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Digital engineering - lessons learnt from a major Sydney tunnel project

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ABSTRACT: Over the last 10 years, major tunnel projects have seen a significant expansion in the requirements for digital engineering (DE). Whilst in the building industry, digital engineering requirements have become relatively well defined and developed, in underground construction, some aspects of DE are less clear. Government and industry bodies have the ongoing task of refining guidelines for underground structures by drawing on the experiences and documentation from other parts of the world where digital engineering is well established and also the lessons learnt from previous projects. For example, the unique tunnelling conditions in Sydney and bespoke ground support systems are not well considered by current DE guidelines, which has led to bespoke DE requirements for elements such as ground support. However, other elements such as civil, mechanical and electrical systems are very well defined, albeit they are potentially onerous DE requirements. As part of this paper, the authors will explore some of the challenges faced in delivering the digital engineering requirements for a recent major Sydney tunnel and offer some possible solutions.

1 BACKGROUND

Digital engineering (DE), often referred to as BIM (Building Information Management), is a very broad subject which encompasses the management and processing of digital information through the many stages of development of a project from concept through to delivery and operation. In a NSW, Australia context, one of the major infrastructure asset owners, TfNSW, describe it as “A collaborative way of working, using digital processes, to enable more productive methods of planning, designing, constructing, operating and maintaining assets.” 0TfNSW (2022).

Digital information is extensive on modern major infrastructure projects. DE is not only about the storage of data, but also how data is shared and exchanged across multiple platforms and between the various parties involved in delivery of a project over its lifecycle.

For the purposes of this paper, the authors will focus on one aspect of DE; the creation, development and management of a 3D geometric model based on their views and experiences developing a complex model for a major underground infrastructure project in Sydney. They will focus on some of the detailed challenges which were faced and overcome which are not fully addressed in existing local and international guidelines which by necessity have to be broad and high level to cover a range of applications and environments.

At present, noting that the road transport industry in NSW still requires full production of comprehensive drawing sets and reports, the cumulative impact of design production including DE (both 3D modelling and asset data management) costs the industry millions of dollars. This comes at a time when there is increasing pressure on our industry to reduce escalating design and construction costs. It is recognized that many aspects of DE including clash detection and design coordination offer significant benefits to complex projects. In the long term, there should ultimately be benefits for all parties involved in a project with a reduction of whole of life project costs.

2 APPROACH

2.1 *Current approach*

The rapid progression of technology, software and tools for data management has seen BIM/ DE change how underground infrastructure and tunnelling are designed, constructed and maintained. While the development of DE has improved the way projects are delivered it has also led to a degree of uncertainty and ambiguity regarding some of the DE concepts and their implementation. This uncertainty is also further exacerbated by differences between the expectations of the parties engaged on a project.

At present the requirements associated with the design documentation for major infrastructure projects are particularly onerous. Considerable effort is required to develop design solutions and document outcomes on thousands of drawings and in reports comprising thousands of pages to demonstrate compliance with the guidelines, project particular specifications, design standards and the opinion of the many reviewers involved in a project.

In addition, over the last decade, industry has seen an increased demand for the development of 3D models. This is generally yet to correspond with a reduction in conventional design documentation, reflecting duplication of information rather than replacement. As a result, significant associated effort and cost is added to projects to develop, review, manage and manipulate these models by all parties (Client, Contractor and Designer).

If we take the example of a major tunnel infrastructure project which brings together a diverse range of disciplines including tunnels, civil (alignment, roads, drainage, pavements), structures, mechanical and electrical (M&E), the way in which a 3D geometrical model is created is as equally diverse as the disciplines involved. For example, in the civil environment, complex 3D models have been created for a significant period of time using proprietary software packages such as 12d or OpenRoads. A similar situation exists in underground structures, where 3D models can be created using software such as Civil3D or Revit. In M&E, Revit is often the preferred modelling tool. However, for tunnel engineering design, where it is necessary to create long linear models along a control alignment, which includes complex geometry at cross passages, ventilation structures and underground traffic merge/ diverges, although there are proprietary software packages on the market, most have limitations. Further discussion on the modelling tools for tunnels is included below.

Cross discipline coordination; although an essential part of design development on large infrastructure projects; and coordination of 3D models takes considerable effort for a number of reasons:

- Package sizes and boundary limits vary between disciplines.
- The design program for each discipline are phased and sequenced slightly differently.
- There are many cross-discipline dependencies on large infrastructure projects which need to be frozen at different times to enable designs to be fixed.
- The level of design detail required for each discipline may vary.

As a result, a dedicated DE team is required to facilitate and navigate the complexities of interdisciplinary model coordination.

2.2 *Future approach*

Ideally, as technology develops, the significant effort required to create, develop and coordinate a 3D model will be offset by a reduction in other aspects of design documentation. However, this will require a change in the approach to some aspects of design since at present this is not feasible for a number of reasons:

- On most major transport projects there is no requirement for models to be certified, which would be necessary if they are to be used as a basis for construction. For example, on recent D&C major tunnel projects the Contractor has built an independent 3D tunnel model from the 2D information provided as part of the design documentation and used the 3D model provided by the Designer as a reference source to provide additional supplementary information in geometrically complex areas.

- Drawings associated with underground construction include a substantial number of notes which provide additional details and guidance on design boundary conditions, limitations and construction sequences. In a 3D model, where would these notes and details live?
- Can 2D drawings be created from 3D models? The answer is yes but this needs to be qualified because the intelligence of geometry (radii, angles, arcs) are often lost as geometry is converted to polylines or segmented arcs comprising a series of short straights to idealise a curve.
- How are the tunnel excavation and support sequence requirements such as maximum advance lengths for different ground conditions supposed to be captured in a model?
- Where the design includes a suite of pre-determined tunnel support types which are applied based on the exposed ground conditions, how can these be included in a 3D model?
- Do subcontractors have the capability to view manipulate and interrogate 3D models or do they require information to be distilled into a series of drawings and schedules?

3 LESSONS LEARNT ON A MAJOR TUNNELLING PROJECT

Over the last 10 years, industry has experienced progressive growth in DE requirements. A number of the authors' recent experiences are described below.

3.1 *Level of detail – How detailed is detailed enough?*

This is a complex issue because the expectations within a project team (Designer, Contractor, Owner, Operator) can vary significantly. It is therefore important to establish a clear set of guidelines and project requirements to achieve alignment.

Currently in Australia, guidelines only partially exist. There are no tunnel specific guidelines, although there are a number of standards and international guidelines which provide guidance such as 0 AS ISO 7817 (2024), 0 AIA (2024). In addition, the ITA WG22 is in the process of drafting a guideline for tunnelling 0 ITA (2022) and 0 Vojtech et al (2022) . These documents are high level and hence general in nature. At a local level clients have created a digital framework 0 Sydney Metro (2021) and 0, 0, 0 and 0 TfNSW (2022) to support projects and provide a means of connecting technologies across various disciplines. At a project level, clients create specific digital engineering technical requirements.

Whilst for disciplines such as civil, structures/ bridges, pavements and drainage, the requirements are well defined, in tunnelling the requirements are less clear. As a result, there is a need for guidelines regarding the level of detail that is necessary and achievable in 3D models. In the authors' experience there is often a tendency to over specify and request unnecessary detail.

International and local guidelines and standards often refer to this as the LOD, which is a confusing acronym as both level of development and level of detail are very different. Furthermore, the BIM Forum 0 AIA (2024) introduced the concept of Level of Information Need as described below as shown in

Figure *1*.

Level of Information Need, as defined in 0 AS ISO 7817-1:2024, is the quality, quantity, and granularity of geometric, alphanumeric, and documentation information to be included in a deliverable. While Level of Information Need requires geometry to be defined, it provides no guidance on how to do so.

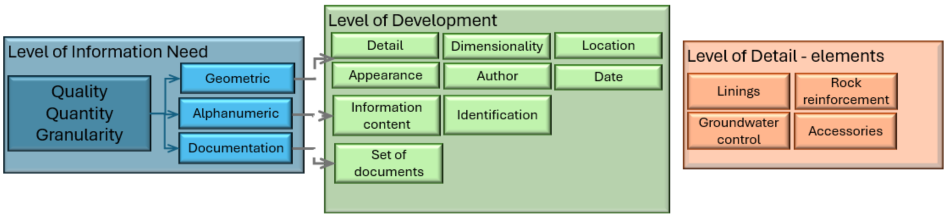

Figure 1. Relationship between Level of Detail and Level of Information Need

– Level of Development (LOD), which sits within the broader framework of Level of Information Need, defines the detail, dimensionality, location, appearance, author, and date of geometric information.

Therefore, in order to determine an appropriate level of detail for inclusion in a 3D tunnel model, it is important for the following aspects to be clearly understood:

– The specifics of the tunnelling environment
– The types of tunnels which are typically constructed and the uniqueness of the ground support systems which are employed
– The construction sequences which are adopted

For example, this is particularly important in Sydney where the underground environment is generally suited to the construction of drained tunnels and caverns which form a complex arrangement of large inter-connected spaces as shown in Figure 2. Within these underground networks, the ground is typically supported with a combination of permanent rockbolts and permanent sprayed concrete (shotcrete) linings 0 Czegledi et al (2020) in pre-designed support types, developed to suit the different predicted ground conditions. The actual support type cannot be determined until the ground conditions are exposed and known. Therefore, inclusion of the actual ground support in a 3D model including individual rockbolts, spiles or canopy tubes is not practical. Instead, design shotcrete thicknesses can be modelled based on agreed tolerances and a surface created depicting the distal end of the element as shown in Figure 2.

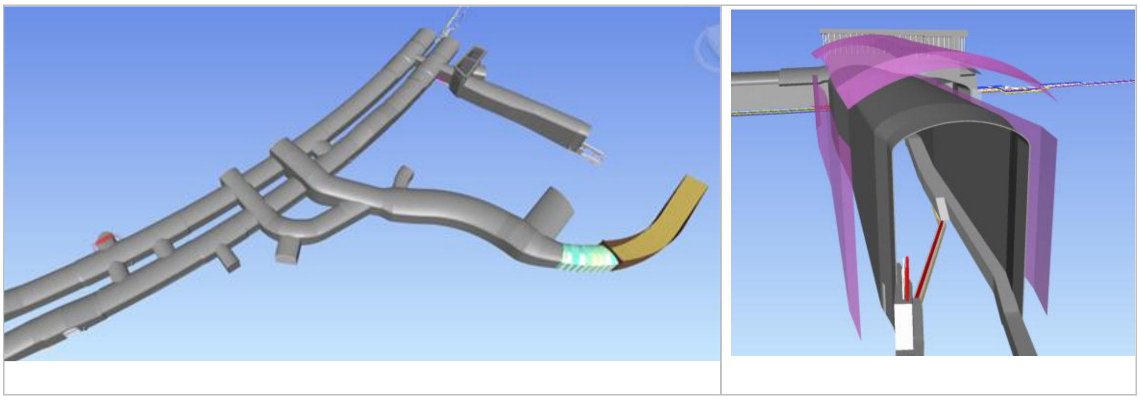

Figure 2. Approach for modelling rock reinforcement

The level of detail to be included in a model at various design gates is another area where differing expectations exist. International guidelines such as 0 DAUB (2019) and also 0 TfNSW (2022) suggests that the detail within a model is progressively developed and enhanced as designs are progressively refined through a series of design gates or stages. Whilst this approach is satisfactory in theory, a more appropriate approach would be to include more detail in the early design stages where feasible but qualify the elements in terms of their reliability, ie the level of development. The reason for this approach is because:

– The inclusion of the necessary objects, layers and thicknesses in a model in the early stages, even if there is uncertainty associated with geometry helps with interdisciplinary coordination and visualisation of complex areas.
– As shown in Figure 3, in areas such as the cross-passage junctions in a road tunnel, where there are a significant number of services and interactions, the geometry particularly complex. Hence modelling a bank of services as a box 0 AS ISO 7817-1:2024 rather than individual conduits does not provide a realistic representation of these complex areas. It would be more valuable to make assumptions regarding the number, size, spacing which would enable coordination with other services and disciplines to commence earlier than would otherwise have been possible. Hence pinch points could be identified and additional space incorporated early in design development rather than late when the impact of design changes has increased knock-on effects.

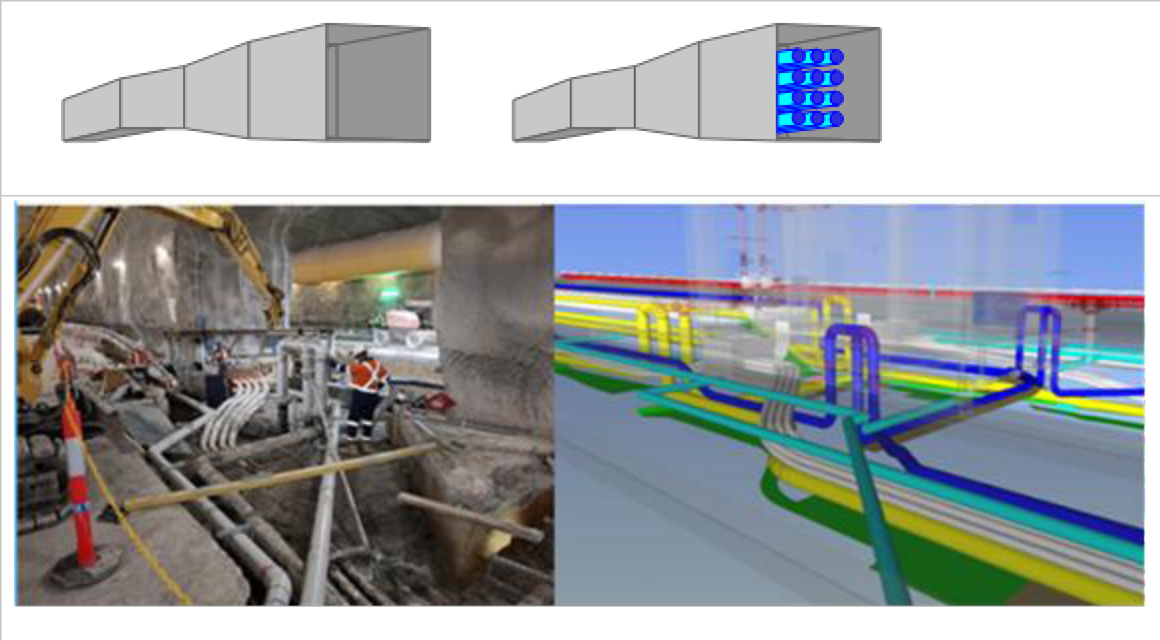

Figure 3. Example of complex services interactions

3.2 *Application of tolerances*

Construction of any form of infrastructure is not an exact science. For example, precast concrete tunnel segments incorporate very small tolerances because they have to be cast with a high degree of accuracy but the tolerances applied to the excavation of a mined tunnel have to be large, because of the accuracy of the plant which is used and because the elements which have to be included within the tunnel require different tolerances. This is why an important part of design is to consider how tolerances are applied and hence how they influence design assumptions. Hence in the old (non-DE) world, perfection was not required in design documentation provided key dimensions were defined. In the current world, where everything is modelled in a 3D environment, all too often we find ourselves chasing unnecessary high degrees of accuracy because, as an example, connections do not intersect correctly in a model which creates errors and clashes. Future projects should consider a pragmatic approach to clashes associated with tolerances, where real clashes can be differentiated from those that are the result of the cumulative effect of unlikely tolerances.

3.3 *Software and modelling challenges*

As noted above, there are many proprietary software packages on the market which can be used for design and 3D modelling of the various elements within a tunnel. These include Synergy 12D or Bentley OpenRoads for alignment, pavements, barriers and drainage design, AutoDesk Civil 3D and Revit for structural work.

3.4 *Tunnel*

The experience of the authors has highlighted that creation of a 3D model of the tunnel support system, which can comprise multilayer shotcrete lining shells, rock reinforcement, waterproofing layers and reinforced concrete linings and segments, temporary support elements is not straightforward. Whilst there are proprietary software packages on the market, such as 12D, Revit, Rhinoceros and Infraworks, they all have limitations. They may be able to accommodate uniform geometry well such as a segmentally lined bored tunnel or tunnel which incorporates a cast concrete lining but in Sydney, the prevailing ground conditions enable construction of particularly complex geometries which require complex geometrical transitions between uniform and non-uniform tunnel profiles. These complex geometries (see Figure *2*) prove challenging to model, particularly with string-based modelling programs.

In addition, as tunnellers and constructors of long linear infrastructure, we like uniformity. Uniformity means simpler design and easier construction, which also results in reduced programs and lower capital costs. However, whilst in theory it may appear that there is repetition between sections of tunnels, such as say the layout of services in cross passage apron areas, geometrically they can all be slightly different because control lines may not be perfectly parallel or at exactly the same elevations or junctions may not be precisely 90degrees. These are important factors which must be addressed if a 3D model is to be developed, which is accurate and suitable for use as a source for construction.

In the background behind any type of 3D model is a huge amount of data, which includes the following:

– Input parameters from different disciplines such as geometric profile data eg, coordinates, chainages, alignment data, space and clearances for civil and structural fitout within a tunnel, M&E equipment and systems or construction requirements and egress requirements.
– Output data such as the parameters which define a 3D shape such as the centre point of arcs, their lengths and radii together with start and end chainages for profiles.

Storage and management of all this data as well as the coordination of changes to this data as a project develops and evolves is therefore a complex process.

As a result, on recent major tunnel project, advances have been made in the storage of data, management of changes and creation/modelling of the tunnel shell and complicated geometrical transitions. This has been achieved as follows and illustrated in Figure *4*.

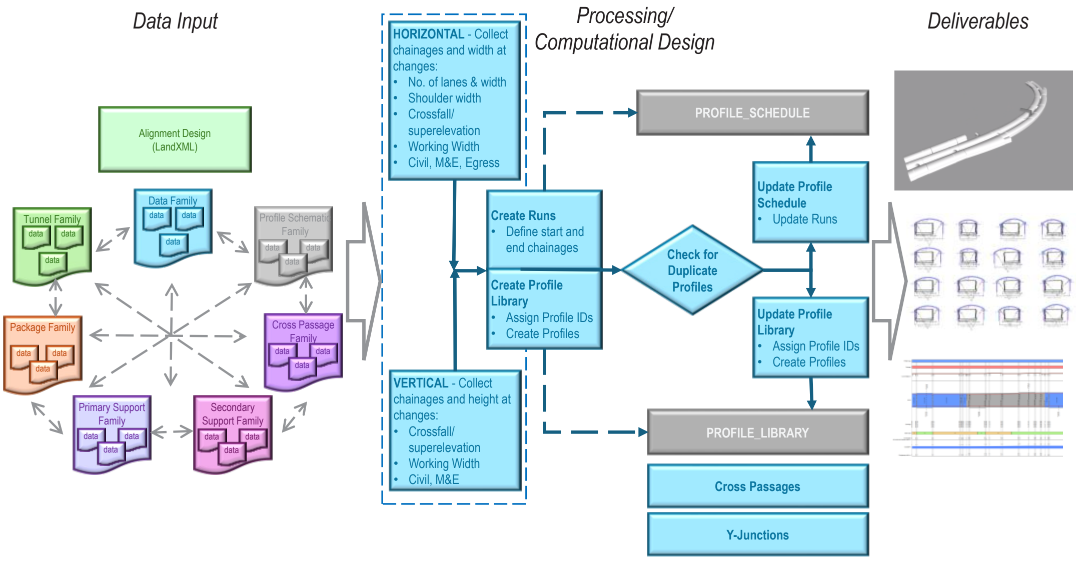

Figure 4. Process for creation of 3D Tunnel Model

– Refinement of the methodology defined in 0 Czegledi et al (2020) into a workflow which recalls geometric design parameters, runs them through in-house processing scripts which create a 3D tunnel shell and then outputs the data into a variety of formats for downstream use such as design deliverables.
– Using a database which contains a series of linked tables that use unique parameter names which creates consistency and avoids data repetition.
– Development of a series of coded scripts using C# and Grasshopper to create the tunnel shell.

3.5 *Automation*

An enormous number of parameters and variables are used in the development and definition of a 3D model. As a result, there are many opportunities for errors to occur if data is incorrect and changes are not appropriately controlled. The definition of the tunnel shell is the outcome of cross-discipline coordination and consideration of tunnel design inputs which can easily be overlooked during the busy delivery phase of a D&C project. Automation is an important tool in reducing the workload associated with maintaining coordination between disciplines. This type of difficulty can be overcome through automated coordination of design inputs. For instance, as shown in the workflow outlined in Figure *4*, the incorporation of the road design as alignment strings is an automated process. Any changes to the road design are transferred automatically into the tunnel modelling process giving real time outputs. Previously this type of design change would have been implemented manually which takes time and risks errors. However, for the process to be automated data must be shared in a particular and consistent format to suit the code routines which have been developed.

An understanding of the input design is also required, while the layman may expect the widening of the edge of a traffic lane to be a straight edge change in direction this is in fact often represented in road modelling software as a chamfer between two straights. For identification of a change to the tunnel profile a simplification on the tunnel design side needs to be implemented as part of the automation.

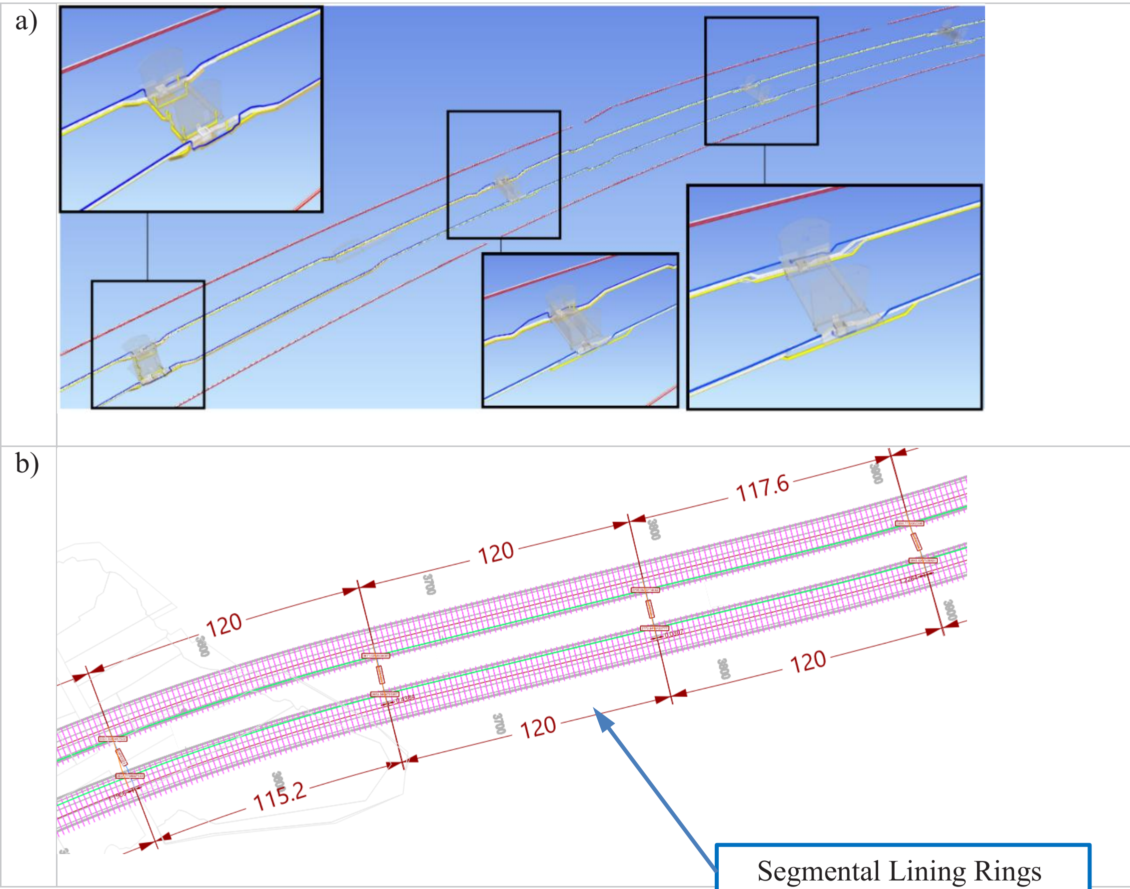

Figure 5. Uses of CoDe a) Buried Services b) Cross passage set out

In addition, the linear nature of tunnels creates opportunities for standardisation and repetition of common elements. Some elements of tunnel modelling such as creating tunnel profiles, modelling of buried services or setting out cross passages are therefore ideally suited to automation and adoption of computational design (CoDe) routines.

For example, Figure 5 illustrates how CoDe has been used to define the layout for the buried services in standard cross passages. However, whilst in the example there appears to be significant repetition, in reality, each cross passage is geometrically slightly different because they are at different locations along the alignment. Hence the tunnels at each end are at different levels, the tunnels are not perfectly parallel and the alignment geometry is different at each location. As a result, the cross passages may not all be at exactly 90° to the mainlines. These are all important aspects to consider because the routines developed need be cognisant of the geometric variations.

Similarly, setout routines can also be developed for cross passages by checking the distances around curves such that that the maximum spacing is never exceeded as shown in Figure *5*

3.6 *Asset Referencing*

The long term usefulness of a 3D Model is its ability to be used during construction and operation / maintenance. The correct referencing of assets is integral to this and the scope for use, particularly in asset management is broad.

In the authors' experience asset referencing during the design process faces similar difficulties to that found in implementation of LoD requirements. While referencing is useful in finalised models, the effort expended to perfect and keep it updated during the stages of design development is disproportionate to value added.

Anecdotally the uptake in the use of the 3D model during construction activities is limited. This could be due to a number of factors including lack of integration into construction workflows, availability of appropriate software, limited skills in interrogating 3D models and impracticalities involved in taking screens into the tunnel.

The future use of the 3D model as an asset maintenance tool is an intended outcome of the high LoD requirements during the design phase, and further research into the successful implementation of the 3D model into asset maintenance processes is recommended.

4 CONCLUSIONS

As technology continues to advance and the benefits and capabilities of 3D modelling continue to be realized, there are significant opportunities to streamline design and construction processes. In particular, there are a number of areas for focus such as:

- Implementation of practical approaches to digital documentation requirements (LoD, tolerances and asset referencing) through the various design stages.
- Smart automation of workflows to facilitate collaboration, particularly asset referencing.
- Streamlining of design documentation and reduction of duplication.
- Improvements and changes to the ways of working on site.

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