Parametric Design and Structural Optimisation for Early Design Exploration
Dominik Holzer, Richard Hough and Mark Burry
The investigation presented in this paper focuses on the following questions: How can engineering and architectural expertise, assisted by a process of digital optimisation, promote structural awareness regarding design alterations in the conceptual design stages? Can building geometry be set up computationally to render it sensitive to structural input? Which software tools are required to foster this interaction and what kind of decision support is needed to allow both architects and structural engineers to interact concurrently in this optimisation process? The authors of this paper form a team of researchers and practitioners from architectural and structural engineering background who combine their efforts to address the issue of interconnecting design intelligence across disciplines and advancing revised work methodologies in practice assisted by academic research. The research has shown that an integrated transfer of design information between architectural and structural designers in the early stages is beneficial to the collaboration if experts from both professions agree on common goals and define suitability rules that guide optimisation processes from the very beginning. To enable this, software tools are required that provide ad hoc decision support to create a wider array of informed design alternatives from which to choose.
I. INTRODUCTION: SOFTWARE TOOLS FOR ARCHITECTS AND ENGINEERS

“Removing engineering and engineers from the design process has gradually separated architecture from the general technological knowledge of culture.” [1]

In recent years architects have adopted digital software tools for generating design in an unprecedented manner, but they seem to have stopped short of exploring the effects of the novel design possibilities offered by the digital beyond the boundaries of their own profession. The bigger picture, which is seldom addressed, is the interconnection of architectural design with building-performance related issues and the associated sharing of design intelligence across the AEC industry (architecture, engineering and construction).

Similar to architecture, digital software tools have revolutionised the work methodology structural engineers are applying in everyday practice. In this context, Coenders and Wagemans [2] argue that software tools for structural design and structural analysis/optimisation should be seen as separate entities. The way they are being applied in practice, in particular for complex design processes, displays different characteristics. Whilst software tools for structural analysis and optimisation are aiming at deriving precise data in a convergent process, computational structural design tools are used in a more divergent process where precise answers are not required as much as indicators about the effect of changes. Maintaining sufficient space to manoeuvre and to accommodate changes in an informed manner is highly relevant to allow creative processes to unfold in the early design stages. Traditional engineering methods would see the structural optimisation occur after the structural design is finalised; in this sense the divergent and convergent processes occur as consecutive steps. Due to increased automation capabilities assisted by computational means and the speed with which results can be generated, structural engineers can now inform their design process through optimisation results that can be generated in parallel with structural design. The software tools that enable the engineers to do this take over parts of activities such as calculus and code-checking (which are by nature of convergent character) whilst providing the kind of feedback needed for divergent design exploration in the conceptual design phase.

How can architects profit from the newly-found possibilities offered to their design partners? Software tools used by architects for design and drafting are often limited to geometry generation whilst the structural engineers’ analysis and optimisation software is dedicated to specific structural tasks. In both cases, these tools have little to no intrinsic capability for interfacing design intelligence across disciplines. [3, 4]. In a recent report on integrated practice, the American Institute of Architects (AIA) identifies that the feedback from specialists to the designers in the AEC industry occurs only at “discrete points with varying frequency” [5] which causes
Delays and discontinuities in the workflow and consequently is responsible for coordination errors and the necessity for rework. Seen in a historical context, the progressive specialisation within their individual domains has led to a growing gap in the understanding between architects and structural engineers [6]. Although working on common projects, architects and structural engineers are inherently concerned with different theories and objectives, using different measures and tools to reach their goal [6].

This paper tests novel ways of linking architectural design more closely to structural optimisation by streamlining the connection between geometry generation, structural analysis and optimisation through the use of parametric design and custom-developed scripts. The interface is established through an informed manipulation of building geometry at a stage where the level of design progress allows for versioning and the inclusion of alterations without requiring a complete redraw. The tests are undertaken in order to better understand the mechanisms in data transfer as well as design communication between architectural and engineering design to inform new design strategies for future projects.

2. ADDRESSING COLLABORATION CHALLENGES

The research presented here has been carried out in a collaborative effort as part of an Australian Federal Government funded research project (Delivering Digital Architecture in Australia – DDAA) which is led by researchers from the Spatial Information Architecture Laboratory (SIAL) at RMIT University in Melbourne, as well as members from Arup in Sydney and Melbourne. SIAL has embedded researchers from an architectural and computer science background at Arup who collaborate with their structural engineers, drafters and IT experts, who themselves often have a proven track record of working on innovative projects in the building sector at a global level. The reason the project is called ‘Embedded Practice’ is that there is a switch from the conventional focus on the research being undertaken within the university at a distance from the end user. Rather, both the research site and the postgraduate researcher is embedded within the practice itself. The project differs from a ‘professional doctorate’ in that the postgraduate (in this case the lead author of this paper) is not an employee of the company in which he or she is embedded.

This collaboration has been conceived as a means of consolidating and extending both the company’s (Arup’s) knowledge base and the expertise of members from the university community (SIAL) on early digitally mediated design projects, where structural and façade engineering input requires significant ad hoc feedback from design optimisation. Prior to the specific collaboration mentioned in this paper, the partners have engaged in common research and they have worked on live projects where synergies could be found in the collaboration between practitioners and academic researchers, supported by computational means. The most challenging
recent example of this was the ‘Watercube’ project (National Aquatics Centre, Beijing), where the structural complexity and the short time available for design and documentation both required automation of some design and documentation processes. A substantial effort had also been applied at Arup in the development of an analysis and optimisation software for a complex stadium roof in the Ukraine linking parametric design to structural optimisation. The experiences referred to above have served to underline the need for a more generalised software tool to serve as interface between geometry and structural performance in an iterative design process, with a robust but flexible schema for bi-directional transport of data between proprietary packages.

There were several other aspects of the drive toward more automation that were of interest to Arup as industry partner in developing the DDAA brief with SIAL. One aspect arose from experiences on gridshell and space-frame structures where the complexity of information on the computer monitor, either as CAD or analysis output, impeded rather than assisted the structural design dialogue between various members of the design team. DDAA therefore includes a module for studying cross-discipline communication methods, including the prospect of increased use of physical models to highlight structural actions.

Two goals were defined by the collaborative team: the first was to provide designers with close-to-real-time structural feedback in the design process for decision support. The second was to integrate engineering intelligence in the morphological generation of geometry in a concurrent, transdisciplinary fashion rather than using it to facilitate the construction of a pre-given idea. This was done by investigating heuristic strategies for both professions to examine the interconnectiveness of their design methods and the exchange of data in a concurrent design process. The authors combine the use of ready-made applications for parametric design and engineering analysis with a custom-developed optimisation and code-checking software to foster the collaborative process. By doing so, challenges and potentials to the modus operandi of architects and engineers arise and current models of interaction between the two professions are scrutinised. Prior to engaging in project work, the authors have undertaken an in-depth literature review of the effect of computational sponsorship of the architectural and structural design process with a particular focus on parametrically defined geometry models. In addition to this, the authors are well advanced in the use of parametric software tools, which they have successfully applied on several projects in research and practice.

3. BACKGROUND RESEARCH

By investigating components of design problems, Lawson asserts: “since design problems defy comprehensive description and offer an inexhaustible number of solutions the design process cannot have a finite identifiable
Designing cannot be understood as a linear activity for problem solving, but as a solution-orientated process where expert input is required for identifying and evaluating complex design issues. Lawson argues that in the conceptual design process, designers must be capable of keeping many things in mind at the same time for rapid decision making [8]. When bringing this notion of a rather non-deterministic design methodology into perspective with common design software for geometry generation and structural optimisation the question arises if the tools available to us are appropriate for this endeavor.

Over the past 20 years advances have been made in both academic research and practice, to develop and advance design software for connecting implicit geometrical relations through declared parameters [9]. Design through declared parameters lends itself as a method which allows designers to structure their models to include variables for geometrical definition and behaviour. In a parametrically defined model, relations between individual design components can be defined and their variables can be altered through a set of rules and constraints which permit intuitive manipulation without losing control over design principles. The designer’s grip on the production process can be fostered through this as well as through data-output from parametric software tools which directly link to manufacturing facilities. The definition of 3D computer geometry as flexible design templates for the creation of alternative design solutions through parametric design is an effective method for opening up a dynamic information flow between various members of an architectural project from the conceptual phase to production [10, 11].

Simple parametric capabilities have been built in design and drafting software such as Archicad™, Revit™ and Vectorworks™, while more advanced parametric applications such as CATIA™/Digital Project™ and Generative Components™ have found their way into leading architectural schools and practices for solving design problems of high complexity. They are used to assist form-finding as well as drafting, manufacturing and even project management processes. Glymph et al., who are counted among some of the pioneers in the use of parametric software on building projects with Gehry Technologies, describe an approach to organising design where designers structure their drawings through behaviour-implicit information, therefore incorporating a design intention rather than a fixed shape [12]. When using design through declared parameters, rules, goals and constraints get defined, assisting a process which enables the designer to generate a variety of design solutions [12]. Designing with the use of parametric values defines a way of structuring geometrical entities through associative variables, relations and dependencies. A design for something, however, is not the outcome but the means to its end. “An object that has been designed reflects deliberate decision-making, not a serendipitous occurrence” [10]. Burry, who is applying parametric design strategies at Gaudí’s Sagrada Familia Church in Barcelona, writes that through the use of
parametric methods architectural design can be kept in a fluid state, allowing for intuitive alterations. It can be kept in balance through a set of rules and constraints which allow for incorporating references from any internal or external source of data. Multiple solutions can be analysed and selected according to the preference of those involved in the design process.

In recent years, a number of designers and design researchers have investigated the possibility of linking parametric design with engineering analysis and optimisation processes to allow for a concurrent work methodology across disciplines. The work on the ‘parametric bridge’ [13] illustrates how a predefined set of geometrical constraints can be the driver for parametric alterations for iterative shape optimisation. In the bridge project, results from the built-in structural analysis package of the parametric software were compared with the analysis software used by the engineers working on the project. Target values were used to drive the shape-optimisation of the bridge through a dedicated interface (Product Engineering Optimiser™).

Optimisation software can address a variety of tasks depending on specific project requirements and the design’s overall progress. As described in Structural Systems Optimisation Techniques for the Building Industry [14], a distinction is required for several structural optimisation tasks between size (member sizes & cross sections), shape (geometry & size of a fixed topology), topology (for a structural system layout) and functional layout optimisation. In this context, the application of the stochastic shape optimisation software EifForm™ with the parametric software Custom Objects™ has shown that, by combining the two, a rich array of solutions can be generated. [15] The upgrade of the role of the computer from being a design assistant to being a design collaborator is possible through a tight link between associative geometry, structural performance evaluation and structural optimisation.

4. RESEARCH METHODOLOGY

A live project has been selected to allow the authors with direct exposure to an actual design problem with a high level of complexity. The project (a stadium roof structure; Cox Group as architects, Arup as structural engineers) was in an advanced stage of schematic design at the commencement of the authors’ involvement, principally the lead author who, as a qualified architect, was embedded within an engineering practice (Arup, Sydney Australia). Working in this conceptual design stage facilitated design input during design development of the project to test structural performance for a variety of alterations to the geometry. The authors were confronted with several unresolved design aspects which required optimisation whilst bearing in mind structural stability, geometrical
constraints of site limits, sight-lines to the stadium-pitch and aesthetic considerations of the architects. The last included inter alia a lightweight appearance for the stadium roof – in particular at the cantilever, a dynamic integration of gridshell elements into the overall curvature of the stadium roof, and the spacing of the underlying triangulation for the gridshells. In order to give the shells a smoother appearance, the maximum size of any edge of a triangle was limited to 6 meters.

The immediate aim of the authors was to optimise the shape of the roof structure to make it aesthetically pleasing, structurally optimised and as visually lightweight as possible. In this phase of design-development, a range of major design changes occurred which had to be accommodated in the parametric geometry model schema. The long term aim was to gain insight into the process of negotiating geometrical alterations with structural behavior and to then propose a framework for both architects and structural engineers to communicate their design in a more streamlined fashion. The authors analysed the individual steps that were required for communicating design intent, establishing rules for geometry alterations, setting up a parametric model, exporting geometrical information from that model to the structural analysis program, setting up load cases and carrying out structural member-optimisation. Ways to most clearly present the information resulting from the structural optimisation to the whole design team for decision support were also investigated. In addition, simple physical working models of parts of the structure were produced to provide a haptic interface beyond the digital representation on the computer monitor. Figure 1 and 2 show shell elements of the roof with the subdivision in triangular facets which were cut from flat cardboard sheets.

The project team at Arup, consisting of structural engineers and design documenters expressed their interest in being able to create variations in the geometry of the project and to run structural analysis and code-checking to determine the feasibility of the project given various load distributions, the overall tonnage and the member sizes required. In order to address these issues, a precise definition of the type of analysis required was communicated amongst the team of architects and engineers in the beginning. Suitability rules were defined by all involved, which related architectural and aesthetic considerations to structural performance by setting up design variables in direct relation to parts of the geometry which
had a strong influence on structural behavior. In order to narrow down the extent of geometry alterations to an acceptable margin for structural analysis, boundaries were defined within those rules to determine the range of changes in the length to height ratio for the main curvature of the roof as well as the individual curvature of the shells at their supports at the outer stadium boundary, the highpoint of the tribunes (the groyne) and the cantilever. This basic configuration required simultaneous input from both architects as well as structural engineers.

5. STADIUM ROOF PROJECT

Once the principles for the relation between the flexible design parameters and the structural optimisation requirements had been defined, the authors created a flexible 3D model in the parametric design software CATIA which allowed for varying the main stadium roof sweep and the sweep of the individual shells of the stadium roof through simple numeric input of a curvature ratio. The range of change for the overall sweep was defined by the ‘high-ball line’ – a minimum height for the roof in accordance to the field of vision of the spectators towards the pitch – and by structural considerations where a sweep of approximately 1:15 (height to length) was desired. In addition to these criteria, the architects (COX Architects) wanted a strong articulation of the individual shells comprising the stadium geometry. Figure 3 shows the guiding curves of both the long and short edge of the stadium roof with the boundary curves of the shells attached. All curvatures are governed by parametric variables. The figure displays three variations for the overall curvature with a height to length ratio of 1:12, 1:18, and 1:24.

We applied a custom developed script running from within CATIA to create a lattice representing the centre-line of steel members for subdividing the individual shells of the stadium roof. Several options for the density and rotation of the grid could be generated and they updated the structural layout automatically once the boundary curves of the shells were altered.

Results from the flexible model were exported from CATIA™ (via Rhino3D™) to the structural analysis packages GSA™ and Strand™ in dxf format. Geometry updates were generated and read into GSA/Strand™ within a timeframe of 5-10 minutes. Figure 4 displays the elevation of 8 variations for parts of the stadium as taken from CATIA™ into Rhino3D™. The different variations for the overall curvature and the individual shells can be recognized. The large elevation on top shows an overlay between the architect’s original model and one approximation from the parametric file.
Load-cases and restraints were transferred from the basic GSA/Strand™ setup without requiring manual input as long as the number and logical definition of nodes and elements did not change. The structural engineers were then able to run a code-checking application (the ‘optimiser’) over the model. Once the optimisation was completed, the software displayed member performance, associated with varying colours which directly corresponded to stresses in those members. Figure 5 shows an isometric view of the stadium roof with a (grayscale) overlay of varying stress distributions. This diagram confirms the assumption by the structural engineers that the structure is too complex to be analysed ‘by hand’ as the distribution of stresses over the whole roof is highly irregular.

The optimiser is a custom-developed application that has been developed within Arup. In contrast to the traditional engineering method of deriving member sizes for stressed elements from tables and charts, it allows iterative evaluation of the most appropriate member size of each structural element individually. The process is not one of optimisation in the true sense – its intelligence is limited to finding better solutions only for one element of a group at a time without understanding the consequences of change to the neighbouring elements. Instead the optimiser works on the very simple principle of constraint satisfaction which carries out design

Figure 4. Elevation of variations of the stadium grid.

Figure 5. Stadium roof stress distribution diagram.
strength checks for each member in a group. One constraint is active each time while a series of checks is being carried out. Other methods would be more rigorous but they cannot be applied for strength analysis as constraints cannot be defined properly (they would work for displacement, buckling or frequency analysis). The setup of any routine for the optimiser is highly input-sensitive depending on a suitable initial choice of a set of section sizes. The significance of this is explained below. It requires expert input as one can otherwise easily get stuck in local minima. The main challenge consists of optimising the section-sizes of a large array of members individually under different loading combinations while aiming at a global optimum for reducing the tonnage and maintaining structural stability. Prior to commencement of the optimisation process, a limited set of section sizes for specific sub-groups of the structure was chosen by the engineers according to production constraints. The grouping occurred according to design variables which dealt with effective length of the steel members, their purpose in the structure, the architect’s requirements and the aim to derive a nicely graded set of member-sizes. This resulted in the definition of five groups of members: the groynes, the groyne-ties, the shells, the front edge and the back edge. After initially selecting the smallest section for each group of members to be optimised, the results were compared to the requirements of the design codes applicable to the project. If all the constraints were satisfied the optimisation was complete, if not, the iterative process resizes those members which did not satisfy the set criteria either up or down. Member size increments were limited to one size increment per iteration. All results were communicated to an ‘MS Access™’ database via an application programming interface that allowed the engineers to read information in and out of the structural optimisation software directly from their custom software. Results from the optimisation process were obtained within a timeframe of approximately 30 minutes. This assisted the research team in their effort to narrow the gap between evaluating results and proposing changes for updating the parametric geometry. Figure 6 displays a close-up of the corner-shell of the roof structure after optimisation. Output from the ‘optimiser’ shows the varying thickness of the grid-members for the roof as part of their cross-section group. The steel members within the shell have the same outer diameter for construction purposes, but the different strength-requirements need to be picked up in varying wall-thicknesses of the hollow steel sections.

The structural engineers decided to first run tests to find the optimal shape for the arches and then to subsequently focus on the curvature in the individual shells. Once this was done, the structural engineers focused their investigation on varying the curvature of the shells for the arch which displayed the best results.

Observations of the results of the geometry variations led to the proposal of a new (smallest) member size for one of the groups (shells).
which initially did not seem achievable. The structural engineers could see that almost 90% of the members in the group were under-utilised. Detailed information about the required diameter and length of steel members was generated by the optimiser and could then be put out as an MS Excel™ spreadsheet and visualised in graphic tables as a by-product of the optimisation process as seen in Figures 7 and 8. The information at hand provided essential decision support for determining the direction in which to alter the curvature sweeps of the stadium. Informed by the graphs, coarse resolutions for the stadium roof geometry were derived initially and then refined over time.
6. CRITICAL ANALYSIS

During the first three months of the development and testing of the parametric model, the design team was logging all ongoing changes in the stadium geometry. In this stage, a series of design parameters which were assumed fixed, had to be altered and consequently the flexible model had to be updated constantly. These changes were required due to aesthetic, convergent, planning, or financial considerations and included inter alia a revision of the main structural grid of the stadium, an alteration in the position of the main roof supports and the variation of the extent of the roof cantilever towards the pitch. Planning considerations were addressed by investigating the ‘best fit’ of the parametric stadium model to the given site-boundaries and the ‘high-ball-line’ being the minimum required field of vision to a ball in play. In most cases, the changes could be accommodated in the CATIA™ model, which led to a setup that was increasingly built on dependencies. At the same time the complexity of these associative dependencies increased, which had its effect on the hierarchical organisation of design parameters within the CATIA™ file. As the main geometry of the stadium was based on a rectangular grid and the arrangement of the roof-support at the outside boundary of the stadium was based on a circular array, some variations of the curvature led to complex intersections. This required the introduction of transfer elements which had to be accommodated in the parametric model retrospectively. For some variations of the grid and shell curvature, the numerical definitions of the parameters would not allow a possible solution to be rendered. This occurred when design elements were over constrained by two or more design criteria.

The design team assessed that the intelligence derived from analysing the decision making process which led to the alterations of the conceptual geometry template, was more important than the geometrical ‘status’ of the parametric model. As illustrated in Figure 9, one particular observation made by the authors was that instead of an expected decrease of indeterminate factors in the design, the number of variable design factors increased during the three-month design development. Because of this fact, the necessity to scrutinise the design intent had become particularly evident, which consequently assisted in developing the structural system in more detail. This exemplifies that in the given case, ‘detailing’ in a parametric context is neither a question of scale nor dependent on fixed parameters, but rather depends on design logic and the correct parametric relations. The fact that many numerical definitions of the stadium geometry were unknown did not raise concerns as long as the parametric template could accommodate them and meet the requirements of the design intent. In addition to this, the structural engineers pointed out that the analysis they required as decision support for understanding the structural behavior did not have to be taken from the final ‘correct’ model, but it could be generated from approximated parametric templates. As much as the...
possibility to work with geometrical information which was not 100% accurate did not cause major concern to the structural engineers, it did pose problems to the design documenters in the industry partner’s practice. The authors have therefore developed a custom script that provides the draftspersons at Arup with a software tool for mapping the analysis-geometry onto the models they were producing for design documentation which were in turn to be passed on to the steel manufacturer via a database. By doing so, the script allows the documenters to define a tolerance within the range of which the script will compare the precise positioning of nodes in the documentation file with geometry coming from the analysis-geometry, and so to subsequently map between them. In order to avoid errors which might occur during the comparison, the process includes support for visual checking by colour-coding of results in the 3D documentation environment. As much as the increased shift from fixed numerical coordinates to a more associative geometry allowed the design team to gain a better understanding of the ‘design intent’, it proved a difficult task to accommodate changes in the parameter schema setup ‘on the fly’, in particular when tight deadlines for submission were involved.

At one point in the setup of the parametric model schema, changes required by the design team were of such a disruptive nature that the parametric model schema could not cope with them. The attempt to
introduce variations of the values of parameters sitting on a high level in the design hierarchy caused dependent 'child' parameters to lose their logical associations. As shown in Figure 10, the 3D model consequently fell apart and parametric integrity could not be re-established in the original model. Lessons learned from this experience led to the insight that the setup of one all-encompassing parametric model schema, capable of accommodating any kind of changes to the geometrical setup of a project is not advisable in the conceptual design stage. As the definition of alterable parameters responds to a clearly defined optimisation process, major changes are likely to interfere with the logical structure of the parametric model. The alternative approach is the setup of not one, but several 'lighter' parametric models that each can each address a particular aspect of the performance optimisation being sought in any given project. The generation of these models is dependent on the standard of knowledge about fixed or changeable design constraints according to the progress within the design stages and the corresponding performance requirements. In the case of the stadium roof project, a parametric model schema was built up from scratch to provide more robust test-beds for targeted optimisation of the roof curvatures without any changes to the stadium-grid or the spacing between the main structural elements.

In regard to increasing the transdisciplinary workflow and the aim for real-time feedback, the link between parametric software (CATIA™) and the structural analysis package GSA™ via dxf was inappropriate for facilitating automation in data transfer and hence real-time interaction between architects and engineers. Direct output of geometrical information from the parametric model via a custom script offered a better alternative and has been facilitated by the authors through direct binary data transfer from CATIA™ to GSA™. The current duration of the optimisation process of approximately 30 minutes is dependent on the complexity of the project and on computational processing speed. With decreasing processing times this obstacle can be overcome in the near future.
7. CONCLUSIONS

By linking parametric design to structural analysis and optimisation, architects and structural engineers can explore design in the conceptual design phase through informed geometry alterations. The setup of any such flexible work environment requires a priori input from experts of both professions to define suitability rules that guide the process towards a specific performance goal. The rate of success depends on the precise definition of quantifiable design variables across disciplines and the awareness of the extent of variations being sought. The implementation of this method and the type of parameters chosen are dependent on the progress of the project according to the design stages. In the case presented, it is neither aimed at finding an initial shape for the project, nor for optimising the design for manufacturing and construction. The link between parametric design and structural optimisation on the stadium project has been applied in an advanced stage of conceptual design where variations of a proposed design solution were sought by the team.

From an architect’s perspective, the immediate visualisation of structural feedback provided by the structural engineers proved valuable to understanding the effects of changes which might otherwise only be driven by aesthetic considerations. In this context, immediacy and clarity of information-display proved to be a decisive factor in facilitating shared authorship. The opportunity of visualising and distributing results from structural optimisation in close-to-real-time enabled the transdisciplinary team to evaluate options and propose changes in a highly informed manner. The more quickly results were communicated across a team, the better the information flow and the collaborative capabilities. The graphic output of the optimisation results gave a clear impression not only of the intelligence the structural engineers are deriving from it, but also allowed the architects to get insight into the working methodology of the engineers.

Tests on the stadium project have shown that if a project team relies on automation routines within a project, members of the team require access to information at any point in the design process for decision support to guide the optimisation process and to propose alternative design solutions. The automation routines run in the background as silent partners whilst open access to the information helps avoid black-box scenarios. The application of parametric variation was not only done to benefit the structure, but it was actually necessary due to the complexity of the structure at hand. Without the iterative experimentation, it would have been impossible even for the experienced structural engineers to understand the nature of the stress-distribution in the structure and to consequently get a feeling for its behaviour.

The experience gained in the stadium project has served to underline the need and definition for a more generalised software tool to act as a data manager in an iterative design process, with a robust but flexible
schema for transport of data between proprietary packages. The data manager would require package-specific plug-ins, which could interface with the target package through APIs (Application Programming Interfaces). The data manager would also have a degree of ‘intelligence’, to allow some minor manipulations to the data in transit between packages – particularly user-specified spreadsheet-type optimisation rules. These, and the data itself, would equally well apply to other aspects of design optimisation beyond structural or aesthetic concerns. The authors propose to make the schema for data transport compatible with the common standard of Industry Foundation Classes (IFC), given the recent uptake internationally in IFC as a CAD-CAD (and to a limited degree CAD-analysis) vehicle.

8. FUTURE RESEARCH

The authors are currently extending their investigations based on the findings described in this paper. Particular attention is being given to the development of a framework for hosting the data manager as described above and a corresponding data-storing mechanism to improve integration and partly automate the processes for linking flexible geometry to building performance.

Part of our ongoing research is the creation of a data manager for closing the information loop between the geometry update and building-performance optimisation. The idea of an intelligent feedback loop guided through suitability rules assisted by the storage of geometrical and non-geometrical information in a database will be central to the manager.

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Dominik Holzer and Mark Burry
Spatial Information Architecture
Laboratory (SIAL),
RMIT University
124 La Trobe Street, Building 9, Level 2,
Melbourne Vic 3000 Australia
dominik.holzer@rmit.edu.au, mburry@rmit.edu.au

Richard Hough
Arup
201 Kent St., Level 10, Sydney NSW 2000, Australia
richard.hough@arup.com