THE APPLICATION OF COMPUTER-OPTIMISED SOLUTIONS TO TIGHTLY DEFINED DESIGN PROBLEMS

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ABSTRACT

Computational simulation is typically used towards the end of the building design process, serving mainly as a design validation tool. In such situations it is applied to well developed design proposals where the majority of the design parameters are known or have been determined by the design team. At conceptual design stage, where even the basic form of the building has not yet been finalised, designers typically rely more upon the guidance of experienced consultants. The sheer number of unknown parameters at this stage are considered to render detailed computational simulation of limited use.

However, with the development of parametric optimisation techniques, there is now significant opportunity for the use of computational simulation during concept design. Whilst the focus of most optimisation research has been on multiple simple numeric design parameters, if these same techniques can be applied with actual building geometry as a parameter, then the potential for form generation based on performance criteria is possible.

Obviously no currently available optimisation method is going to generate a viable building design from a range of performance criteria. However, such a method may be able to generate the optimum site envelope that complies with complex right-to-light restrictions, or the optimum stadium roof shape to maximise solar gains on the playing surface.

The research work presented here has attempted both of these examples. This paper argues that optimised forms based on tightly defined design problems can provide critical information for the designer to integrate into their developing ideas, even at the earliest conceptual stages.

INTRODUCTION

Simulation has long been part of the building design process. However its role has typically been as a validation tool, used by consultants towards the end of the design process, testing highly developed proposals to ensure that performance criteria in the brief will be met. With the availability of more interactive simulation software, analysis is being increasingly used much earlier in the process, and often by the designers themselves not just the environmental and services consultants.

The aim of the research work described here is to involve performance simulation and optimisation techniques much earlier in the design process, right at the most conceptual stages to guide in the development of the built form. This means devising mechanisms by which useful simulation results can be derived from relatively incomplete models and then used to generate or modify their geometry to improve performance.

Resistance to generative systems has always been high within the building design industry - for good reason as the issues involved are very complex and there is often no obvious solution to any particular set of design problems. Also, every building is a compromise between a vast array of competing requirements. Rarely can any building element be truly optimised for a particular use or application, but must be adaptable to many different uses and the compromise is usually the ‘least worst’ solution.

However, this does not preclude the designer from at least knowing what the optimum for a particular application would be. In fact this is how most designers work, they know exactly what they would like to achieve, but then have to work within the constraints of the budget, brief and regulations to achieve the best they can. This is the primary skill of a designer - assimilating a myriad of complex and competing requirements and then making the best set of compromises from a range of available options.

Of most significance here is that designers can work equally well with both objective (quantifiable) and subjective (unquantifiable) constraints. In fact, at the earliest stages of design it is only really possible to work with subjective issues as there is insufficient hard information about the building to calculate many of the objective criteria. Computer systems tend to be of little use in tasks that involve subjective or unquantifiable parameters, but excel at objective tasks with clearly defined and quantifiable parameters, and highly repetitive or iterative problems.

Thus, the purpose of this paper is to propose the best compromise. Computational analysis and simulation can make a significant contribution at the very earliest stages of design by generating optimal solutions to very focused and tightly defined problems. The results may not be immediately and directly applicable, but provide useful information for the designer to assimilate within the broader design context.

TIGHTLY DEFINED DESIGN PROBLEMS

In this paper, a problem is described as tightly defined if all its dependant parameters can be quantified and there are clear and quantifiable criteria against which possible solutions can be tested. Whilst a simple pass/fail test is the most efficient to apply, a problem can still be tightly defined if there are clear boundaries between which the criteria must fall.

Therefore, a loosely defined problem has parameters whose values are not clearly defined. They may be quantifiable, but the criteria for selecting any particular value is essentially arbitrary. Even if there are quantifiable criteria against which possible solutions can be tested, the validity or applicability of the basis on which the solution was generated will always be questionable. This uncertainty can limit the usefulness and impact of the information it provides the designer.

This is an important distinction in this work as the time taken to define and generate solutions for each type of problem is the same, if not longer for loosely defined problems. However, the solution to a tightly defined problem has greater potential to provide meaningful information and real design insight.

OPTIMISATION AND GEOMETRY

Much work is being done on design optimisation algorithms and their application to building systems. Tools such as GenOpt from Lawrence Berkeley Laboratories (Wetter, 04), and others such as DOT (Vanderplaats, 01) and SimuSolv (Stub, 99), allow for low level optimisation of multiple numeric parameters by linking and invoking different analysis tools as part of an iterative solution.

As the work presented here is in its preliminary stages, we are not yet looking at the application of complex mathematical solutions or genetic algorithms. Rather our initial concern is the translation of analysis results into geometric decision-making and the computational generation of building form to meet performance criteria. The integration of more efficient optimisation techniques will follow as the work progresses, however at this stage a much simpler brute-force approach has been taken.

To establish the link between analysis and geometric form, the ECOTECT software (Marsh 1997) was used as it provides an integrated modelling and analysis platform. Moreover its scripting language capabilities allow for the generation and manipulation of model geometry as well as direct access to analysis routines and their results. Thus, scripts were created that iteratively performed calculations, modified the geometry of the model based on calculation results and then repeated the process until specific criteria were met.

Using such scripts, the starting assumptions and the decision-making techniques are fundamental to the result. Different starting points and decision methods will likely yield quite different solutions to the same problem, all equally valid based on the test criteria.

RIGHT-TO-LIGHT: A TIGHTLY DEFINED PROBLEM

In many urban sites there is a need to determine the maximum available development envelope that conforms to local ‘right-to-light’ regulations. One example of such a regulation in London states that any proposed design shall not reduce the daylight availability on existing windows within the facades of surrounding buildings to less than 80% of the existing value. This is possible for a designer to check manually if only a small number of windows are involved, however in a complex urban site, such as that shown in Figure 2 below, there may be many hundreds of windows to check.

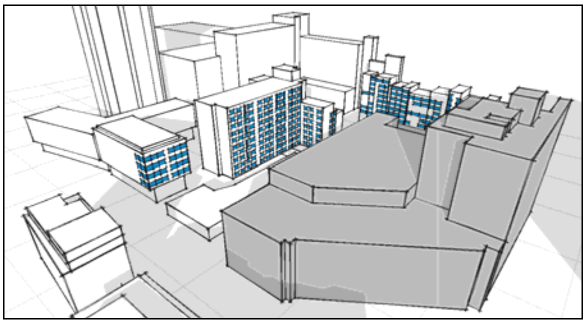

Figure 2 – Example urban site showing existing site and the windows in surrounding facades whose right-to-light must not be adversely impacted.

Such a situation is an obvious application for a computationally generated optimised solution. If the maximum compliant envelope can be determined at the outset, then there will be no need to continually check each design iteration, resulting in significant time savings during the conceptual phase.

Generating the optimum shape requires:

1. A method for computationally determining daylight availability for any window, and
2. A methodology by which the results of each calculation can effectively influence the generation of the next iteration in building form.

Daylight Availability

In this example the UK Building Research Establishment's Vertical Daylight Factor (VSC) (Littlefair 1991) was used as the metric for daylight availability, calculated directly from the shading mask generated for each adjacent window on the site. Shading masks are calculated in ECOTECT using spherical ray-tracing from a grid of points distributed over the surface of each window. Figure 3 shows an example mask for an east-facing window, with the BRE VSC shown in the bottom-right corner.

To determine the percentage change, VSC values were first calculated for each adjacent window based on the existing buildings on the site, and stored in a reference array. The results of subsequent calculations were then compared to these values to test if they were greater than 80% of the original.

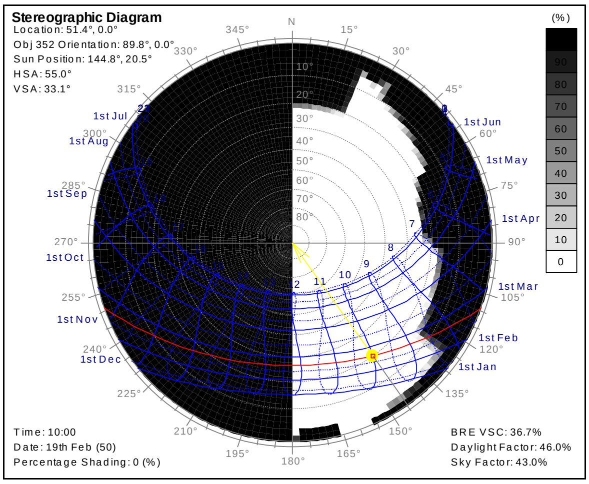

Figure 3 – An example shading mask calculated for a east-facing window on an adjacent façade to the development.

Generative Geometry

In order to generate a development volume, the buildable site boundary was divided into a series of grid segments, as shown in Figure 4. The height of each segment could then be independently controlled by the analysis script.

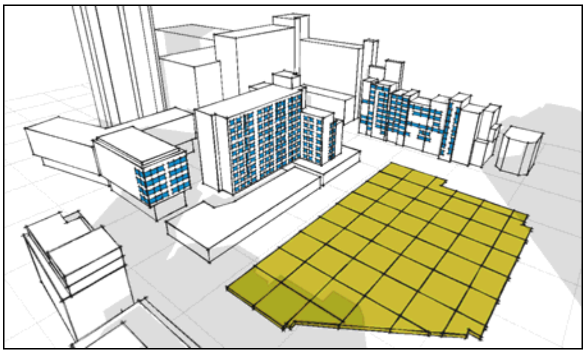

Figure 4 – The site was divided into grid segments whose height could be independently incremented or decremented.

At the start of the calculation, each grid segment was assigned the same starting height and a positive increment value. On each iteration, the VSC for each adjacent window was calculated and compared with its reference value.

If the calculated value for any window fell below 80%, the closest grid segment was found and its increment divided by negative two. This halved the increment of the segment and reversed its direction. The proximity of each segment was based on the linear distance from the geometric centre of its base at ground level to the geometric centre of the window. If the increment value of the closest segment was negative, then the next closest segment with a non-negative increment was used. If the calculated value increased beyond 80%, then the closest negative segment was similarly halved and reversed, but only if the previously calculated value was below 80%.

In the initial runs it was not uncommon for individual segments to be reversed and then 'forgotten' about once the window that caused the reversal regained its 80%. This was because windows could remain below 80% for several iterations, reversing a different segment each time. Rather than attempt to store the reversed segments for each window, a limitation of five consecutive negative increments was imposed, after which the segment reverted to a positive increment. Whilst this increased the total number of iterations required for the resolution of the envelope by approximately 9%, it greatly simplified the scripting.

The process was judged to have been resolved when the increment values of all segments fell below a specified threshold – in this particular case 100mm. The resulting compliant development envelope is shown in Figure 5.

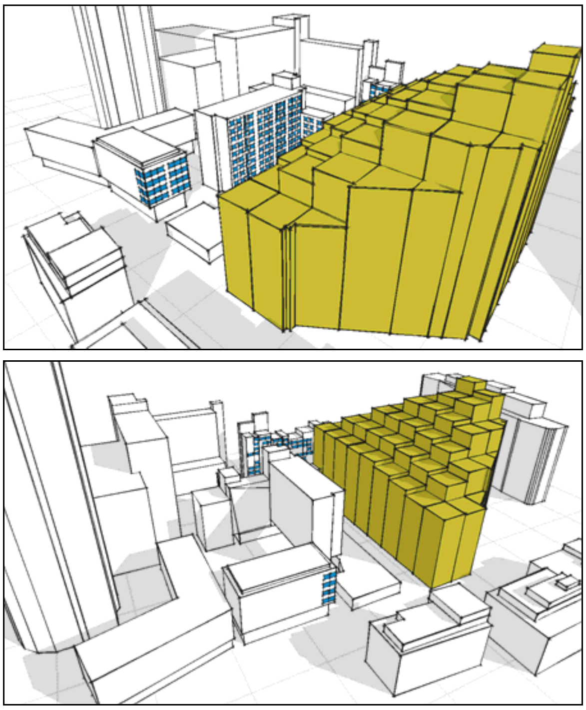

Figure 5 – The resulting maximum development envelope on the site.

INSOLATION: A LOOSELY DEFINED PROBLEM

Not all geometric design problems are suitable for this kind of approach. For example, consider the stadium design shown in Figure 6 below. The requirement here was to determine the optimum location and area of roof glazing to maximise incident solar radiation (insolation) falling on the playing surface, thus maximising grass growth. The stadium model shows the proposed unglazed roof area together with the total annual distribution of solar radiation over the pitch.

To do this, the roof was divided into segments running from the perimeter inwards. The amount of glazing within each segment was controlled within the analysis script by specifying a depth value at each side of the segment, ensuring a continuous edge running around the stadium.

The first issue was the determination of a suitable metric for insolation values. Taking the total annual insolation would bias the result towards Summer, when solar radiation is significantly greater than in Winter and when grass growth is not really a problem. Thus the insolation period needed to consider when the playing surface was under most stress – at times of high usage rates and low radiation levels.

Additionally, stress levels are not usually uniform over all areas of a playing surface.

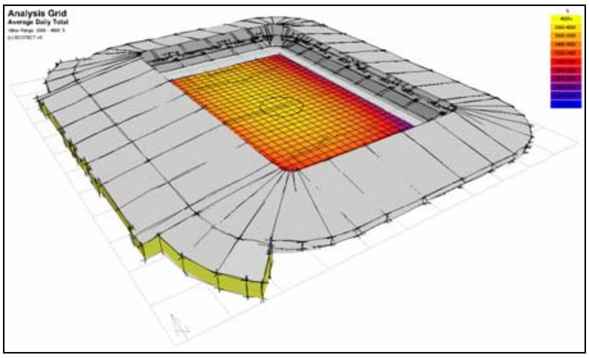

Figure 6 – Stadium model showing the distribution of solar radiation over the playing surface with an unglazed roof.

Traditionally it is the southern end of a pitch that suffers most in the UK as it is in shade for the longest period in winter. This can be accommodated by summing up only the southern half of the playing surface, or even the southern-most quarter.

The specific insolation period chosen and area of pitch area over which the calculation is done will both directly influence the resulting glazed area is the roof. However, there is no available guidance on whether, for example, to take only the three months of winter, or the coldest three months, or even the coldest seven weeks. Similarly, why not the southern-most third of the pitch instead of the southern-most quarter.

The second issue is the definition of what is optimum. If maximum insolation is the only criteria, then the glazing area simply resolves to the entire roof, as shown in Figure 7.

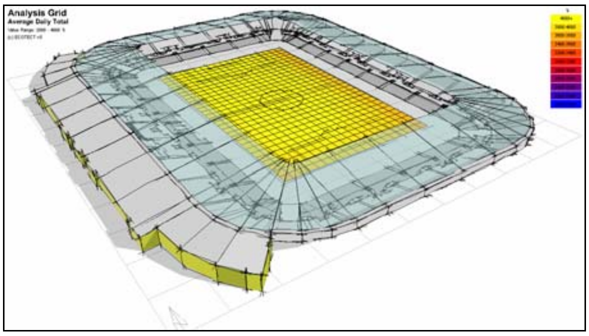

Figure 7 – If incident solar radiation is the only criteria, then the entire roof glazed is the 'optimum' solution.

The obvious constraints to offset this are material and maintenance costs. These need only be expressed as ratios between the costs of the opaque and glazed materials. Additionally, maintenance costs require a period over which they are to be calculated. The script then simply calculates the areas of each material and looks for the point where the total cost and insolation curves meet.

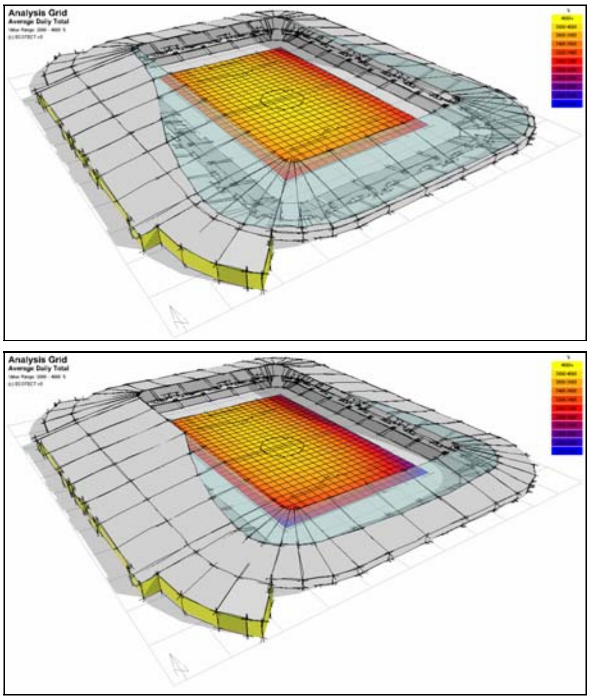

Figure 8 – For the same capital and maintenance cost ratios, the top image shows the result when considered over 10 years and the bottom image over 50 years.

However, here too the specific values chosen for these parameters significantly affect the result. Figure 8 compares two situations in which the capital cost of glazing is twice that of metal decking and its ongoing maintenance is five times higher. The image at the top shows the result if a period of only 10 years is considered whilst the bottom considers a period of 50 years.

The potential for a single relatively arbitrary parameter to so significantly influence the result may be important in a sensitivity analysis, however it demonstrates the uncertainty underlying the results of loosely defined problems.

AN ANALYTICAL SOLUTION

In this particular instance there was a more direct analytical solution to the problem that did not require the designer to apply cost constraints or specify an arbitrary pitch area in order to generate a solution.

If the solar analysis grid is placed over the entire roof area of the stadium instead of on the ground, and the entire playing surface is projected back onto it throughout winter, it is possible to map the most significant areas where obstruction should be minimised.

This is done by determining which cells in the grid the solar radiation must pass through each hour in order to reach the pitch, and summing the instantaneous solar radiation at each hour over the three months of winter.

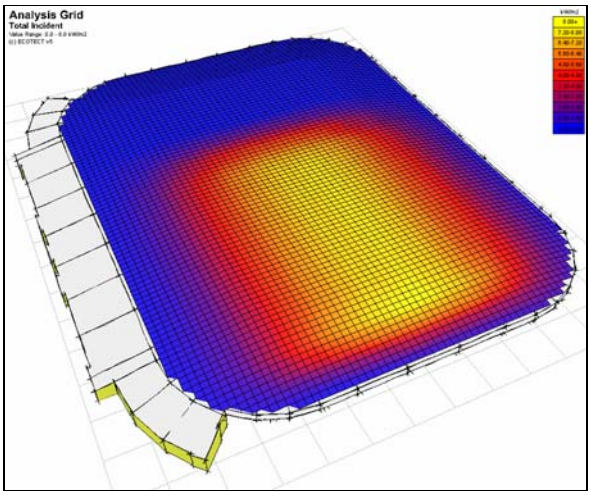

Figure 9 – The optimum location of roof glazing panels can be quickly determined using projections of the playing surface onto the roof area over Winter.

The cells with the highest overall values therefore represent the area through which the most solar radiation passes, and thus the areas in which to avoid obstruction.

If the resulting cumulative data is clipped to only the area of the proposed roof, it clearly shows the most effective location for roof glazing panels.

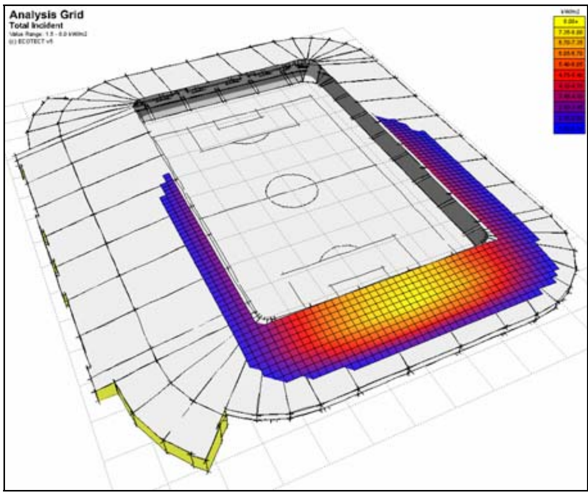

Figure 10 – The optimum location of roof glazing panels can be quickly determined using projections of the playing surface onto the roof area over Winter.

Whilst the analytical solution is still based on a relatively arbitrary time period, that was the only variable parameter as the entire pitch surface was used. As relative costs were not considered it is possible to argue that the result is less meaningful overall, however it is argued here that the increased level of certainty in the result more than compensates for this.

CONCLUSIONS

The examples were selected to demonstrate that building geometry can be used as a parameter in optimisation studies, and that the process is of most benefit to the designer when applied to tightly defined problems. Whilst it would seem logical that the more information you can apply to the optimisation of a computational model, the more useful the result. In fact, because of the nature of the building design process and of the information available to be applied, the opposite is most often true.

Further work in this research now needs to be done looking in more detail at the comparison of results produced by slightly different approaches to the same problem. This includes using a range of starting points in the model-generation scripts and different decision-making methods, as well as the integration of more complex parameter optimisation techniques.

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