Sydney Opera House – Integration of BIM into Design and Management of Architectural Services

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Introduction

To bring the design for such an amazing structure together Jørn Utzon needed to team up with other top tier designers—people who appreciated his vision and were able to bring solutions to the table that may be non-traditional, but would fit the mold and withstand the test of time. Time has moved on and times have changed; we are now in a new era of real life virtuality with all of the advantages of the virtual world that can assist to manage such a facility.

In 2013 the Sydney Opera House started on a journey in digital laser scanning to capture the structure and systems that enable the facility to operate. This journey has explored many methods of data capture and more importantly processes that can be used to enable this data to be leveraged. Utilising a BIM is yielding intelligent systems that are starting to not only document these systems but provide an in-depth window into the operational mechanics of one of Australia’s most iconic structures.

This presentation explores the original methods used to produce the mechanical, electrical and lighting design in this landmark building, and how current technology is enabling these methods to be realised in an integrated approach. Enhancing the understanding of these systems and their inter relationships is providing the Opera House with a road map that presents opportunities in facilities management and design now and into the future.

The Creative Mechanical Systems Designer

For the building ventilation, air conditioning and smoke control, Utzon engaged the services of the very clever and creative mechanical engineer Jørgen Varming. In many ways Jørgen was way ahead of his time. Some of the challenges that he was faced with was no visible mechanical plant, concealed air intakes and exhausts, working with a building that is full of curved lines, and air conditioning large open spaces to strict noise levels. These challenges were solved and the systems have worked well for the past 40 years. Although some of the systems have been replaced, their arrangement and method of operation have for the most part remained unchanged.

To resolve the issue of unsightly visible plant rooms Jørgen used sea water to cool the chillers rather than the more traditionally used cooling towers, this also allowed the chillers to function more efficiently than they would have if cooling towers had been used. The very best sea water filters and pumps were used to operate this system. The original filters are still in use.

Air intakes and reliefs were concealed behind blades in the vertical faces in front of the shells. With much of the outside air drawn in via the top of the sails one challenge was how to then distribute this outside air to the plant rooms at various levels within the building. The answer was to form large plenums which pass between the outer structural shell and the inner void spaces above the opera and concert halls. Grouping some of the major plant rooms vertically assisted with this. (See Figure 1)

One plant room sits above the concert hall, and materials were delivered up to the plant room level via two rails installed between the inner and outer shells’ materials were hoisted up, sliding against these steel rails—another creative idea. Figure 2 shows a section of ductwork being hoisted up to plant room 21. This plant room serves the crown area of the concert hall and the Northern Foyer.

Old Processes and Keeping up with Design Changes

As we know, the design process was all but smooth with differences of opinion between Utzon and the NSW Government. The services designs would have been difficult enough had the process been smooth, but with the major change in leading architect, the process would have been extremely frustrating and difficult.
The design was conveyed on celluloid film paper with layouts and notes indicating which drawing to refer to for further information such as sections and elevations. Some of the plant rooms have three levels of layouts indicating a low, mid and high level plane within the plant room.

The constantly changing form of the structure would have brought about major challenges to keep the mechanical services coordinated. It is hard to imagine the constant exchange of drawings that would have taken place and the numbers of drafting personnel who would have worked to complete the workshop drawings in time to construct the kilometres of ductwork. All of the systems and text were being drawn by hand using ink pens on film paper and all prints were being prepared using ammonia print machines.

The space needed to accommodate the drawing boards and layout tables for the design would be in the order of eight times the space that would be needed today not including the storage space needed for all of the incoming drawings from each discipline and the mark ups that would have occurred during countless design and co-ordination meetings.

Co-ordination would typically be done by overlaying drawings, often using light tables to detect clashes and then to mark up directly on the drawing negative using a blue pencil or a print or tracing paper which would then be copied onto the original celluloid negative. The reflected ceiling plan coordinating supply and return air diffusers and grilles with light fittings, smoke detectors and sprinklers would have been a manual process with check calculations undertaken again and again to ensure that design parameters were being maintained. The electrical systems are in the main reticulated within steel ducting and conduits with these enclosures closely following the form of the structure. This would have compounded the staging issues for construction to ensure that the programme allowed all services to be sequentially installed.

The mechanical shop drawings would have been used to manufacture sections of ductwork. Within the SOH today you can still see the hand marking on the ductwork stating which project it is destined for and where it was to be installed. Approximately 70% of the installed ductwork would have been constructed directly off the workshop drawings with some 30% being constructed following an onsite measure. Measuring and installation would have been difficult due to the height and tightness of the spaces used to reticulate ductwork. As much as 10% of the manufactured ductwork would have been found to be wrong and would have been scrapped or returned to
the manufacturers for alterations. In some instances the ductwork had to be notched to make it fit within the building structure.

On the whole, the mechanical plant is easily accessible but in some instances access is poor with undersized access doorways and low head height within service tunnels, an indication that some areas were understandably not able to be coordinated fully prior to construction.

The information shown on the as-built drawings has been found to be accurate as has the cross referencing between drawings. Changes in design and construction can bring about a change in scope and hence variations to the project. At the time these would have been calculated by identifying and measuring changes and producing reams of paper scheduling out the additions and deletions to the work and schedules of rates to be applied to arrive at a variation in the contracted price.

Verification of the changes would have proved difficult unless processed quickly, since much of the installed ductwork is not readily visible. The final account figure may not have been realised until long after the project completion.

The shop drawings would have been amended several times during construction with a final check and change to produce the as installed drawing. Microfiche was the only alternative method of storing and reviewing drawings and then in later years scanning of drawings for easy and quick retrieval.

All of these processes were very labour intensive but the net results for the installed systems are quite amazing.

Bill Lambert began work on a detailed scaled model in 1966, as a way of testing how the heating, cooling and ventilation would fit, in the days before computer modelling and graphics were available to do this. It took Lambert seven years to build his model, which is 4.5 metres long, three metres wide and 1.8 metres high. The material used was Perspex, a semi-transparent acrylic that can be shaped when heated. The mechanical services are in white acrylic, which shows up through the semi-transparent enclosure.

The model was stored in a crate during the 1970’s and was not re-discovered until 2002 when NSW Department of Public Works handed over to the Sydney Opera House. The model had been stored in pieces and took 2,000 man hours to re-build.

The results of the mechanical services design can be viewed through the transparent scaled model of the Sydney Opera House which is located within Customs House. This shows clearly mechanical services ductwork and some of the plant rooms. We have on occasions viewed this to get clarity on aspects of the mechanical services design.
Figure 6 is of the Western Shells above the Concert Hall and as you can see there is ductwork at the point of the shell that is the outside air intake for the Concert Hall and the surrounding foyers and corridors. This ductwork connected into the plenums that were built vertically down the building and as shown in Figure 1.

The Processes of Today

The process today would be very different but would still need the creative thinking and skill to achieve the brief requirements. There is still no substitute for people to develop original ideas and I am sure that the designers of then would have realised the advantages of BIM (Building Information Model) and would have eagerly taken on board the digital integrated processes of today.

If it was being designed today it would almost certainly still have used sea water to reject heat from the chillers, and would make use of the otherwise rejected heat to pre-heat domestic hot water and to provide heating. The use of the mainly unusable space in the pointy end of the shells for outside air intakes and relief air discharges would still be a great solution. The major difference today would be a greater use of displacement ventilation to condition the spaces and to assist in smoke exhaust, something that has been explored for the major proposed refurbishment work at the Opera House.

As you are aware, today the design would have been undertaken within a 3D BIM model which could have brought a number of additional efficiencies to the process. Working in a collaborative environment with other project stakeholders would have enabled a more fluid design process that could have enabled mechanical solutions to be better moulded to the structure and available space. These solutions would have been able to undergo a number of iterations at a very small cost to find the optimal outcome.

Acoustic analysis could have been easily undertaken dynamically as the design evolved, enabling systems to undergo changes that considered sensitive areas. These changes could be linked to the modeled spaces and resultant acoustics displayed to all parties involved.

Service access and safety in design could have been managed again in a dynamic fashion. Service routes could be easily assessed during design changes dynamically ensuring minimum clearances were also achieved. Key equipment replacement strategies could be assessed and changes made before the contractor has even been appointed.

HVAC System sizing and performance would be available to be assessed rapidly with a BIM. During design changes the House’s HVAC loads could have been assessed at a very rapid rate. While perhaps the shell material and construction solutions would have had minor effects on the end load, differences in the selected Glazing performance, angles to the water and surrounding environment would have significant influence on the final HVAC loading and certainly the final HVAC design.

Lighting calculations could also be carried out highly accurately using a BIM. Rapid calculation using raytracing and radiosity calculation tools are able to utilize the geometry and material finishes in the BIM and the changes in geometry particularly through the design phase could be rapidly updated giving the ability of assessing the total solution.
Power and data design would utilise power density links to not only track and manage estimated power usage throughout the facility but would inform distribution board sizing and power requirements again in a dynamic environment. This ability would not only drive the decisions regarding power redundancy, reticulation and component sizing but would be informed by the HVAC designs, and lighting requirements as the design progressed.

Energy analysis and the Houses green credentials could also be tracked as the design progresses. Energy models could be rapidly produced to calculate the different design options and iterations used to finesse a total solution that gave an optimal outcome not only from a functional aspect but one that considers its environment and carbon footprint. During construction material types and qualities could also be managed to ascertain the estimated embodied energy in the selected materials, and decisions regarding design with a focus on minimising undesirable products would be considered.

Early contractor involvement would not only ensure efficiencies in build ability, but would certainly shorten the design to construction phase. Not only could contractors contribute to the construction staging, construction methods and techniques, but when the design stage was complete they essentially could further populate the same BIM again drastically reducing the lead time to construction.

The unique nature of the design, and the limitations to access, could have likely been a catalyst to prefabricate significant sections of the installation. This solution would have both great benefits to the construction process not only in the reduced timescales to achieve what was an extremely difficult installation but also, and more importantly, to the safety of the workpeople installing the equipment. Generating integrated sections that incorporate ductwork, hydraulic elements, electrical elements and service access would have bought about an integrated solution that was tailored to the facility.

While virtual models are able to value add to a significant degree it is likely we still would have looked to provide some physical models in conjunction with the Architect. These however would have been able to be produced at a very rapid rate to a high degree of accuracy and at a very low cost. Today we look to use 3D paper printing to provide actual scaled models. Again these can be produced from the BIM directly and can be reproduced as needed.

Model coordination would play a critical role in the success of the design. While design changes are taking place the federated model could be assessed with all the designer and consultant input in place on a weekly format. Issues that are highlighted could be addressed in a virtual environment not only saving cost in manufacture and reducing waste but also without effect to the Project timeline.

Cost and budgeting estimation not only used to ascertain project critical paths analysis but also to assist in JIT (Just In Time) management techniques. A project of this nature would require systems to be ready for installation in tight margins and would demand a high degree of success in terms of the fit. Budgeting could also be not only closely estimated but again could be dynamic. As changes are suggested and alternate designs developed, the cost of each solution could assist in the evaluation of the suitability of each system.

The final installation would have, by the nature of a BIM, also yielded a design that was not only fully and completely documented, but one that was almost perfect in its accuracy. This output would have provided the House with a completely integrated set of documentation that not only would be referable in a single location but that would have been generated but an intelligent model that could display information ranging from geometric data of a piece of ductwork, to design and commissioning data of a chiller that could provide a whole mired of interfaces from electronic QR tagging access to a complete BMS interface.

Finally Validation of what has been built against what was originally designed can be done through an as installed Laser scan of the constructed project.

Managing the Facility

Planned preventative maintenance systems have been around for many years to ensure the upkeep of assets. During the 1950s the Ministry of Public Building and Works (UK) introduced them into all of the armed forces and government facilities that they were responsible for maintaining. They were effective and efficient but very labour intensive in the management of the system. Since then spread sheets and data bases have been used to present and manage the work flow given to the service personnel and to track completed tasks and any repair work required. Any uncompleted
tasks for one week would be carried forward into the next week and this would be sorted manually. All of this can now be achieved through BIM and FM integration.

Fig. 7. Plantroom in the house converted into a BIM using a PCS.

Our 3D Virtual World

With the emergence of BIM we are able to link a 3D model to maintenance databases which link assets locations and Planned Preventative Maintenance tasks. Location of mobile assets via RFD tagging and triangulation positioning and Wayfinding systems can assist in rapid transition of maintenance crews to the required location. Using QR tags could also assist not only in the rapid acquisition of systems data but in the collection of faults by staff in an ad hoc fashion. By the linking of a BIM into the BMCS these systems can not only log failure in operation but feedback performance data for re-analysis to enable systems tuning many years after the final install is complete.

Using a BIM to carry out risk analysis of egress in Fire or emergency mode or validating security strategies could also be leveraged. In a facility that hosts many exhibitions and productions of the worlds most prominent performers dynamic analysis could be carried out using sophisticated crowd algorithms. While this would be used during design it could also be used after refurbishments are made, or to analyses a unique performances or crowd. The way in which building operations can be linked into a 3D model are endless.

So how do we achieve a 3D BIM model of such an iconic building much of which cannot be easily accessed for accurate measurement? Laser scanning has been employed for capture of the geometry of the outside of the building to represent the outer shell of the building as a point cloud scan (PCS). A PCS is a collection of many single points, recording x, y, and z along with an red, green, blue (RGB) value. Many millions of these points are then collected and when surmised create a highly accurate representation of the geometry and a visual aesthetic of the structure. Some of the more recent projects have been designed using BIM technology by utilising a PCS coupled with feature extraction algorithms to assist in the generation of a BIM. Once the BIM has been established asset data has been populated into BIM elements then extracted into live databases that can be used to inform other systems.

Like any drawing or model it has to be managed and if not it will soon become outdated and the information that it holds unreliable. The size of the data held within models of large facilities is huge and this in itself can be a problem but utilising a federated model, which all revisions are based, is essential to ensure that coordination and currency is maintained.

The Scanning Process

The Process of scanning whole or parts of a building is relatively straightforward but to produce something useful from that scan is much more difficult and involved.

Laser scanners are able to capture data only in the line of site. The amount of scanning is then reliant on the density of these points required and the complexity of the geometry that is being extracted. Flat monolithic features can be captured quite rapidly while intricate complex geometry require a greater number of scans to capture all the information.

Once the data has been collated the information results in many hundreds of gigabytes, and in the case of the House tera bytes of data. Not all this data is useful so the process of post-production begins. Aside from the process of registration overlaps in the data, particularly in complex parts of the structure, often results in a doubling and even tripling of the information. Again algorithms can be employed to undergo a process of data simplification to rationalize the amount of data. This process not only considers data density but also considers geometric shape, seeking to define critical point for optimal shape representation. This assists not only in data storage by producing registered scans that are far more data efficient but in integration and the linking process into a BIM during conversion and extraction.
Fig. 8. Scanned Image of the Concert Hall and Box Office Entry

In addition to BIM generation, laser scans are also an amazing representation of artifacts. This technology has been used all over the world, particularly on artifacts of cultural significance to preserve this information and provide digital access to areas that are usually inaccessible to the general public. Elements can also be reproduced from laser scans using 3D printing technologies for a variety of functions.

Organisations such as Cyark are now storing this information for future generations. Similar to Seed Bank organisations Cyark is a non for profit organisation that has now digitally stored in excess of 250 sites from across the world, the Sydney Opera House among them.

**The House Today**

The continuation of keeping the facility running to its optimal performance—both from an operational aspect and the consideration of the importance the Opera House has to Australia—will continue to strive to utilise new technologies to assist. Future works and ongoing maintenance will always look to what Utzon has achieved and will strive to continue his design philosophies to achieve what was truly an elegant solution to an amazing building.
Notes

i A process called registration which looks to form relationship between scans to enable a consolidated result.

ii A process called discretisation that assesses point density