Exploration of spatial structures made from reused elements and the design of optimal kits-of-parts

J. Brütting & C. Fivet
Structural Xploration Lab, Swiss Federal Institute of Technology (EPFL), Fribourg, Switzerland, jan.bruetting@epfl.ch

G.Senatore
Applied Computing and Mechanics Laboratory, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland

ABSTRACT: *Reuse* reduces raw material use, waste generation and energy consumption caused by building construction. A substantial share of these impacts is contributed by load-bearing systems, because of their mass- and energy-intensive production process. Therefore, reusing structural components has the potential to improve the sustainability of building structures. However, reusing structural elements entails reversing the conventional structural design process: the mechanical and geometric properties of available elements predetermine the layout of a structure. This paper presents structural optimization techniques: 1) for the design of multiple spatial structures from an element stock, and 2) for the synthesis of a *kit-of-parts* whose elements can be reused in multiple structures. In both cases, the optimal assignment of elements to the structure is obtained via combinatorial optimization. In addition, geometry optimization is employed to best-fit the structure geometry to the lengths of assigned stock elements. The potential of the proposed methods for large-scale applications is demonstrated via case studies of three spatial structures.

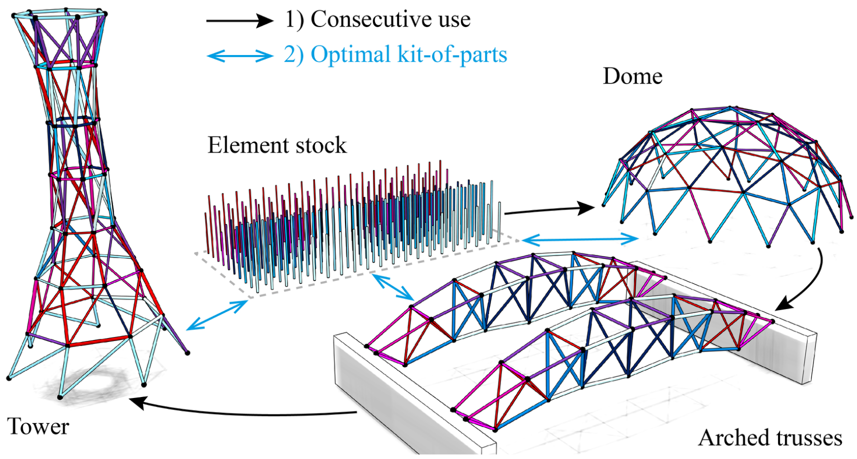

Figure 1. Three spatial structures made from reused elements: 1) consecutive use of stock elements for different structures, and 2) synthesis of an optimal kit-of-parts to reuse its elements in multiple structures.

1 INTRODUCTION

Recent trends in research and practice have identified the potentials of *reuse* to lower the environmental footprint of buildings (Gorgolewski, 2017). Reuse aims at avoiding raw material use and at reducing the energy spent for transformations as well as at reducing waste by keeping products for multiple service-lives as close as possible to their original form.

Figure 1 shows two reuse strategies: 1) designing multiple structures from one stock, and 2) the synthesis of an optimal kit-of-parts whose elements can be reused in multiple structures. In both cases, reusing structural elements entails reversing the conventional design process by taking the mechanical and geometric properties of available elements as the input of a design. In this work, structural optimization methods are employed to carry out the design of structures made from reused elements.

2 METHODS

Two optimization methods for scenario 1), the design of multiple spatial structures from one stock of elements, are formulated: (A) the *assignment* of individual elements to positions in the truss, and (B) a *bin-packing* approach, where multiple members can be cut from single elements. In both methods the availability, length and force capacity of stock elements is considered. Method (A) has been previously presented in Brütting et al. (2018). The bin-packing case has been studied by Bukauskas et al. (2017) for the design of trusses made from timber logs by applying heuristic algorithms. Instead, all formulations of this paper employ deterministic combinatorial optimization methods, such as *mixed-integer linear programming*, to obtain globally optimal solutions.

Method (A) is extended to the synthesis of an optimal kit-of-parts 2), by including the element lengths and quantities as design variables. Scenario 2) can be thought as the "inverse" of (A). This problem has so far received little attention. Nadir et al. (2004) studied the reconfiguration of truss members in order to react to changing load actions. Tugilimana et al. (2017) considered the reuse of unit-cells in modular bridges of different spans. In contrast, this work aims at optimizing a kit-of-parts for multiple structures while maximizing the number of reuse cycles per single element.

3 CASE STUDIES

A first case study considers the consecutive construction of the three spatial structures shown in Figure 1 from one stock of elements. The system layouts are defined parametrically to adjust their member lengths to be similar to those of the available stock elements. Methods (A) and (B) are employed to obtain an optimal use of the available elements. The system geometries are subsequently optimized to reduce element cutting, yet constraints are set to maintain initial design intentions, for instance all dome nodes are required to remain on a spherical surface.

A second case study considers the optimal synthesis of a kit-of-parts for building each of the three spatial structures individually with a minimum amount of stock elements and without any cutting. Two optimal solutions with only ten and six different stock element types are shown.

4 CONCLUSION

This paper presents structural optimization techniques for the design of spatial structures from reused elements. Further, an effective method for synthesizing an optimal kit-of-parts whose elements can be reused in multiple structures is presented. Case studies show the potential for application of these methods to large-scale spatial structures. A key challenge for future research and realizations of this work in practice is the design and custom manufacturing of joints.

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