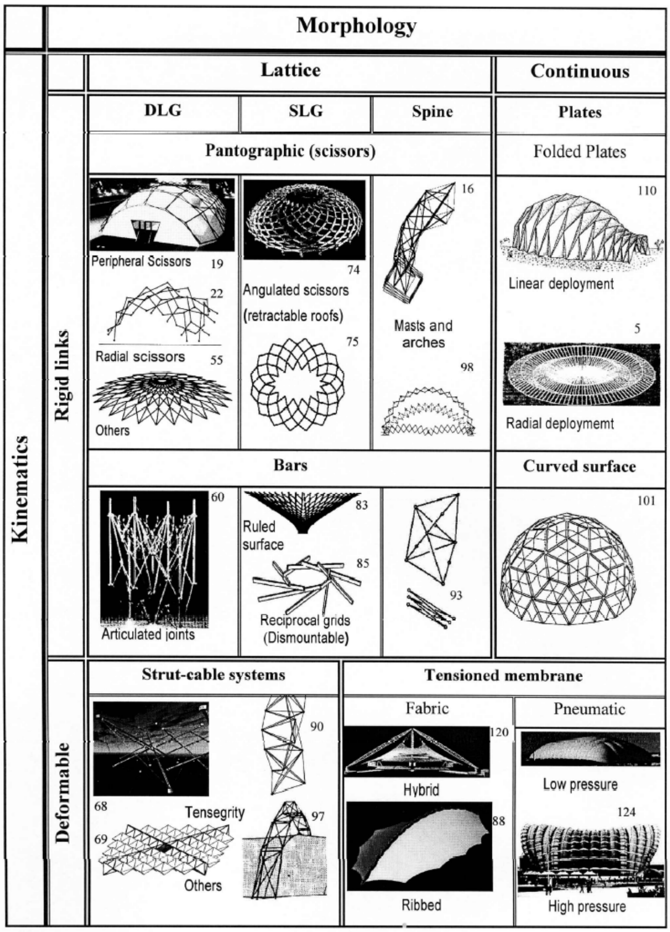

Figure 5: Classification of structural systems for deployable structures by their morphological and kinematic characteristics (Hanaor and Levy [4]).

In the following paragraphs it is described how structural mechanisms can be put to use for architectural engineering applications.

3.1 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 (Fig. 6). It is in the fully deployed configuration that they are able to 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.

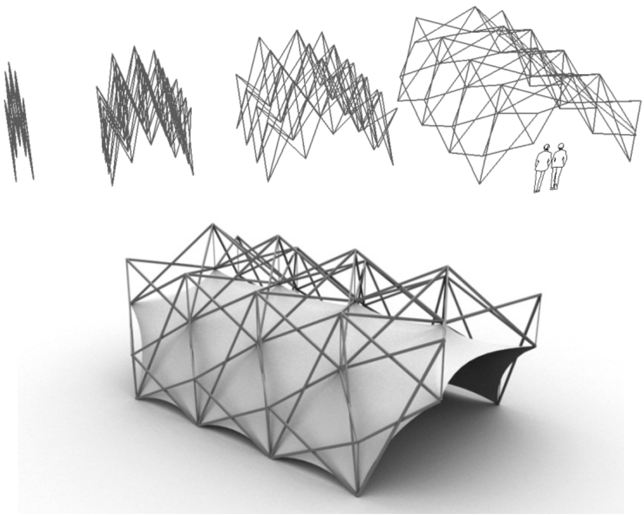

Figure 6: Design for a deployable tower based on angulated scissor components. The tower doubles up as a lifting mechanism and as the final supporting structure for the membrane canopy [3].

A wide range of structural systems have been used for mobile deployable structures such as scissor (or pantographic) structures [6, 7], deployable tensegrity [8], structural origami [9], foldable membrane structures [10] and – more recently – tensairity [11].

3.2 Retractable roof structures

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. The structural system used for the transformable sub-structures in permanent constructions can sometimes be quite different from the systems typically used for mobile applications: cable-pulley-controlled membranes, rotating or translating roof segments or air-supported tensile surfaces [5]. The biggest difference lies in the fact that there is a permanent construction which can act as a supporting and guiding structure for the transformable system.

One of the oldest known examples is the velum for the Roman Coliseum, but in recent times technology has evolved in such a way that computer controlled systems can deploy a canopy in a matter of minutes. A successful example is the retractable roof for Centre Court in Wimbledon. The auditorium cover by Escrig in Sevilla is an example which makes use of scissor structure technology, but applied in an unconventional way.

4 Demountable kit-of-parts

This concept relies on the philosophy of designing and building like a 'meccano' system with dry, reversible connections allowing a gradual transformation of the structure over time (Figs. 7 and 8). Only a few components are used as the basic building blocks, but with the possibility to compose a myriad of configurations.

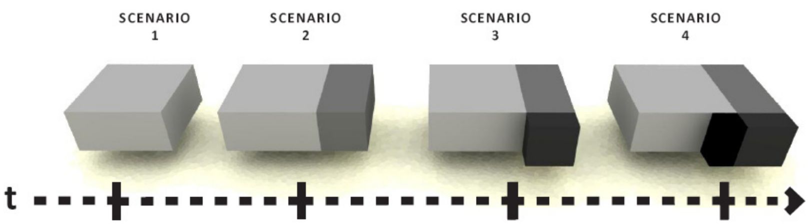

Figure 7: Transformation of a construction over time trough the addition of compatible components in order to adapt to changing requirements (image: M. Lefeber).

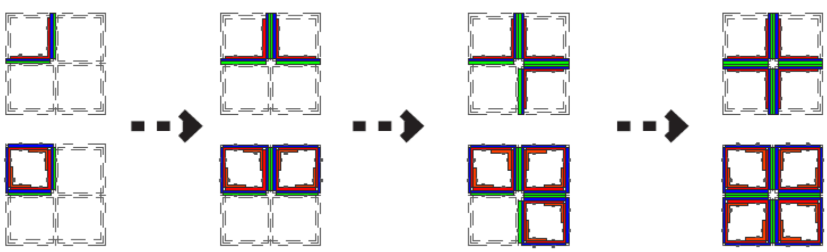

Figure 8: Transformation of a component (section view of steel column) by the addition of compatible sub-components in order to be able to cope with increased or altered loads (image M. Lefeber).

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Where mobile deployable structures are generally used to realise an instant transformation, demountable kit-of-parts systems are well-suited to perform a gradual transformation. For example, a static construction can be transformed by adding, replacing or reconfiguring its components [2].

Additionally, a *generative dimensioning system* can be used as an underlying geometric grid and guarantees that existing and future components will be compatible with the system (cfr. Lego system). This enables the design to easily meet changing needs, or to effortlessly adapt to new architectural or structural requirements.

On that note, it is a common misconception that a reduction of the number of components, combined with a uniformisation of the component shapes and dimensions, automatically leads to a reduction in richness of the possible configurations. Quite the contrary: the higher the component uniformity, with the least amount of specific, unique shapes, the higher the number of possible geometric compositions that can be made.

The use of a generative dimensioning system can be used on all levels or scales: from the lowest constitutive component, over several subsequent levels of sub-assemblies, up to the level of the structure, and even beyond. From an engineering point of view, the emphasis lies on the component and structure level.

5 Design and analysis

In recent years, the computing capacity of computer hardware and software has increased exponentially and specific design and calculation tools have become widely available and affordable. However, when it comes to deployable systems, which border on the fields of architectural, structural and mechanical engineering, suitable analysis software which takes into account all aspects of the analysis is not widely available. There is a real need for conceptual design tools which can provide the designer with instant feedback on a proposed concept, whereby the geometrical, structural and kinematical parameters are taken into account. Subsequent analysis could be done in established, high end structural analysis software. However, most software tools cannot cope with the specific boundary conditions and requirements of deployable systems.

On the other hand, the development of easy-to-use geometric design software has taken a quantum leap. One of the best known examples is Rhinoceros® 3D [12], which is a three-dimensional modelling program. Although very proficient in generating all kinds of complex structures, its power lies in the many innovative plugins, often developed by the user community and of which many are available for free. One plugin that attracts a great deal of attention is Grasshopper® [13], allowing full parametric design in Rhino, even for non-programmers (Fig. 9). The fact that it also accepts additional plugins for live physics, FEM-analysis and evolutionary solvers seems promising for futures developments. Not only is parametric modelling great for effortlessly generating and adapting one's geometry, in this research it is also a great tool to instantly assess the kinematic behaviour (deployment) of structural mechanisms.

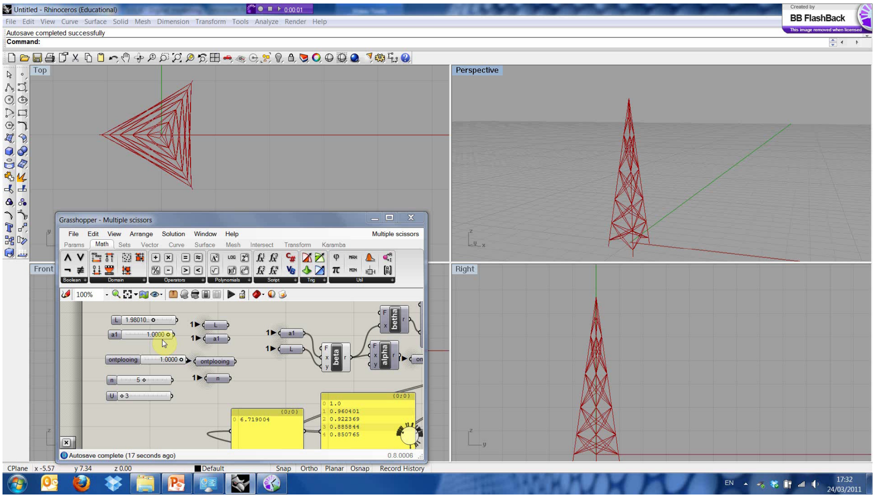

Figure 9: Screenshot of the parametric design plug-in Grasshopper, generating a deployable scissor structure in the software Rhinoceros 3D.

This is not the first time it has been mentioned, but one cannot underestimate the importance of physical models [3]. Software tools are great and allow an idea to be quickly executed without too much hassle. But when it comes to really gaining a profound insight in a structure, preferably in the early design stages, physical (scale) models are still of great use. Ideally, a balanced combination of digital and physical modelling is used to grasp the strengths and weaknesses of a design. Within the context of transformable structures, this is certainly a valued approach.

6 Sustainability through engineering

In recent years, sustainability has become such a big and widespread topic, that, when mentioning the concept, it becomes necessary to refine the definition depending on the context. There is a plethora of subtopics that can be studied, all of which are related to sustainability in one way or another with plenty of opportunities for assessment and evaluation (some rather qualitative than quantitative). That said there is a straightforward and useful link between transformable structures and sustainability [3, 14].

Generally, sustainable design can interact on one or more of three levels [2]:

- *material* (e.g. recycling, up-or downcycling),
- *component* (e.g. reuse, reconfiguration),
- *structure* (e.g. reuse, expansion)

In this research, the focus lies on the *component* level, and on the *structure* level. When structures can be compactly folded, are lightweight, can be transported and easily erected, and after their use can be compacted again, leaving no trace on sensitive sites, and subsequently be reused, it can be argued that these structures subscribe to the principles of sustainable design. A structure which can evolve over time by adding, reconfiguring, or adapting components connected by dry, reversible connections, in order to adapt to changing circumstances (climatological requirements, alternative use, disassembly, relocation) is equally catering for sustainable design. This way of designing and realising structures, aimed at contributing towards sustainability, relies heavily on engineering.

7 Conclusions

In this paper an overview has been given of the main research topics of the Transformable Structures research group of the Vrije Universiteit Brussel.

It is clear that the main focus lies on the transformation of structures, in order to provide them with a *transformational capacity* allowing them to be able 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. This 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. In some cases a hybrid system, combining the two systems is possible [15].

The design and analysis of transformable structures is quite particular. From the earliest design stage, the aspect *transformation* lies at the very core of the concept and completely determines the process. When designing *deployable structures*, 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 [16, 17]. When designing *demountable kit-of-parts systems* a lot of the design and engineering effort has to be directed towards the components of a structure, focusing on the compatibility and connectivity of the components. The transformation, and possible reuse of the structure, and its constitutive components, is enabled through the use of dry, reversible connections.

Software tools have become a cornerstone of the design and analysis of structures. They can deliver profound analysis of specific aspects of a design. However, only engineers who master every aspect of the design and analysis can interpret these results and use it as a tool. Particular software for the design and kinematic and structural analysis of complex systems such as deployable structures is generally not readily available to the design and engineering community. However, in terms of preliminary design tools, including parametric modelling of structures, there is a lot of development going on, and this seems promising. There is still a role of importance for physical (scale) models, because they provide a good insight in possible flaws in the design and the detailing, from the earliest stages of the design.

With such tremendous possibilities, in terms of digital modelling and analysis tools, computer controlled manufacturing systems, and new materials, one can raise the question: what will be the challenge of the future engineers? Could our engineering efforts be directed more towards designing and building more rational – and sustainable – structures [18], making sure they can transform over time, be reused, or even be easily removed?

Currently, our group is expanding the research to include the conceptual design and immediate structural evaluation of deployable scissor structures (see paper of L. Alegria Mira). Also, the knowledge gained on deployable systems is being applied to the design and analysis of responsive building skins, acting as the interface between inside and outside, therefore enabling to regulate e.g. airflow, solar shading in the façade of a building (A. Vergauwen). Further, research is done on how existing conventional building materials can be used for innovative transformable construction (M. Vandenbroucke). Flexible renovation, according to a specific methodology which allows change in terms of future (unknown) scenarios, based on the Hendrickx-Vanwalleghem Design Approach, is another part of our expertise (A. Paduart). On a more abstract level, we are looking on how to expand the principles of transformable or adaptable design approaches to the urban level. This includes studying the complexity of systems and the evaluation of the transformational capacity of urban fragments (P. Herthogs).

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