Integrating Performance Modelling into the Initial Stages of Design.

Andrew Marsh*

This paper follows on from work presented at the last ANZAScA conference. Work has progressed on the Ecotect suite of integrated performance modelling tools. Whilst structured mainly around the analysis of building models, the suite also consists of tools for climatic/psychrometric analysis, material/panel design and sound/noise propagation.

These tools are unique in that they are intended for use at the very earliest stages of design, before any decisions regarding form or planning have even been considered. The aim is to allow the designer to begin with very rudimentary forms, experimenting with the effects of orientation, materials, window size, shading devices and planning. As these experiments progress, the design should gradually resolve itself. Constant feedback in many simultaneous areas, acoustic and thermal performance, solar penetration, overshadowing, lighting levels, etc, allows the designer to reconcile aesthetic and other cultural concerns with their effect on actual performance during the initial phases of design resolution. As the amount of detail increases, so too does the accuracy of any calculations. The final result is that the designer should not only have an indication as to how the building will perform, but will have seen the ramifications of each design decision and, thus, understand why it will perform that way.

Given that the previous paper described these tools in detail, and the fact that most of the modelling and simulation techniques used are well known, the focus of this paper is mainly on the type and structure of data required to define a dynamic building model as well as the information that can readily be derived or calculated.

Introduction

Of primary concern to the author of this paper is the incredibly low priority apparently given to environmental and building performance issues by most architects. Whilst there are many reasons for this, it is something that the profession can ill afford.

Whilst an alarming number of architects feel that such considerations are of only trivial concern, easily resolved by ordering larger air-conditioning units or more luminaires, it is the author's belief that the majority do recognise their importance, but lack the necessary time and skills to adequately address them. Often the laborious nature of calculations required for performance modelling means that they are simply not done.

In view of this, the author has been developing and testing a suite of software aimed at assisting designers in this area. What is unique about this particular software is that it is intended as an interactive design tool, not simply a modeller within which a completed design is tested. This way, the most rudimentary idea or sketch can be gradually developed within the application into a detailed model with performance feedback at every step.

This is extremely important as architects normally address only one or two performance criteria within any particular part of a building. However, every decision has ramifications for all other aspects of performance, many of which do not become apparent until after the building is up. As a result, the simultaneous

---

The School of Architecture and Fine Arts
The University of Western Australia
NEDLANDS 6009

analysis of many different performance parameters is absolutely essential, something that previously required a number of different modelling packages, each needing detailed input in their own special format.

Application Intent

The primary aim of this work was to absolutely minimise the amount of application specific data that the designer has to input and make it as graphically intuitive and interactive as possible. This means that the designer uses a single application to generate the geometry of a building and assign material properties to each element. As the library is easily customised to automatically select the most appropriate material for each element, material assignment is not a significant chore.

Once a model has been defined, the application itself is responsible for extracting all of the detailed information it requires for any particular analysis. This vastly reduces the load on the user, is relatively simple to derive and usually produces more accurate results than user-supplied data anyway.

This approach does place a significant burden on the user interface as this is the primary input mechanism and will dictate how the software is used and what it is used for. The ability to quickly and interactively create/edit models was considered of paramount importance. Numerical accuracy is provided for through direct entry input fields, object snap points and snap grids. However, most models do not require that high a degree of precision, especially at the most formative stages. Thus, significant effort has been devoted to the interactive interface, resulting in the development of a new 3D cursor system for the manipulation of geometry in perspective projection.

In keeping with this approach, and the visual nature of design, the interactive manipulation of view was also considered significant. As a result, the view can be rotated and panned at any time using the right mouse button, even in the middle of another command or whilst creating an element. Refresh rates of even the most complex models are fast enough to allow real-time rotation without simplifying or abstracting the geometry.

It is hoped that, having observed the following points at all levels of application development:

- Keeping the interface as simple and intuitive as possible.
- Optimising the creation and manipulation of geometry.
- Automating the extraction of analysis data from the model.
- Making analysis and calculation as simple and straightforward as possible.
- Making the results of all calculations as meaningful as possible.

a useful and useable tool has been created. One that allows the designer to retain creative control and maintain responsibility for all aesthetic decisions, yet be more informed as to the full ramifications of those decisions.

Modelling Space

In order to facilitate automatic extraction of data from the model, a detailed set of relational information is required. Typical CAD applications simply use a set of geometric primitives out of which a complex geometry can be constructed. Within such a construct there are no inherent indications as to the role of each primitive or set of primitives in the model, or of their relationship to each other. The existence of enclosed space is simply a by-product of defined surface geometry.

This highlights one of the fundamental shifts in approach taken here. In this work, the model consists of a series of defined spaces. The application can test each space for adjacency with any other and then, by examining the area of interface, determine exactly how the two will interact. This means that the designer now works by arranging spaces, or zones, instead of a series of elements.

Obviously geometric elements are needed in order to define and enclose each zone, however, they now exist as a by-product of the space, not the other way around. Interactively moving a zone moves all of its defining elements. Moving an element simply redefines the space.

This approach facilitates interactive manipulation far more than traditional CAD applications. Whilst the definition of a zone as a complex closed polyhedra was considered far too restrictive, significant work has been done on a system of relational mapping between elements that greatly enhances the editability of each zone, and the model. Relationships are established during construction of the model and consist mainly of spatial links between nodes and a referential parent-child hierarchy.

This means that manipulating the shape of a floor, from which walls and a ceiling were extruded, will automatically update the position and shape of related elements. This includes rotating and resizing walls, relocating windows and doors within those walls and reshaping the ceiling. Whilst this is a very simple example, the system extends to any geometry.

A zone may be defined by any number of complex elements of any shape, and assigned any number of different materials. These defining elements do not need to be related in any way, or even fully enclose the zone. As a result, all relationships between elements are completely dynamic and easily modified or removed. This allows zones to contain multiple floors, which need not necessarily even be flat. They may also contain any number of internal partitions, suspended floors or ceiling panels.

This system has proved quite successful in the tests carried out thus far, providing a simple and intuitive facility for quickly manipulating complex geometries whilst still allowing sufficient flexibility to create and incorporate forms of any shape and size.

Establishing a Knowledge Base

To meet the primary aim, it was necessary to balance the complexity of input with the amount of model information required. It was, however, of fundamental importance to know the function of each element within the model. As a result, whenever elements are created, they are created as a particular type. For example, the user chooses to create a floor plane, or insert a window into a wall, a skylight into a ceiling, a partition within a zone, etc. The following is a list of the 12 basic element types defined in the application:

- Void
- Roof
- Floor
- Ceiling
- Wall
- Partition
- Window
- Panel
- Door
- Point
- Speaker
- Light

These type definitions imbue the model with an inherent knowledge base. Surface areas and statistical data can easily be determined, for example, the ratio of north/south facing glass to floor area. Calculating the distances between doorways, and hence the adherence to fire codes, becomes relatively trivial. Knowing that an element is a roof plane, yet has only a shallow incline, means that the properties of air flow and air-film resistance can be accurately modelled.

It also eases material assignments as a large material library may contain over 100 materials, but only 8 internal partitions or 12 ceilings.

Model Analysis

Even when a model has been only partially defined, it is possible to begin analysis. The type of information required by architects at progressive stages of design often changes quite dramatically. One would hope that, at the most formative stages, external factors such as climate and siting would form the main concerns. Then overall form and planning of the building may begin to dominate, leading to the stage where detailed performance of individual parts of the project become important. It is hoped that this software can contribute at each of these levels.

Solar Penetration and Shadow Analysis

The hand calculation of solar penetration or the design of shading devices from solar tables can be an extremely laborious and tedious process. The result is that rules of thumb and design by precedent predominate. However, a small computer model can greatly simplify this process.

The suite discussed here provides two facilities for analysing shading and penetration. The first of these is a simple application based on a parametric window model. This allows the designer to simply play with shading devices and window shapes in order to establish the best approach for a particular location and orientation. It allows multiple horizontal, vertical and detached shades to be applied to any size window, with shading and penetration displayed graphically at any date and time. A stereographic diagram for any particular configuration can also be generated as well as solar position and shadow angles.

The second facility is contained within the geometric modeller itself. As the application can easily discern windows and voids from other elements, the calculation of solar position and, thus, shadow generation is quite trivial. The date and time can be entered manually or cycled via hotkeys, as can the location.

As the default view of the model is only wireframe, displaying shadows on every plane can occasionally be confusing as internal shading merges with external overshadowing. As a result, specific elements or groups can be isolated and tagged to receive shadows whilst other elements are ignored. This is fairly intuitive and particularly useful when considering internal penetration in specific zones or shading on a facade.

Additionally, a stereographic diagram can be generated at any point within the model. If a complex object is selected, the diagram is taken at its geometric centre. It is therefore possible to model adjacent buildings and vegetation to determine their overshadowing effect on any window by simply selecting it. Changing the selection set or moving the selected point automatically updates the diagram.

Thermal Performance

The use of zones within the model greatly simplifies the process of calculating heat flow and internal temperatures. The application simply tests each element within a zone for adjacency with elements from any other zone. The surface area of the interface is determined and the heat flow calculated. Any part of an element that is not adjacent to another zone is considered to interface with outside conditions and contributes to the overall Building Loss Coefficient (BLC). Any non-enclosed zones or those containing large voids are assumed to directly follow outside conditions.

Using the BLC, steady-state thermal analysis is easily performed. If degree-day figures for a particular location are available, monthly and annual heating/cooling loads can be estimated instantly. This allows instant feedback when assigning different materials, resizing elements or adding windows.

The internal temperature of individual zones over any period can also be calculated using the Admittance Method. This is a more involved calculation that considers the orientation of each element, its exposure to direct solar radiation and the internal temperature of adjacent zones. As such, it must be set running and can take several minuted to produce a result. This calculation also returns the Response Factor (FR) of the model.

When considering the orientation of elements, the age-old problem of inconsistent surface normals was encountered. If constructed within the modeller itself, the surface normals of all elements automatically face outwards, away from the centre of the zone. The orientation of each element is then simply the horizontal angle between the surface normal and the positive Y axis. If the geometry is imported from another application, via a DXF file for example, the direction of the surface normal is dependant on the order of vertices and usually results in some inward-facing normals. Whilst it is a simple task to reverse them, no algorithm has yet been implemented to automatically detect this, meaning that it is up to the user to both detect and correct any such inconsistencies.

The intention was also to interface this application with the National Housing Energy Rating Scheme (NatHERS) thermal performance engine. However, information as to input file formats and underlying assumptions have been difficult to obtain. As this engine is based on CHEETAH, which was, in turn, based on the much older ZSTEP program, it is currently only possible to output ZSTEP files. Whilst the NatHERS engine has moved more towards a parametric model, it is still considered sufficiently compatible to warrant the effort when this information is made available. If the demand is there, the author is also interested in the generation of DOE2 input files.

Daylighting

Daylighting levels can be determined at any number of points within the model using the BRS Daylight Factor method. Whilst the manual method makes use of daylight factor protractors to calculate the horizontal and vertical exposure angles of each window, this application uses a ray-tracing method.

In this method, the sky sphere is divided into equal angle segments. A ray is then cast at that angle and traced to see which elements it intersects. If it only intersects voids and windows, or hits nothing at all, it is added to the sky component. If it passes though a window but then hits an opaque object, or the ground, it is added to the externally reflected component. If the first intersected object is opaque, then that ray contributes to the internally reflected component.

As defined, the internally reflected component is given by an algebraic formula based on the average reflectance of elements above and below the work plane as well as the average angle of external obstruction. These average reflectances are determined in this method by recording the reflectance of each intersected element as well as the altitude of the intersecting ray. The altitude of each ray contributing to the externally reflected component is also recorded to determine the average angle of external obstruction.

The precision of this calculation can be varied to quickly provide a rough indication or accurately calculate the exact value. Set to medium accuracy, a single point in a reasonably complex model takes around 10-15 seconds. This means that the effects of different window sizes, shading devices or eaves overhang can quickly be determined. Similarly the effects of fences, adjacent buildings and trees can be considered.

Electric Lighting

An acceptable solution to electric lighting levels is still to be resolved. The only method currently implemented is the Point-by-Point method for point lighting levels. As this method does not accurately consider reflected light, it underestimates levels and may result in more luminaires being used than really necessary.

The aim of this work is to assist architects optimise building performance in order to optimise energy use. As a result, a more accurate method that does consider internal reflections will be included in a future release. For a similar reason, the Lumen method for designing luminaire grids, which would be relatively simple to implement, is considered inconsistent with efficient energy use when directional or task lighting is usually more appropriate.

As a result, work in this area has focussed mostly on the generation of Radiance model files. Radiance is a lighting simulation package developed as part of the IECs Project 21. Unfortunately, it is freely available on the Unix platform but only available for PC as part of the ADELINE commercial lighting release.

Acoustic Performance

Any analysis of acoustic performance is usually quite rare and almost always done by an acoustic consultant. Whilst quite a specialised field, this work makes use of the enormous amount of geometric information inherent within the model to provide a comprehensive and relatively sophisticated analysis. There are four main components to the information thus available.

Statistical Analysis

The room averaged Reverberation Time (RT) of each zone is determined from the absorption coefficients of all internal surfaces and the volume. The most appropriate algorithm is chosen based on the range and distribution of coefficients, as follows:

- Sabine (uniformly distributed absorption),
- Millington-Sette (widely varying absorption),
- Norris-Eyring (highly absorbent spaces).

As each material has defined absorption values for each octave band, the RT can be determined at 0.5, 1, 2, 4, and 8kHz.

Acoustic Raytracing

This uses the method of images to accurately determine early reflections and a hybrid raytracing method to provide a sample of late reflections. The threshold of each method can be easily set to provide the optimum combination. Using this system, it is possible to generate the impulse response for up to 32 points simultaneously, up to a depth of 32 reflections.

Once generated, the impulse response is hot-linked to the acoustic rays from which it was generated. Rays can be selected from either the graph or the model, highlighting each one so that the actual path travelled is clear. This allows spurious echoes and other acoustic defects to be quickly tracked to their source. Also, changing the material or absorption coefficients of elements instantly updates the impulse response as long as the geometry remains unchanged. This means that the most appropriate materials for each surface can be quickly determined. Also, it is possible to view the intersection points on any selected elements along with a graph of the distribution of incidence angle. This enables the selection of an absorber with the most appropriate characteristics for particular locations.

From the impulse response, a number of objective measures of acoustic performance can be derived. These include the Reverberation Time, Early Decay Time, Clarity and Definition values, Speech Intelligibility and, to some extent, the Speech Transmission Index. Also, the distribution of images can be displayed along with a polar diagram showing the apparent spatial distribution of each impulse.

A tool is also provided that will take an acoustically dry signal of any sort and convolve it with a calculated impulse response. As early reflections play a significant part in the aural perception of sound within an enclosure, and late reverberant sound is easily simulated, it is almost possible to accurately simulate the effects of playing a particular sound in the modelled enclosure. The actual convolution takes quite some time to calculate, so real-time simulation is still some way off.

Reflection Analysis

One of the most useful acoustic features of this suite, especially at the early stages, is the ability to spray acoustic rays from a point source. This allows plan and section shapes to be easily assessed over a wide number of source positions, as well as acoustic reflectors accurately positioned. Interactively moving the source point automatically updates the sprayed rays from the new position.

Another useful feature is the ability to display either the delay or level of each sprayed ray relative to the direct sound. This can quickly highlight areas where late reflections may be a problem or isolate acoustically dead areas.

Noise Transmission

Using the same technique as when calculating heat flow, sound transmission between zones can be quickly determined. Each element is tested for adjacency with every other zone and then its transmission characteristics, surface area, the reverberation time of the tested zone and the sound level in any adjacent zones is recorded in order to determine the resultant background noise level. Any element without an adjacent zone is assumed to interface with outside conditions.

In this way, even quite complex transmission paths can be discovered. However, the method does not yet accurately consider structure-borne sound across zones. This area will be addresses in a future release.

Conclusion

Whilst work such as this can never be considered complete, it has reached a stage where it is becoming quite a useable set of tools. Many of the individual applications have been tested extensively by a number of architecture students over the past two years, and major modifications made as a result.

It is hoped that tools such as this will encourage architects to pay more attention to performance issues much earlier in their design formulation. Instead of evaluating performance at the very end of the process, where only minor modifications can be made, good design should include a continuous evaluation of performance in as many areas as possible.

Whilst some of the algorithms implemented are relatively simple and unsophisticated, often that is all that is required. As long as they accurately indicate the relative effect of changes within the model, then decisions can be effectively evaluated. In most cases, the absolute value is of no real significance. Consider heat loadings: whilst the calculated monthly load is useful as a ballpark figure, the most important information is whether altering the window size will increase or decrease the value, and by what ratio. This is where simple and immediate feedback is of most use.

Acknowledgments

The author would like to thank Dr Derek Carruthers for his enormous patience and support in the supervision of this work.