Proceedings of the International Association for Shell and Spatial Structures (IASS)
Symposium 2015, Amsterdam
Future Visions
17 - 20 August 2015, Amsterdam, The Netherlands

Computational Reuse Optimisation for Stadium Design

Jorn VAN DER STEEN[a]*, Jeroen COENDERS[b], Sander PASTERKAMP[c], Anke ROLVINK[d], Joost VAN STEEKELENBURG[e]

Oude Langendijk 9A, 2611 GK, Delft
Jorn.vanderSteen@gmail.com

[b&d] Delft University of Technology and White Lioness technologies
[c] Delft University of Technology
[e] Royal BAM Group

Abstract

This paper presents a proof of concept study into a computational strategy for reusing structural stadium elements. The strategy goal is overcoming the reuse design strain through implementation of a genetic algorithm. This algorithm is calibrated to search for a structural frame configuration, while using a reusable element set, meeting floor space requirements and following the building mass shape. The most important benefit of the algorithm implementation is its method of scouting the solution space. It accelerates the design process and presents the results in a transparent manner. These strategy aspects reduce the complications of reuse design and support the goal of encouraging the application of reuse design in practice. This will lead to a more sustainable construction industry.
The algorithm has been applied on the Al Wakrah stadium for the 2022 FIFA World Cup. In this project the developer aims to deconstruct the second ring after the tournament. The presented strategy resulted in four unique structural frames, which use 100% of the reusable structural elements, while deviating 1% from the required floor space and 3% from the given building mass.

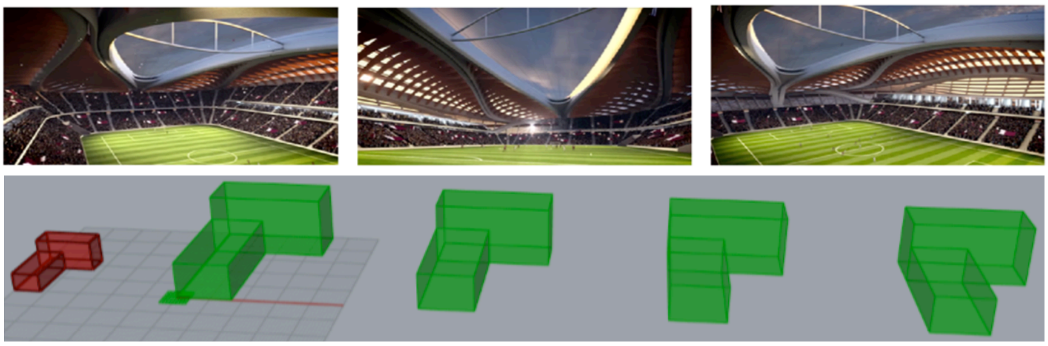

Figure 1: Reusing the stadium elements of the second ring (top), to create 4 schools (bottom).

Keywords: Stadium Reuse, Structural Elements, Computational Design, Genetic Algorithm, Frame Configuration, Reuse Design, 3D Visualisation, Sustainable Design and Lifetime Utilisation.

1. Introduction

In the stadium industry, big sporting events can require new venues that are not fitting the demand for the structure's total technical lifetime. This leads to underuse or vacancy of the property. However, to be economically feasible these venues require other revenue streams than just the initial event [1].
Multiple solution strategies are available to overcome this (Figure 1). The 'Neglect' option is undesirable, since it does not generate the required income streams. The 'Solve' option generates new revenues, but due to the absence of suitable events, this option is not always available. The third option, 'Transport', holds a demand risk: do future events require this transportable venue? Therefore, this paper looks into the 'Reuse' strategy, allowing elements to be reused in different configurations.

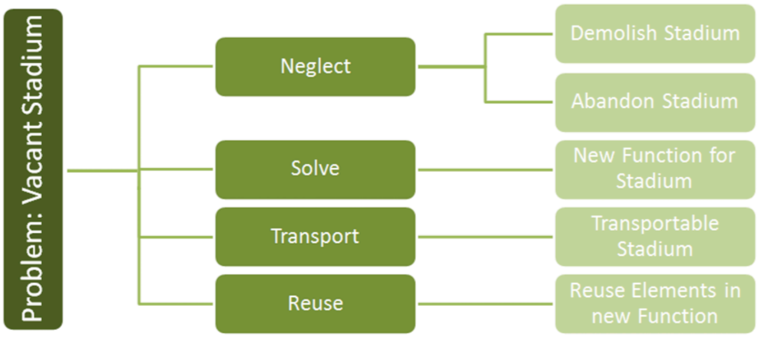

Figure 2: Possible outcomes for stadiums after events [2].

2. Stadium Reuse

The 'Reuse' strategy proposed in the introduction has not been successfully applied in practice yet. To create the computational reuse strategy the input side of the application will be defined first.

2.1 Reusable Elements

The theories of 'Slim Bouwen' and 'Open Bouwen' (Dutch for: 'Smart Construction' and 'Open Construction'), present respectively a hierarchic lifespan based division in element levels and sequential installation process (*Figure 3*). By reducing the inter-connectivity between the levels, accessibility for change during the building lifetime is created. [3]

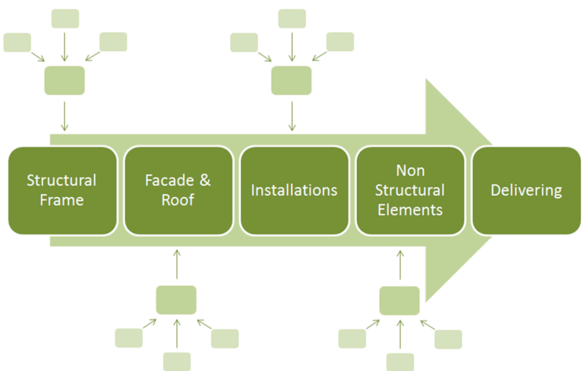

Figure 3: The sequential building process of the 'Slim Bouwen' method.

Due to the amount of expected change in requirements and differences in life expectancies, the decision is made to create a reuse strategy aimed on reusing the structural elements. Due to their generic character, the elements suitable for reuse are columns, beams and floor plates. On average, these elements account for 90% of the structural mass, creating a big impact on the environmental footprint of the building [4]. Combined with the positive economic feasibility study, this indicates the relevance of forming a reuse strategy for structural elements [1]

2.2 Reuse Design Strain

The design process changes when reusable elements are implemented. The reusable elements reduce the design freedom and flexibility, while increasing the amount of design constraints by the wish to apply the reusable set. The reusable element set also causes a difference in detailing level between different design aspects. The reduced flexibility of the structural elements forces other design aspects to be shaped towards it, causing a strain on the design process (*Figure 4*). This increased design difficulty is one of the bottlenecks identified for implementing IFD in practice [5].

Figure 4: Influence of design aspects on eachother, non-reuse design left and reuse design right.

Looking at the detailing level of the reuse elements the quantities, geometrics and material properties are known. This means the remaining design freedom is the frame configuration. Consequently the remaining design problem is finding the structural configuration that follows the architectural shape, while meeting the floor space requirements and reuses as many elements possible.

2.3 Genetic Algorithm

Computational design tools developed for the conceptual design stage can aid the engineer in exploring the design space [6]. In this case providing a solution direction for the strained design process. In essence the strain is caused because the reuse design space has fewer satisfactory results due to the extra constraints caused by the reusable set. Therefore, the computational tool will take over parts of the design process, looking for these solutions in an efficient manner.

Based on the characteristics of the problem the choice is made to implement a customised 'Genetic Algorithm' (GA) [7]. The GA is a search method that shows similarities with the design process of structures. Both strive to find the best-fit solution among an enormous number of possibilities. Doing so by evolving the most feasible concepts into new ones and combining their strong points. The difference between the two is that the designer makes these decisions based on deduction and experience, while the algorithm does this based on random variation. However, due to the similarities between GA's and the design process, GA's are thought to be a suitable algorithm type for designing with reusable elements.

3. Application Design

From the viewpoint of flexibility the application is implemented in the 'Conceptual Design' stage. During this phase the available data consists of the list of requirements (LoR), the available set of reusable elements and a building mass study. The application goal will be to create a structural frame from reused elements in the given mass study, while respecting the required floor space following from the LoR (*Figure 5*). This section describes the creation of the algorithm based on figures where the steps are guided by the footnotes.

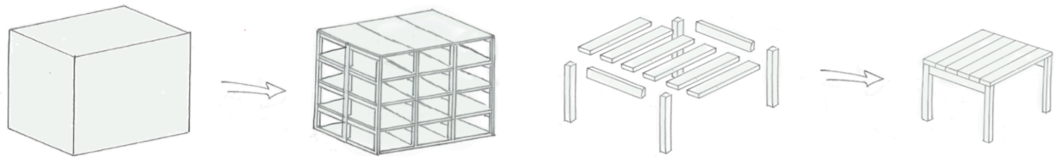

Figure 5: The application seeks the frame configuration fitting the building mass, by compiling subsets of elements. These subsets consist of floorplates, beams and columns (figure on the right).

3.1 Degrees of Freedom

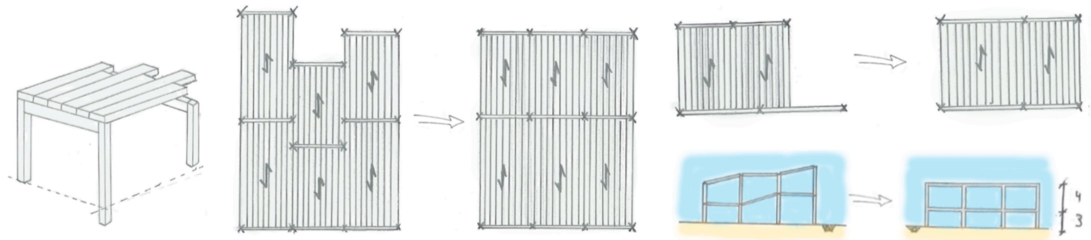

Figure 6: To create usable subsets, element per type inside a subset are the same. The algorithm can also only assign 1 type of floorplate per building ‘row’ and 1 type of beam per building ‘column', furthermore the columns per floor have the same dimensions.

3.2 Chromosome Buildup

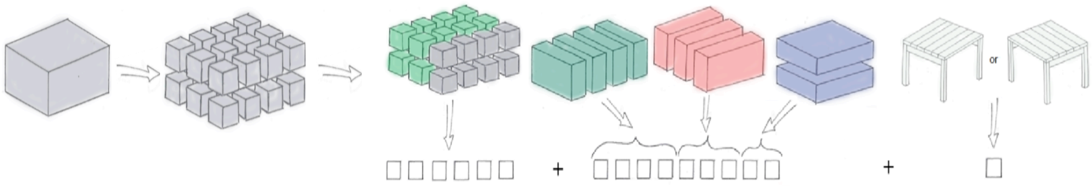

Figure 7: The application divides the building mass in blocks. The chromosome variables are defined by: which subsets are constructed, which element types are assigned to each block and the orientation of the blocks.

3.3 Fitness Function

With the algorithm chromosome completed, the optimisation process can start. To optimise towards the fittest solution in the search space, a fitness function was designed that scores each chromosome:

$$F = \sum_{n=1}^{B} |A_{sn} - A_r| * w_a + \sum_{i=1}^{ES} |E_{ui} - E_{ai}| * w_c + \sum_{j=1}^{S} |V_{cj} - V_{bj}| * w_s \qquad (1)$$

$F =$ Fitness Score
$B =$ Number of Buildings
$A_{sn} =$ Area supplied in Building n
$A_r =$ Area required
$W_a =$ Weight Factor Area

$ES =$ Element Set
$E_{ui} =$ Elements used from Set i
$E_{ai} =$ Elements available in Set i
$W_e =$ Weight Factor Elements

$S =$ Number of building boxes
$V_{cj} =$ Volume created at building box j
$V_{bj} =$ Volume supplied building mass for building box j
$W_s =$ Weight Factor Shape

During execution, the algorithm returns the scores of the fittest solution and average score of the generation. The algorithm awards points for errors, therefor the lower the blue line in *Figure 8*, the fitter the solution.

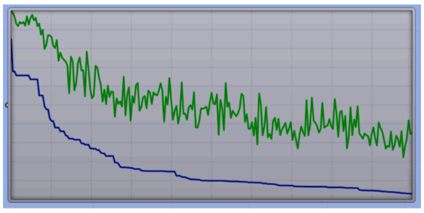

Figure 8: Algorithm scores.

4. Al Wakrah Test Case

4.1 Reusable Elements

The second stadium ring consists of 5312 elements, from which the elements types shown in *Figure 9* are reusable. There are 5084 reusable elements (95,7% of total amount). The elements that are not reusable are specialised elements (raking beams & ramps) and stabilising elements (concrete walls).

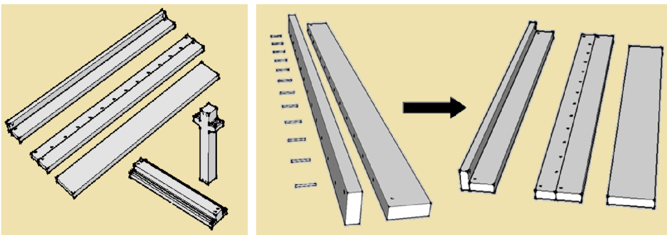

Figure 9: Reusable stadium elements

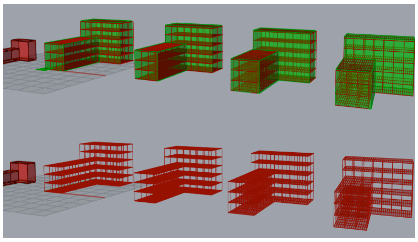

Figure 10: Structural frames

4.2 Algorithm Results

The algorithmic strategy resulted in four unique structural frames (*Figure 10*), together using 100% of the available set, while deviating 1% from the required floor space and 3% from the building mass shape. With the output being a structural frame, accompanied by the reuse percentages, floor space per building and reuse coordinates of each element, the design is not yet completed. The next design step is defining the (global) stability mechanisms and non-structural elements, like interior walls and the facade.

Next Steps

The reuse algorithm does not provide a solution that can be constructed directly. Calculations on structural safety and design decisions on stability system, installations, facade and non-structural elements still need to be done. The application setup does allow the addition of more design intelligence rules, possibly allowing these steps to be implemented in the algorithm in the future.

Discussion & Conclusions

The flexible design strategies used as foundation for the application divide the design process in clear phases. However, in practice interaction exists between the proposed levels, for instance the influence of vertical transportation on the structural frame. This interaction is not taken into account in the application, potentially reducing the usability of the application results.

Also, due to the characteristics of a 'Genetic Algorithm' it cannot not be said with 100% certainty that the fittest solution is found, however this same statement can also be made for non-reuse design.

Based on changing user requirements and lifetime utilisation the application focused on reuse of structural elements. For design flexibility reasons the application is implemented in the preliminary design phase. Because the element set is defined, the goal of the application is to find the structural configuration, which it finds using the subset method described in the application design.

Acknowledgements

This paper is one of the results of a Master's Thesis at the BEMNext Lab at Delft University of Technology, created in collaboration with White Lioness technologies and the Royal BAM Group [8]. The authors would like to acknowledge these organisations for their contributions to the research.

References

[1] Klomp MC. *Preliminary structural design and financial feasibility study of a transportable multifunctional stadium.* Master's Thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences, 2013.

[2] Loosjes M. *Preliminary structural design of a demountable stadium.* Master's Thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences, 2011

[3] Lichtenberg J. *Slim Bouwen*. Boxtel, 2005

[4] Naber N.R. *Reuse of Hollow Core Slabs.* Master's Thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences, 2012

[5] Roders M.J. *'IFD Building in Japan, America and Europe', IFD construction – Congress proceedings.* ISARC 2003 Congress. Technical University Eindhoven

[6] Van den Weerd B., Rolvink A. & Coenders J.L. *Structural Components – A Software system for Conceptual Structural Design.* IASS-APCS 2012. Seoul

[7] Mitchell M. *An Introduction into Genetic Algorithms.* Cambridge (Massachusetts), MIT Press 1999

[8] Van der Steen J.D. *Computational Reus Design.* Master's Thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences, 2014