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Computational Design for Sport Buildings

M.Turrin[a,b] * D.Yang [a,b], A.D'Aquilio[b], R.Sileryte[b], Y.Sun[a]

[a]State Key Lab of Subtropical Building Science, South China University of Technology, Guangzhou, China

[b]Delft University of Technology, Julianalaan 134, 2628 BL Delft, NL

Abstract

The design of sport buildings has great impact on top-sport as well as on recreational sport-activities. It implies challenging tasks in meeting the performance-requirements. This includes the control of factors like daylight/lighting, air flow, thermal conditions, just to name a few. Such factors impact the performance of athletes and are hard to control in large sport halls; their control is even harder when the public/audience is located within the halls and require different climate conditions. While mechanical installations are often needed during competitions in order to guarantee constant conditions, relaying on mechanical installations during the daily and recreational use of the venues challenges their medium/long term sustainability. Computational form finding approaches can favour the achievement of high-performing and sustainable sport buildings. In this light, the paper tackles the use of Multi-objective and Multidisciplinary design optimization. The paper presents the concept of Multi-objective Multidisciplinary design optimization techniques to support trade-off decisions between multiple conflicting design objectives and interdisciplinary design methodology, during the conceptual design of sport buildings. The proposed method is based on parametric modelling, performance simulation tools and algorithms for computational optimization, for which the paper tackles three specific aspects. First of all, due to the complexity of large sport buildings, the formulation of the optimization and the screening of the related design variables is crucial in order to obtain a meaningful design space, which helps reducing unnecessary computational burden. Secondly, assessing performance based on measurements and analyses is crucial and can be supported by performance simulations tools; however effectively integrating performance simulations tools in the early phase of the design requires new tools. In this light, a customized computational process for the rapid assessment of temperature and airflow patterns is presented. Thirdly, the process requires the combination of design optimization and design exploration, while searching for well-performing solutions. The importance of design exploration is emphasized also for sub-optimal solutions. In order to facilitate the design exploration, the combination of optimization algorithms, multi-variate analysis algorithms and options for exploring design solutions via an interactive dashboard connected to a database are presented. To exemplify the method, specific case studies are developed as collaboration between Delft university of Technology and South China university of Technology.

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*Keywords:*sport buildings;design optimization; parametric design; multidisciplinary design.

1. Introduction

The design of sport buildings has great impact on top-sport as well as on recreational sport-activities. The performances and records of top-athletes do not entirely depend only on the athletes and on the equipment, but for many sports also the sport venue is relevant. Top sports require venues designed for top performances, in case of both competitions and training. This often entails the control of indoor climate based on many factors, such as control of light, air flow, thermal conditions, just to name a few. In most cases, such control is achieved through mechanical installations. While the use of mechanical installations might be needed during competitions in order to guarantee constant conditions, relaying on mechanical installations during the daily and recreational use of the venues leads to unsustainable situations. The building sector is giving increasing attention to the design of sport venues allowing low in-use energy. The importance of this aspect is highlighted in recent practice as well as previous research. High relevance is given to low-energy consumption for example in the recent design of the Velodrome for London 2012 [1], among others. Shui and Li [2] highlight a potential for energy savings in large public buildings in China, such as sports

* Corresponding author. Tel.: +31-015-2787351
E-mail address: M.Turrin@tudelft.nl

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buildings. Field measurements and simulations reported the occurrence of high energy consumption on typical indoor sports buildings in different climate zones across China [3, 4, 5] and specifically regarding heating, cooling and lighting [6, 7].

Focusing on daily (recreational) use and low level events (e.g. amateur competitions and training), the ultimate goal of this research is to facilitate the design of sport buildings able to achieve proper indoor climate conditions as much as possible passively. With respect to the topics introduced above, this research claims the relevance of applying Multi-Objective and Multi-Disciplinary Optimization (M-MDO) during the early phase of the architectural design process for sport buildings. Specifically, Multi-Objective Optimization helps making better trade-off decisions between conflicting performance requirements, as it supports identifying a representative set of Pareto optimal solutions and quantifying the trade-offs in achieving different objectives during the design decision making process [8]. Among the precedents, relevant examples can be found in [9, 10]. Multi-Disciplinary Optimization takes simultaneous consideration of multiple disciplines instead of optimizing each discipline sequentially. It allows for decomposing complex systems into smaller subsystems (solved separately) and for coordinating the subsystem solutions between different disciplines, towards an optimal system design [8]. Among the precedents, relevant examples can be found in [11]. Nevertheless, the application of M-MDO to the design of sport buildings implies challenges, some of which are addressed in the research presented in this paper.

This research is on-going as a collaboration between Delft University of Technology and South China University of Technology. This paper presents the work developed by a research team in Delft, with applications on a design provided by Yimin Sun Studio (SCUT). The second section of this paper presents the case study and the overall approach, which is based on parametric models of the designs; simulations tools for performance evaluation in early design phases; and optimization for design explorations. These three aspects are individually tackled in the third, fourth and fifth section of the paper, respectively.

2. Integrating parametric models of sport buildings with performance simulations and an optimization platform

The proposed method is based on three looped components: parametric modelling, performance simulation and algorithms for computational optimization. Parametric modeling allows representing geometric entities having editable attributes, and relationships by means of associations. Attributes can be expressed by independent values, which act as input to the model. These are design variables; their eventual variations generate different solutions of the model. Associations allow for processing the data across the related geometric entities; thus the different solutions of the model are generated while respecting the consistency of pre-established relations among geometric entities. Thanks to these and other abilities, parametric modelling is applied to integrate engineering aspects during the architectural design process, especially when dealing with complex geometries; and is used to support design explorations of different alternatives [12, 13]. For each design solution parametrically generated, performance indicators can be measured and analyzed by using building performance simulation tools. Connecting the performance simulation tools to the parametric modeler may allow automate the process. Finally, in order to identify the well-performing solutions within large set of possible parametric solutions, optimization algorithms can guide the geometry generation (and related performance analysis) toward the convergence to optimal solutions. In all three components, this process showed major potentials; but each component implies also challenges. Three challenges are introduced here following.

First of all, in order to be effective, parametric modelling requires the identification of the meaningful design variables to be included in the parametric model, according to the formulation of the optimization problem. Due to the complexity (in terms of both geometry and multidisciplinarity) of large buildings such as stadia, sport-halls, buildings for indoor swimming pools, velodromes, etc., this task is not simple. The support of this task is discussed in section 3. Secondly, for each design solution parametrically generated, the performance indicators can be quantified in performance simulation tools. However most of currently available simulation tools are not meant for quickly assessing early design alternatives and imply computationally expensive processes. As a consequence, applying performance simulations on many design alternatives of large buildings such as sport buildings is often impractical with current simulation tools. This aspect is tackled in section 4, which presents an example of a simplified simulation tool to allow quick evaluation of indoor air-flows. Thirdly, the geometry generation and performance analysis of a large number of parametric alternatives produces design alternatives and related performance data that has high value to make informed design decisions. However, understanding the design implications by simply looking at the numeric results of the optimizations is challenging due to the complexity of data. Moreover it is unnatural for architects, who need to consider also the architectural qualities of the spaces. This aspect is tackled in section 5, which presents the combination of optimization and multi-variate analysis algorithms; and options for exploring the design solutions via an interactive dashboard connected to a database in which the design alternatives are stored.

In the team work, Ding Yang focused his contribution on the formulation of the design optimization problem and related design variables; Antonio D'Aquilio on the quick evaluation of indoor air-flows; Rusne Sileryte on the combination of optimization and multi-variate analysis algorithms and on the development of a dashboard for interactive design exploration. The work presented in sections 3, 4 and 5 is demonstrated on a case study. The case study is a building project currently under detailed development designed by Sun Yimin Studio of the Architectural Design & Research Institute of South China University of Technology. The building is a large swimming hall, that will be used for sport events of national level. It is part of a larger intervention, the Jiangmen Sports Center located in Jiangmen, China. The intervention consists of various sport facilities, including also a stadium and a gymnasium. It is designed to be suitable for fifteenth games of Guangdong province in 2018 and for international competitions, big events and public comprehensive activities. The standard swimming pool has a clear height of diving platform area higher than 16 m; has a 50x25 m (to meet the requirements for swimming, synchronized swimming, water polo match); the training swimming pool is 50x25 m, with the depth of 1.5-2.0 m; the seats are 2000, with the total construction area of about 25000 square meters.

For this research, the parametric modelling is performed in Grasshopper, a plug-in for Rhinoceros (Mc-Neel). Once the parametric design alternatives are generated in Grasshopper, performance simulations can be run. The performance simulations are performed in a variety of tools connected to Grasshopper, such as CONTAM and as Ladybug and Honeybee, plug-in for Grasshopper, using Radiance and Daysim. In order to explore large set of design alternatives, optimization algorithms and multi-variate analysis are applied, for which modeFRONTIER (ESTECO) is used in connection to Grasshopper.

3. Design optimization formulation and variable screening

This section focuses on the set up of the parametric models to include appropriate design variables. Specifically, it focuses on the formulation of the design optimization problem and related identification of the meaningful variables. Especially when dealing with the geometric and multidisciplinary complexity of the conceptual design of indoor sports buildings, the formulation of the design optimization problem is a very important step before formally solving the problem by using the optimization algorithms. When focusing on parametric modelling of sport buildings, the geometric complexity relates to the large scale and often complex shapes of the buildings. It is also determined by the number of design variables and their ranges, embodied in the parametric model. The multidisciplinary complexity is mainly related to different performance criteria or design requirements from various disciplines. These requirements and criteria can be expressed as optimization objectives or constrains in multi-objective optimization problems. Considering these complexities, variable screening techniques are necessary to refine the design space before running the optimization, and thus make the optimization more efficient and feasible within the limited time-frame of real projects. Variable screening here refers to the identification of the design variables that have the higher impacts on the selected performance criteria; of their meaningful or sensitive ranges.

In the case of the Jiangmen swimming hall, the design variables initially selected include those related to the building shape, to the position of skylights, and to the thermal properties of construction materials. This selection was based on "educated guess" and led to a huge design space. Searching for optimal solutions in such a huge design space is practically difficult, due to the limited time-frame and computational resources. The optimization is even more challenging in case of multidisciplinary multi-objectives, such as regarding energy use, thermal comfort, daylighting condition, and energy production. Other than solely focusing on the "narrow/convergent" design optimization as many existing methods, the "broad/divergent" design exploration of the entire design space can be highlighted as crucial. In the Jiangmen case, sensitive analysis is being used to quantify the relative importance of design variables on each performance criterion; and new knowledge regarding the input-output relationship is expected to be extracted via the systematic design exploration. Based on current work, the knowledge-extraction may help to sufficiently understand the overall behavior of the system at hand, thus reformulate the design space in a more informed/meaningful manner, saving the computational effort.

4. Rapid assessment of temperature and airflow patterns

Once the parametric model is set, the connected performance simulations can run. Focusing on simulations for performance assessment in the early design phases, this sections tackles the need of quick assessments. This general need is exemplified by focusing on the case of natural ventilation. Performance assessments can support the early design decision making to improve thermal comfort by applying passive cooling through natural ventilation in large indoor sport halls. However, current computational means for performance analysis have limitations. Detailed assessment of natural ventilation (such as CFD analysis) can give detailed information on the airflow and temperature patterns in large indoor spaces, but require long computational time to achieve convergence, and is therefore unsuitable in the early design phase. Faster calculation methods such as Airflow Network (in software like CONTAM) often lack thermal analysis. On the other hand, energy simulation software mostly assumes constant infiltration rates, which do not reflect known dependencies on indoor-outdoor conditions and ventilation system operation [14, 15].

To allow the rapid assessment of temperature and airflow patterns, this work proposes a series of customized Grasshopper components to evaluate a given model using CONTAM and EnergyPlus software as simulation engine. This allows to run design optimizations taking into account outputs for both air temperature and airflow rates for determining the passive control of indoor comfort and the related energy saving potential. The validation was performed in order to establish the reliability of the proposed method in steering early design choices towards better performance. Two levels of validation were used, both using the DesignBuilder (DB) software as comparison calculation model, for its accurate energy modeling and reliable CFD simulation[16]. The first level is the overall “behavior” of a design, in terms of thermal and airflow results. This is important to establish reliability in overall trend of dependencies between the building shape and average indoor temperatures under natural ventilation conditions. The second is a detailed level of comparison, where Computational Fluid Dynamics (CFD) simulations from the DB software are compared with snapshots from the developed process. This aimed at assessing the precision at which it is possible to predict differences in temperatures and air velocities within the large indoor volume of a swimming pool. The comparison was based on the building model used as case study as explained in the following section. Results shown a good level of reliability for the early stages of design and shared similar trend to CFD analysis results.

In the case of the Jiangmen swimming hall, the method was applied to investigate the indoor microclimate in which both spectators and athletes would be standing. Jiangmen has a hot and humid climate. The swimming hall is naturally ventilated during the day (from 8 to 20, in the worst summer scenario), through operable windows located on the facades and the operable skylights. In the parametric model, the design variables were the number of operable skylights, the dimensions of operable façade windows and the total effective height of the roof. The stack effect induced by the shape of the roof was the main principle investigated for air displacement to deliver natural ventilation. Two different configurations were tested for a hourly snapshot in June. One has small operable windows (0.5m height) located on the glazed side facades, as in figure 1(a), while the second one has bigger operable windows (2m height) as in 1(b). The building was divided into four zones. Let the zone on the right side be ‘zone 1’ and the one on the opposite side be ‘zone 2’, the zone at the bottom is ‘zone 3’ and the one at the top ‘zone 4’. Zones 1 and 2 are dedicated to spectators, while zone 3 is the athletes area; the top zone 4 is used to better represent the indoor temperature gradient. The results showed that high temperatures characterize all the zones of the first configuration (as shown in Fig. 1a), even though ventilation is introduced thanks to 0.5m height windows running for the whole width of the façade (and exhausted through four roof skylights). The airflow speeds, calculated with an average speed per zone, resulted respectively 0.16, 0.16, 0.06, 0.05 m/s. Further investigations are needed in order to achieve better temperature ranges without affecting the low ventilation rates. The main parameter to be optimized is the ventilation opening area, without changing the construction of the whole building. An educated guess or simple empirical formulas can suffice to estimate airflow rates and temperatures. However, in case of swimming halls, the requirements for specific ranges of indoor air speed are crucial. Parameters such as the airflow speed (which needs to be lower than 0,2 m/s in case of athletes swimming) cannot be neglected. A second design solution was considered, where the side façade had a larger operable area (2m window height). In this case the zone temperatures dropped more than 1°C (Fig. 1b). The outputs for average air speeds resulted: 0.15, 0.14, 0.07, 0.07 m/s. These results evidently showed that the second design option is better than the first one, because without changing the roof shape or envelope construction, a better design (for this specific hourly snapshot) can be achieved. In fact, 1°C can make a difference in terms of thermal comfort, especially at high relative humidity levels. These results were achieved in a faster way than via usual CFD analysis and suggested that this type of simulation method can steer a project towards better solutions early in the design process.

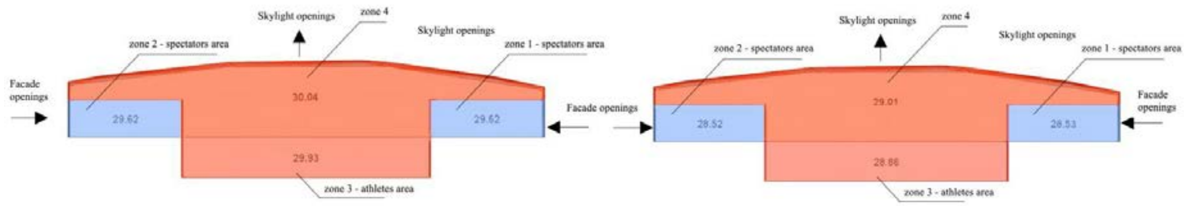

Fig. 1. Analysis on the swimming pool of the Jiangmen Sports Center (a) results for the first design configuration; (b) results for the second design configuration.

5. Multidisciplinary optimization for design exploration

The combination of parametric modelling and rapid assessment tools allows quick generation of a large number of design alternatives and their numeric evaluations. This can be well combined with optimization algorithms for obtaining optimal performance-driven design. While optimization algorithms are one of the widely explored topics used in various engineering disciplines, it is still rarely applied in architectural design. One of the reasons behind this lack of practice is that architectural problems involve not only numerically expressed performance values but also a number of ill-defined criteria, such as aesthetics, constructability, navigability, etc. The automated optimization procedures fail to take advantage of designer’s expertise, while in architectural design an important role should be given to the learning process of a designer, providing him with knowledge on the trade-offs between various disciplines and performance objectives.

In this research, the problem is tackled through engaging multivariate analysis algorithms into the post processing of numerous optimization data. Additionally, portrayal of geometry is introduced as an extension of conventional data analysis and visualization methods, which accounts for the evaluation of ill-defined design criteria by using designer’s expertise. The system for optimization and exploration of design alternatives is computationally efficient and integrated into an environment familiar to architects. It relies on multivariate analysis algorithms together with database querying capabilities and an interactive dashboard developed for geometry portrayal. The multivariate analysis algorithms are provided by the modeFRONTIER software and include Self Organizing Maps (SOM) and Hierarchical Clustering. They are more suitable for capturing interrelated effects within a broad design space compared to conventional data visualization methods, like scatter plots or parallelograms. However, these algorithms can only account for the numerically defined performance values, while the exploration of the design problem requires a portrayal of corresponding geometry. In order to address this problem, the chosen clusters or parts of SOM are visualized in a custom-developed Grasshopper-based dashboard through a series of images, which correspond to the generated design solutions. All functions are embedded as customized Grasshopper components scripted in Python programming language. A PostgreSQL database is used as an intermediary between the two software for the efficient organization and querying functionality, as well as preserving a backup of collected data. The possibility to re-explore previous definitions, as well as combinations of multiple design spaces or their parts, is also enabled by employing the database. An example of the developed dashboard can be seen in Fig. 2.

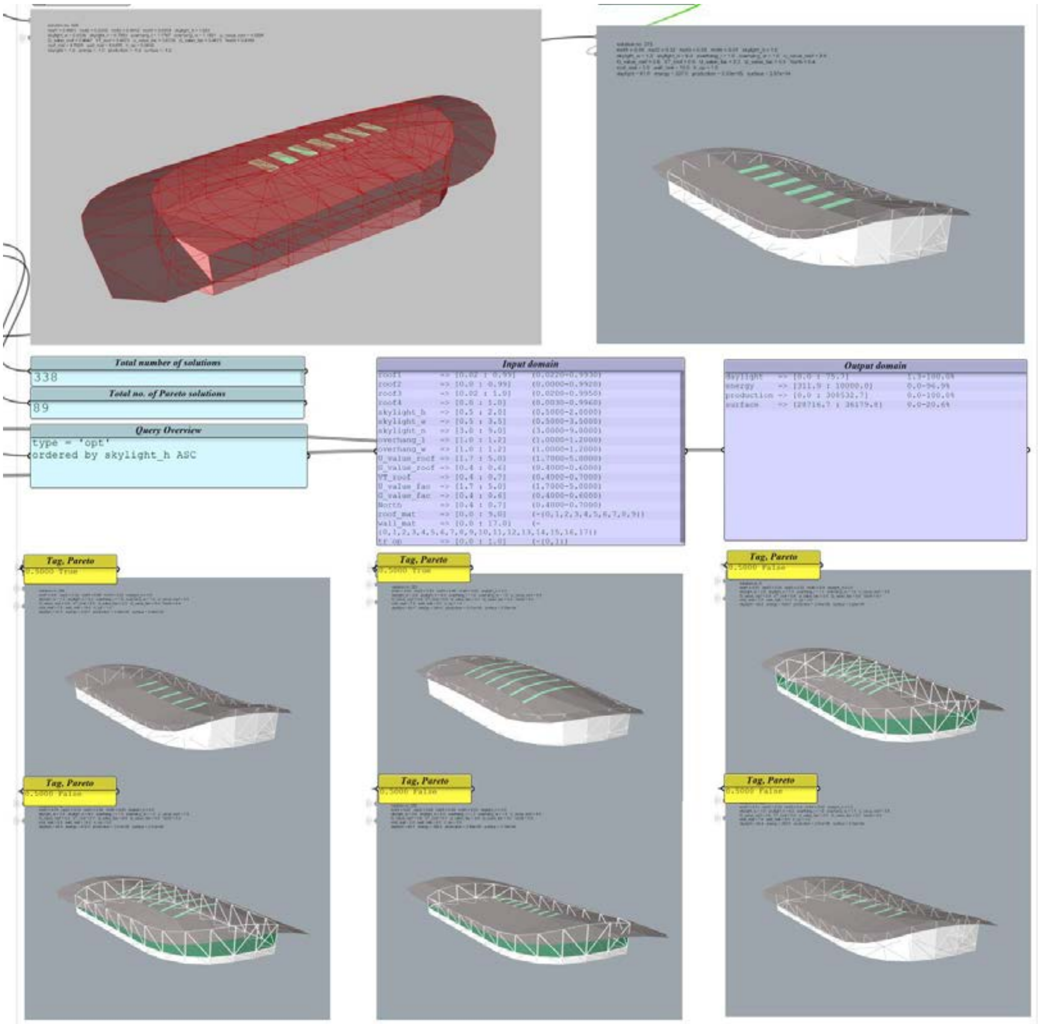

Fig. 2. Design options for the swimming pool of the Jiangmen Sports Center explored via the developed dashboard.

The process was tested by using the swimming pool of the Jiangmen Sports Center. The input parameter space is composed of 18 variables, including such geometrical parameters as roof curvature and dimensions, skylight number and dimensions, construction material properties, building rotation and presence of glazing. Four performance values have been set as objectives: maximizing of average useful daylight illuminance value, minimizing of the energy need (kWh/m2) in terms of cooling and heating, maximizing of energy production using photovoltaics and minimizing the construction costs of a large span roof. An ill-defined criterion is set for building aesthetics, which is decided using the expertise of a designer.

After exploring the results of multivariate analysis combined with the geometry visualization on the dashboard, a number of conclusions were drawn about the relationships between the parameters and performance values. A couple of exemplar insights are mentioned hereafter. While browsing through the clusters based on specified input variables, it was noted that a combination of small skylights, no facade glazing and non-expressive roof results in poor aesthetical performance. The same was noted about clusters, which have bigger skylights, however, display a box-like appeal not compliant with the initial concept of the building. By looking at the performance domains of these clusters, it was obvious that they are not falling into the range of the highest performance values either. Therefore, such sets could be safely discarded. Clusters based on output variables suggested that the most desired behavior can be found among the designs with expressive roof curvature that is also preferred by the architect. It was noticed that only certain types of wall and roof materials fall within these clusters, however, since they are mostly not influencing building aesthetics, they can be chosen purely based on numerically expressed performance values. SOM analysis also suggested that a combination of small skylights and glazed facade, as well as big skylights concentrated close to each other, results into poor performance and should be avoided. Finally, a number of dependencies, that have been noticed to exist between the design parameters and its objectives, exceed the specificities of one particular project and add up to the expertise of a designer who is using the system.

6. Conclusions

The paper presented a computational method based on parametric modelling, performance simulation tools and algorithms for optimization and design exploration of sport buildings during the early phase of design. It tackled three aspects specifically. The formulation of the optimization problem together with the screening of the related design variables was tackled especially in relation to the complexity of sport buildings. The need of customized performance simulation tools was tackled to cope with the specificities of sport buildings in the early design phase; and a simplified simulation tool to allow quick evaluation of indoor air-flows was presented. The need of supporting the design by integrating the search for well-performing solutions via numeric assessments as well as design preferences was addressed; and the combination of optimization algorithms, multi-variate analysis algorithms and an interactive dashboard connected to a database was presented. Each aspect was also discussed in relation to a case study from an on-going project in Chinese design practice. The overall work is part of an on-going research and its current state resulted promising. The present main challenges concern the computational burden. Future work is on-going both regarding additional testing of the method on more complete casa studies from practice; and regarding the integration of further computational methods (such as response surface methods) to cope with the high amount of computation currently needed to perform the process.

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