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The application of building information modelling across the road project life cycle

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Roads are an integral component of civil infrastructure, providing safe and reliable connectivity between origins and destinations. With rapid urbanisation and the pursuit of smart cities, the demand for effective road planning, design, construction, and maintenance continues to grow. Sustainability and innovation are increasingly central to this process, driving the development of better and more intelligent infrastructure solutions.

Building information modelling (BIM) has been implemented, adopted, and mandated by many countries across the world as an intelligent and innovative necessity for enhanced civil infrastructure planning, design, construction, and maintenance. Numerous technical papers and demonstrations have explored the application of BIM across a range of projects, with the majority focusing on the built environment.

This paper provides an overview of how BIM technologies can be applied across the phases of a typical road project life cycle. It aims to highlight the pertinence of BIM in road infrastructure, giving road professionals insight into its practical application and associated benefits. In particular, it considers how BIM can help address common project challenges, as well as recent developments in its integration with complementary technologies such as geographic information systems and artificial intelligence.

Keywords: building information modelling (BIM), civil engineering, construction management, digital transformation, road design and construction

INTRODUCTION

Building information modelling (BIM) can be described as an intelligent technological process that gives architecture, engineering, and construction professionals the insight and tools to better plan, design, construct, and manage buildings and infrastructure, with all project information housed within a common data environment (CDE). BIM is inherently collaborative and information-driven, and is underpinned by the ISO 19650 series, an international standard for managing information over the entire life cycle of a built asset using BIM principles. BIM extends beyond 3D models on a project (3D), with the ability to integrate additional dimensions such as time (4D), cost (5D), operations (6D), and sustainability (7D) (Patel 2025), which can be leveraged by companies and professionals to arrive at more optimal solutions.

This results in a data-rich project information model, which ultimately evolves into an asset information model (AIM) upon project handover. The AIM supports more effective operations and maintenance by fulfilling the role of the digital replica in the digital twinning process, which integrates the internet of things (IoT) for smart asset management.

BIM has predominantly been championed by architects, but its application and adoption in civil engineering is increasing. A survey conducted in 2019 by the Institute of Civil Engineers (ICE) and ALLPLAN UK involving 250 ICE members measured the civil engineering profession's latest progress in implementing BIM. Participants in the survey included civil engineers, technicians, designers, and consultants from a variety of organisation types. According to the survey, most civil engineers (82%) believed the adoption of BIM was a smart decision, with over a third stating it has

contributed to increased profitability (35%) and delivery speed (41%), as well as reduced cost overruns (37%) (ICE & ALLPLAN UK 2019).

In the context of road projects, BIM can be seen as a necessary means to overcome challenges and pressures faced by the road infrastructure industry and its professionals in an increasingly urbanised world. This paper provides a high-level technical overview of BIM and related technologies across a typical road project cycle and equips industry professionals (primarily consultants, design, and construction professionals) with insights into how they can leverage technology to arrive at road solutions that are more efficient, effective, and innovative. Ultimately, it aims to encourage and promote a higher adoption of BIM and innovative practices in South Africa and developing regions for effective road infrastructure delivery.

BIM ACROSS A TYPICAL ROAD PROJECT LIFE CYCLE

Planning and conceptual design

Site creation

BIM technologies can be applied as early as the proposal stage, providing consultants with intelligent, dynamic data. With the road location and characteristics defined in the tender briefing, model creation can now begin. Depending on BIM technology capabilities, online cloud and geospatial engines can be utilised to arrive at the creation of a site model which could comprise:

- A geolocated site with the associated aerial imagery
- A preliminary survey/terrain surface of the site extents (elevation data)
- Relative positioning of infrastructure within the site vicinity (roads, buildings, rivers, etc.)
- The ability to incorporate geographic information systems (GIS) data (existing infrastructure information), supporting better contextual planning.

Roadway creation

With an intelligent, parametric site model created in minutes, road design can commence. The horizontal and vertical alignments can be designed in accordance with standards such as AASHTO, including widenings, intersections, and roundabouts. Design automation and intelligence provided by BIM technologies will vary by vendor,

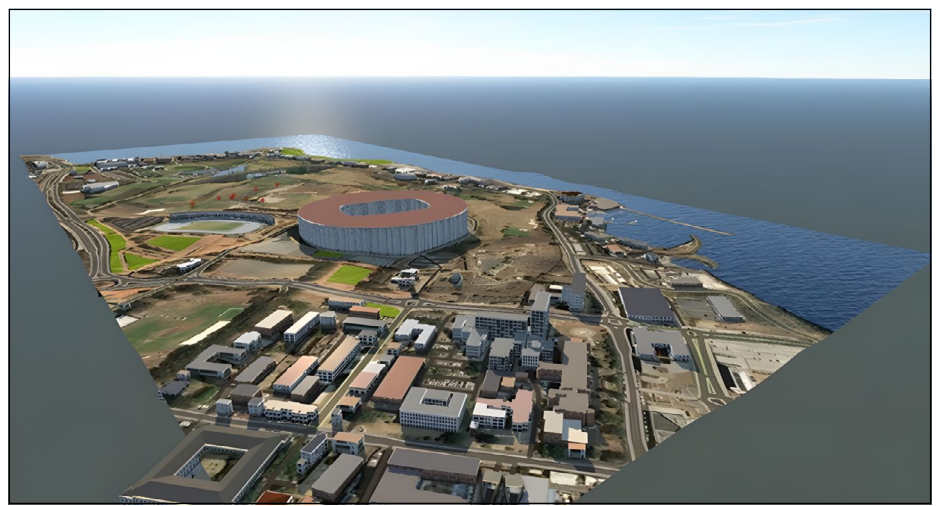


Figure 1 Example of a site model around Green Point Stadium in Cape Town (created by Shuaib Yunos using BIM technology)

with notable functionalities provided by the BIM software used in this paper being:

- Automatic creation of road intersections upon intersection/crossing of road alignments which can be modified accordingly, with the ability to swap to a roundabout
- Modification on road cross section, alignments, and profiles relative to preliminary terrain data
- Integration with a variety of data sources such as GIS, point clouds, and 3D model files
- Cloud computational functionality such as watershed and road drainage analysis, traffic and mobility simulations, and road profile and corridor optimisation analysis which takes into account the terrain, cost, avoidance zones, and specified geometric criteria to generate a suitable route, with the option to automatically insert bridges and tunnels (based on constraints input

by the designer) between the specified start and end points of a road

- The linking in of best derived/suitable routes from GIS applications
- Contextual design and quantification of road and related infrastructure (earthworks, pavement layers, kerbing, light posts, barriers, etc.).

These capabilities, available at the early stages of a road project, equip road professionals and consultancies with the information needed to develop multiple viable design options, enabling the selection of the most appropriate solution aligned with the project's objectives, requirements, and cost constraints.

The project and associated data are stored in a CDE, ensuring that all project data is in a central location. CDE features will differ based on vendor offerings, with this paper using a cloud-based CDE that integrates with the BIM technologies used, ensuring streamlined project coordination

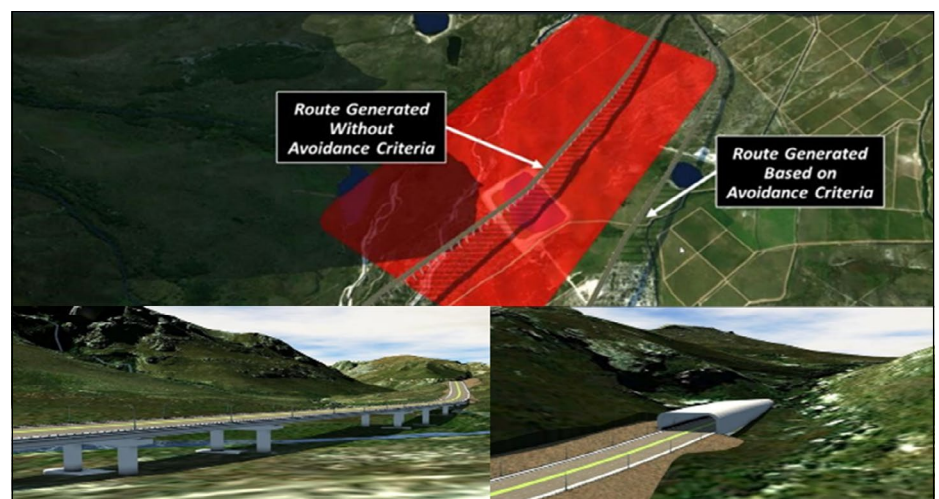


Figure 2 Example of cloud computed road routing result with an avoidance zone and automatic insertion of a parametric bridge and tunnel (corridor optimisation) (created by Shuaib Yunos using BIM technology)

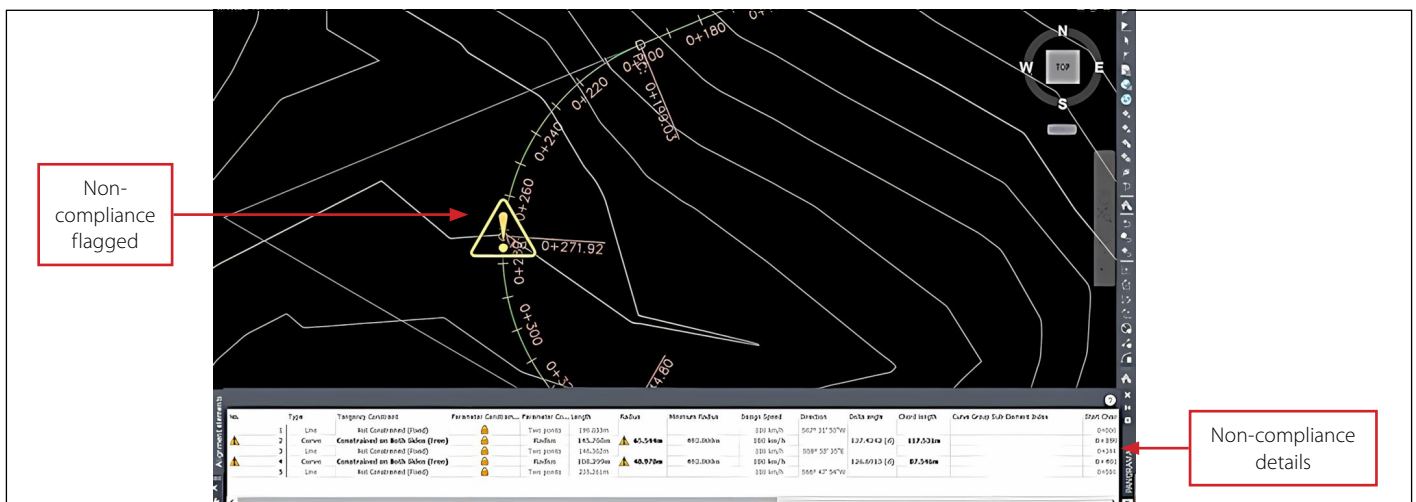


Figure 3 Curve radius automatically flagged as non-compliant for design speed (created by Shuaib Yunos using BIM technology)

and collaboration, including a range of team and document management features such as access levels, automated file version control and tracking, and mark ups.

Detailed engineering design

Upon completion of the conceptual design, the 3D model and associated data can be incorporated into the detailed design phase. The BIM technology used in this paper enabled the linking of the conceptual design files from the CDE directly into the detailed design applications. This reuse of data eliminates the silo effect experienced in traditional workflows, saving time and rework. The road design can now be tweaked much more stringently to comply with engineering standards. Conceptual terrain/survey data in the conceptual phase can be updated or replaced upon receipt of the detailed survey data, and due to the dynamic nature of BIM technologies, all associated data will update accordingly in line with the newly set data reference. Geometric design components such as sight distance, superelevation and other

associated standards can be set, flagging noncompliance automatically as illustrated below.

Further customisation and automation can be incorporated using supported add-ons, plugins, scripts, visual scripting, customised objects/libraries, and catalogues. Point clouds can be incorporated during the conceptual or detailed engineering design depending on availability or access, from which a triangular irregular network (TIN) surface can be extracted. This TIN surface can then be referenced for detailed engineering design and analysis. Swept path analysis can be conducted to validate the suitability of the road corridor for the desired design vehicle, producing an envelope depicting the vehicle's movement. This analysis is popularly used to gauge the suitability of curve radii and roundabouts based on the envisaged traffic and design vehicles.

GIS data can also be incorporated into the detailed design, promoting contextual design relative to the project area and surrounding infrastructure/environment.

For stakeholder input and design reviews, the detailed design can be pushed back to the conceptual design environment. This results in teams being able to view the technical data in a highly visual manner, which can be used to communicate progress and design intent to non-technical project members.

Clash detection and interference checks can also be conducted by teams to ensure that their designs do not interfere with other disciplines and surrounding infrastructure, proactively identifying construction issues/conflicts ahead of the construction phase. This is usually achieved by sharing the design models to the BIM coordinator, who is responsible for aggregating all design models from all disciplines, arriving at an aggregated model that can be reviewed for constructability issues/clashes. All files are stored and shared using the CDE, with issues, markups, and revisions digitally tracked for enhanced transparency.

Stormwater design

With the road corridor being optimised and designed as per design standards, the road stormwater network can be concurrently designed and analysed. The network can be used to further justify the correctness of the corridor based on runoff and stormwater flow, ensuring the efficient and effective discard of runoff, contributing to safety and design life. A watershed analysis can be run on the site extents, resulting in the derivation of catchment areas based on the topography characteristics, as illustrated in Figure 5.

With the watersheds computed, the network can now be modelled and analysed. This can be done using the features available in the chosen BIM technology,

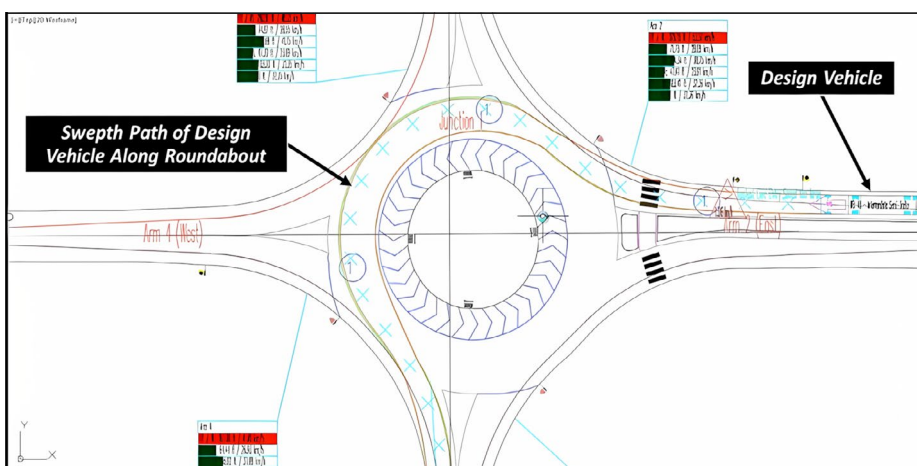


Figure 4 Simulation of a design vehicle's swept path to check design suitability (created by Shuaib Yunos using BIM technology)

or with an add-on for further automation. For this paper, a locally developed South African add-on was used for stormwater design and analysis, which included other automated features relative to road design, and content suitable to the South African market. The process comprised the automatic creation of a stormwater network from a polyline and modification of road corridors using popularly used pipe and structure catalogues in South Africa, including local road kerb catalogues and typical cross sections.

Bridges

When it comes to roads and bridges, coordination between geometric and structural professionals is of critical importance. With the advantage of streamlined coordination provided by BIM technologies, geometric and structural professionals are interconnected, with each team prompted if any changes occurred. The workflow applied links the bridge with the road corridor, and due to the parametric nature, adjusts the bridge components accordingly upon updating, facilitated using the CDE. The rebar detailing, bending schedules and bridge quantities can be extracted from the bridge model and, with the use of rebar constraints, the rebar requirements can be updated in the case of geometry changes.

This interconnectivity between disciplines can also be leveraged to ensure that design models are correctly geolocated, where project components by disciplines

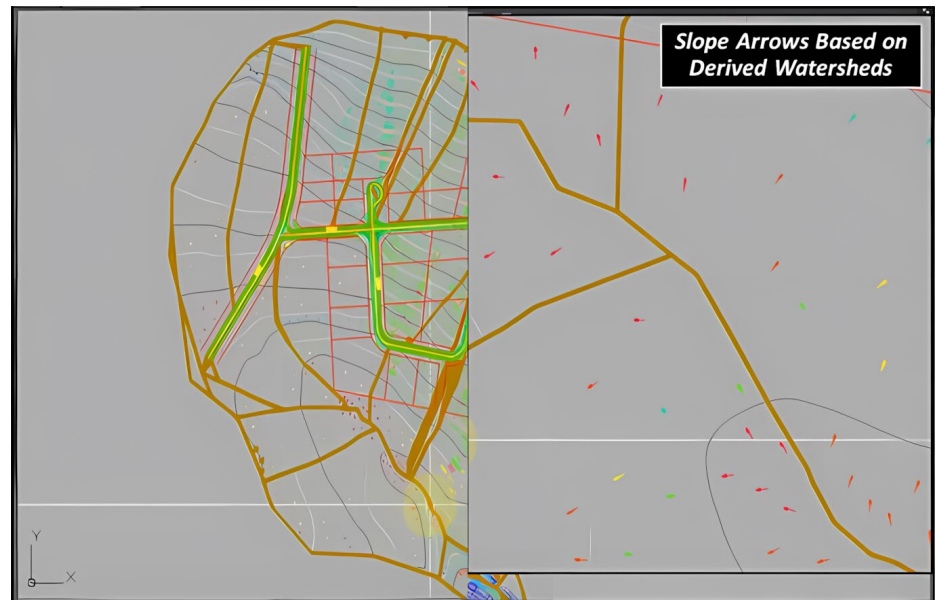


Figure 5 Watershed analysis computation (created by Shuaib Yunos using BIM technology)

such as architectural and structural are positioned correctly on the site layout, having the correct coordinate system information crucial for accurate setting out on site.

Construction documentation

With the detailed engineering design complete, construction documentation such as road construction drawings can be derived from the model, setting out data and quantities. Excavation quantities for the stormwater network can also be derived, as illustrated in Figure 7, in accordance with SABS 1200. This includes the quantification of both pipes and associated structures.

Construction and project management

With all the project information housed in the cloud CDE, design and construction teams can easily be given access to the data they require. All other features and benefits mentioned previously are still available to teams during the construction phase. CDEs with mobile connectivity or dedicated apps can be used by construction teams, ensuring dynamic communications with the design office on elements such as construction issues, requests for information, logging of site conditions, attaching photos, claims, punch lists, etc. This ensures that instructions and feedback are received



Figure 6 Randselva Bridge, currently the world's longest bridge built without drawings using BIM (Savland et al 2022)

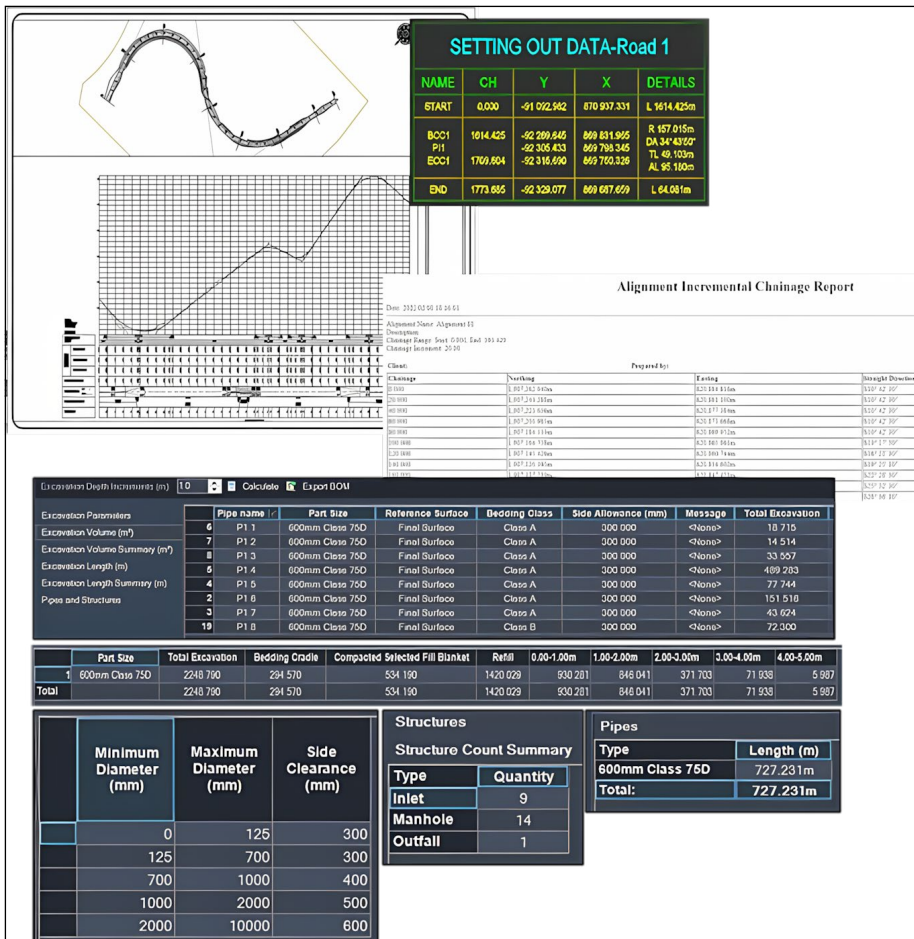


Figure 7 Construction documentation and design outputs (created by Shuaib Yunus using BIM technology)

as soon as possible, mitigating delays. Depending on CDE vendor, the CDE may have an array of project management features to track and monitor activities during construction, having available dashboards that display data as the project progresses,

with the possibility to add custom integrations and data sources.

Other features advantageous to construction professionals include approvals (for example logging a claim using an automated preset workflow with the outcomes

being approved, rejected, need more info, etc.) and capturing of site meeting minutes and follow up tasks that can be assigned to individuals or teams. Specific forms, QA/QC files, templates, schedules, etc. can be uploaded to the CDE, so teams have access to them for their required tasks, enhancing project quality and standardisation.

All information is tracked within the CDE, which maintains a complete digital audit trail of activities (user, time stamp, actions, etc.) and can be exported where required. In the case of sites located in remote areas with limited or no internet connectivity, there are BIM apps that allow data to be captured and stored offline on the device. This information can then be synchronised once connectivity is restored, or alternatively uploaded manually to the CDE when an internet connection becomes available.

As-builts

Upon completion of construction, as-built records can be generated by incorporating survey levels captured by the surveyor into the BIM model. Elevation profiles can then be adjusted to reflect any discrepancies between the design and constructed works, after which updated documentation can be produced and issued for handover.

Another option enabled by BIM technologies is the use of laser scanning and photogrammetry via unmanned aerial vehicles (UAVs). A predefined UAV flight path can be used to capture the project area, with surveyed ground control points

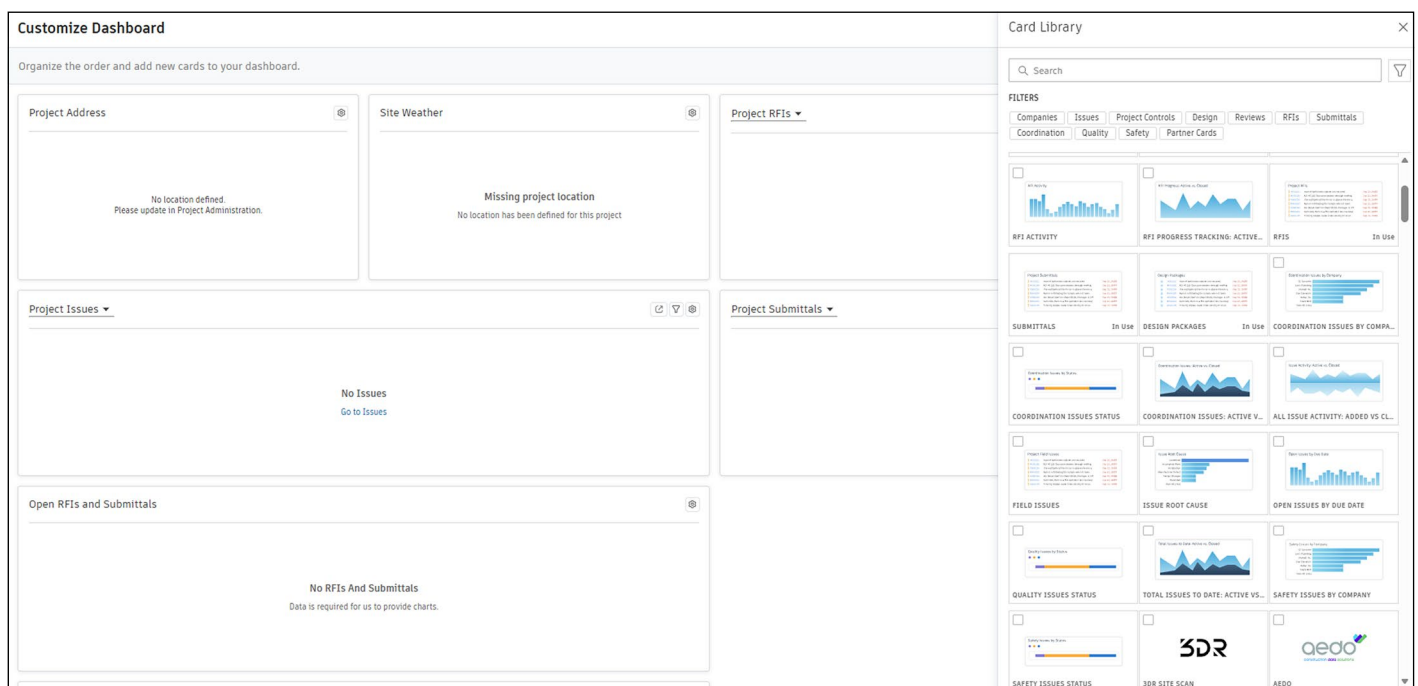


Figure 8 Example of a project CDE dashboard

integrated to improve the accuracy of the dataset. The resulting photogrammetry and/or laser scan data can then be registered and processed to generate a point cloud.

Linear extraction features can then be used to derive elevation profiles for elements such as the road centreline, edge of travel way, and other required datasets. These extracted features can be imported into the supporting BIM platform and used as profiles to generate the road corridor model. From this, the necessary construction documentation can be produced to support the as-built handover.

Depending on the project conditions agreed at project inception (as defined in the contract and other binding information), the BIM model itself may or may not form part of the final deliverables. Where the model is included in the handover, this may be subject to additional fees as agreed with the consultant.

Operations and maintenance

Condition assessments

UAVs are becoming increasingly popular in capturing the existing conditions of the roadway over time, at scheduled intervals. This saves on time required, and captures the site extents in its entirety, allowing maintenance teams to make better decisions and propose the best remedial options.

Should the BIM model be available to the asset owner (usually the local municipality), this data can be overlaid on the as-built BIM model and updated accordingly. This updated model can then be uploaded to the CDE using the same file/model name, which will allow the cloud to keep track of the version history and compare the changes over the design life of the roadway. These changes and developments can be studied, and lessons and data acquired applied to future road projects resulting in more resilient road infrastructure.

Digital twinning

Digital twins (DT) is a trending topic in the industry and can be applied to individual assets or collectively in the pursuit of smart infrastructure and/or smart cities. The BIM model can be used as a foundational requirement in this process, serving as the digital replica of the roadway. With the use of IoT, sensors and dashboards can be configured to monitor the roadway

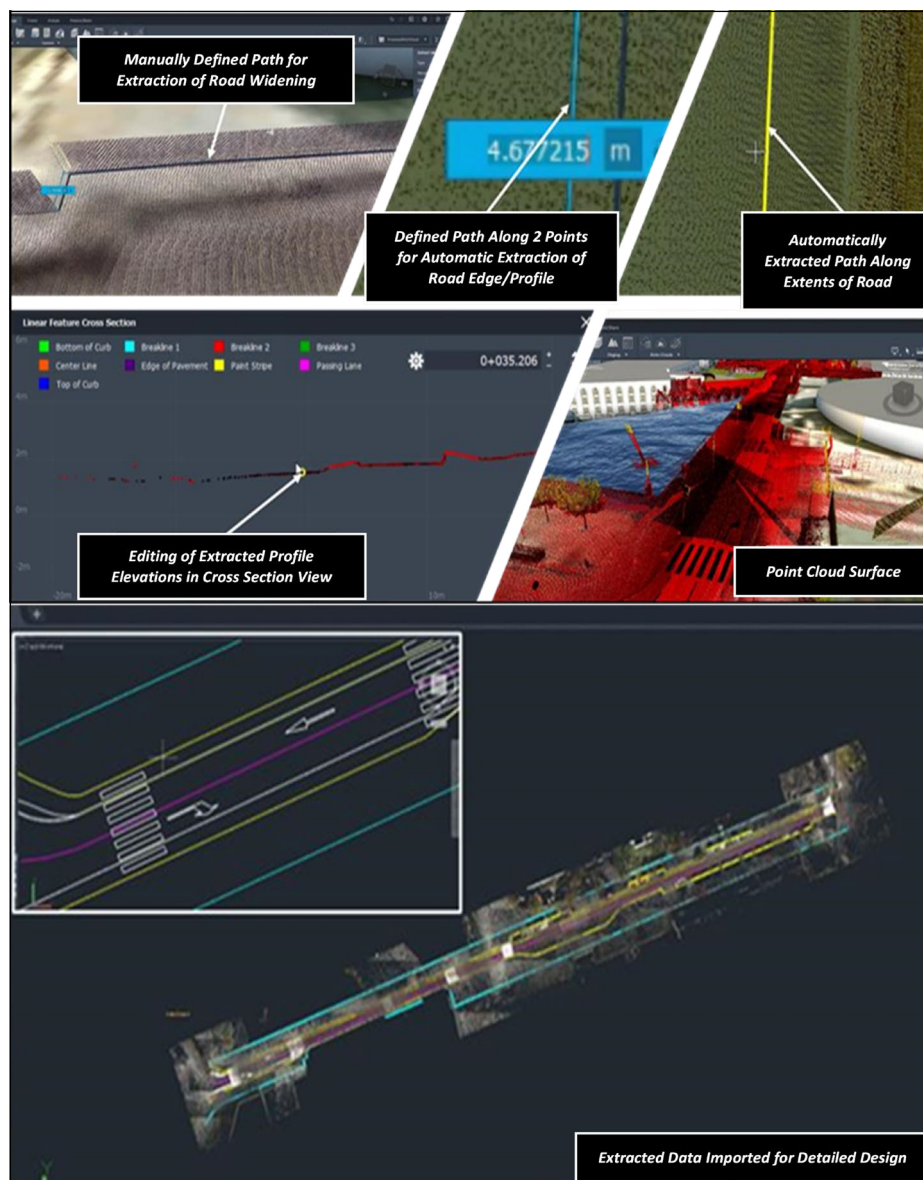


Figure 9 Linear road features extracted from point cloud of existing road (created by Shuaib Yunos using BIM technology)

in real time. Aspects such as traffic and pavement conditions can be monitored and actions taken based on data feeding into the DT, resulting in preventative rather than reactive maintenance. This DT can then be incorporated into the DT of an entire city or region, taking into

consideration surrounding infrastructure and occurrences.

FINDINGS AND BENEFITS

Once consultants are awarded a project, the model created during the proposal stage

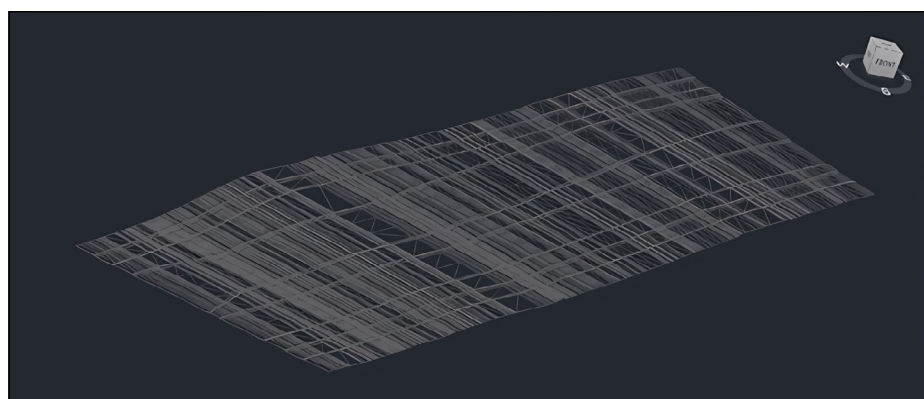


Figure 10 Extracted TIN surface from an existing roadway (created by Shuaib Yunos using BIM technology)

can be reused and further developed during the preliminary design phase. The ownership and management responsibilities of the model are typically defined in the BIM Execution Plan, which serves as a project charter outlining the roles, responsibilities, workflows, and deliverables associated with the project. This approach helps eliminate the siloed workflows often associated with traditional project delivery methods, where consultants are dependent on receiving survey information before design work can commence. By leveraging BIM technologies and integrated workflows, design development can begin earlier and progress more efficiently. As a result, consultants are often able to advance substantially towards detailed design during this stage, reflecting the progressive shift in effort illustrated by the MacLeamy Curve in Figure 11.

The MacLeamy Curve compares traditional and preferred project delivery approaches in relation to the ability to influence project cost and the cost of design changes. BIM aligns closely with the preferred approach, where a significant portion of project effort is concentrated during the transitional phase between preliminary and detailed design, represented by the peak in Graph 4 of Figure 11. This is made possible by the insight, intelligence, and versatility provided by BIM technologies from the outset of the project life cycle, enabling consultants and designers to troubleshoot, compare and analyse their designs before construction.

With the level of flexibility and intelligence available at this stage, consultants and designers are often able to develop designs to a detailed or even final construction level. This is enabled by the time savings, automation, intelligence, and efficiencies offered by BIM and cloud-based technologies and the possibilities they afford from the preliminary design stage, including the negation of data loss from the proposal stage.

When reflecting upon traditional processes versus BIM approaches across the road project life cycle, it is apparent that BIM is the more intelligent, efficient, and economical approach, aligning closely, if not perfectly, with the MacLeamy Curve. BIM therefore presents the following main benefits:

- Proposal preparation and submission by civil consultants is more intelligent, efficient, and economical, affording the consultant the versatility to provide design options, 3D visuals and terrain/elevation data that is reusable and dynamic.
- BIM enables consultants to be more creative and competitive, increasing their chances of winning a bid, while providing greater insight and tools for contractors to schedule and manage their construction programmes.
- Cloud computing and intelligence can be applied for design optioneering, including GIS and a variety of available data sources to propose the most sustainable and economical solution

for route determination, with multiple options in one model.

- Road intersections, roundabouts, interchanges, widenings, superelevation, and other design criteria are intelligently designed using criteria-based design and automation.
- Associated road infrastructure such as stormwater networks, bridges, tunnels, and services can be easily integrated into the design, with enhanced coordination and analysis capabilities.
- Quantification is automated and dynamic, resulting in an accurate bill of quantities.
- BIM workflows and a common data environment eliminate the silo effect, ensuring all data is accessible, usable, and housed in a secure central location, providing a single source of truth.
- Direct integration of BIM and cloud technologies, as well as the broader available ecosystem, provides an unprecedented advantage in which teams can connect and collaborate from any part of the globe.
- Clash detection can be executed before hitting the ground in construction, reducing or avoiding errors and costly construction bottlenecks that affect service delivery.
- Design vehicles can be simulated and analysed in terms of their axle configurations and swept path envelopes to ensure that the roadway is adequately constructed and accommodating.

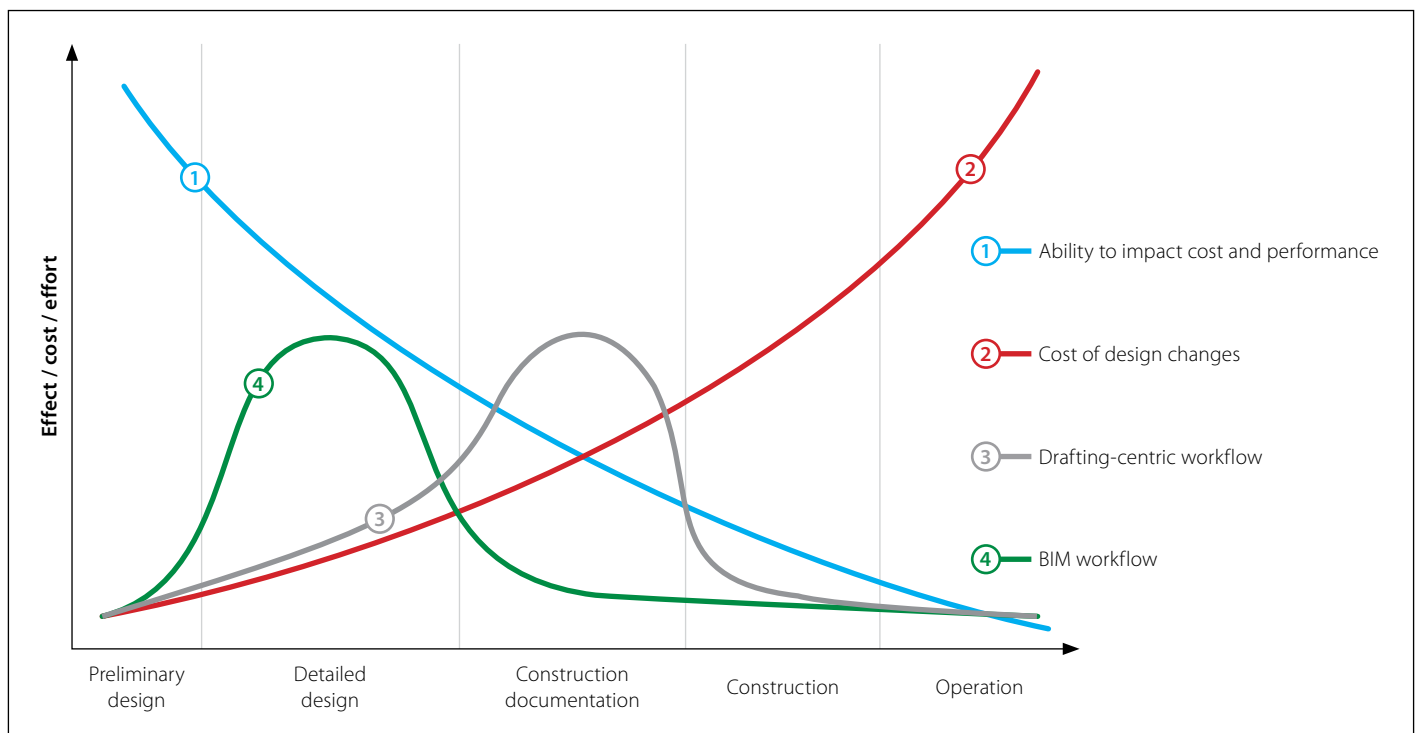


Figure 11 The MacLeamy Curve (Fathi 2022)

- Virtual reality, gamification, and visualisation result in immersive and contextual design, providing insight and a broader lens through which the design can be seen in its interactive environment, as well as realism before and during construction.
- As-built data can be incorporated into the core design model to reflect the as-built nature of the roadway in the form of an as-built BIM model, which then can be used as an accurate means for effective operations and maintenance.
- Design and construction teams can be linked, managed and communicate effectively using the cloud, ensuring that any construction queries, snags, issues and revisions are tackled as soon as possible.
- Multidisciplinary collaboration and coordination are transparent and actionable in a more streamlined and accountable manner, ensuring that all involved are working on the correct version of design drawings, costs, instructions, etc.
- BIM provides the basis for futuristic and innovative asset management, fulfilling the foundational requirement of digital twinning by providing a digital replica of the future virtual asset.

BIM is also seen to have business advantages on transportation projects. A study asked BIM users to rate the degree to which BIM generates nine business benefits related to transportation infrastructure projects on a scale of one to five (none, low, medium, high, very high). From a staffing perspective, BIM's impact on improving a company's ability to show younger staff how projects go together is the top benefit, rated high/very high by 59% of respondents.

Half of BIM users (50%) experience a high/very high benefit from BIM's ability to allow their staff to spend less time documenting and more time designing. A notable percentage (43%) also considers BIM as being highly effective in helping them recruit and retain staff (SmartMarket Report 2017).

RECENT DEVELOPMENTS: ARCGIS GEOBIM AND AI

With the rapid pace of technological advancement, disruptive technologies continue to reshape the way things are done. Technologies such as ArcGIS GeoBIM and artificial intelligence (AI) fall in this category, providing innovative ways

for industry professionals to accomplish their tasks.

ArcGIS GeoBIM is the result of the partnership between Autodesk and ESRI – both global leaders in BIM and GIS. ArcGIS GeoBIM is described as a solution for exploring BIM models, engineering documents, and project issues in a geographic context to analyse designs, site characteristics, risks, costs, and timelines. It allows users to integrate and visualise GIS data with engineering documents and issues from Autodesk Construction Cloud (ACC) to make coordinated and collaborative decisions across project teams.

This integration results in enhanced collaboration not just on road or transportation projects, but civil engineering projects as a whole, enabling the linking of BIM and GIS data in a shared context for improved decision making through better visualisation of project impact and risks (like natural disasters), increased efficiency, reduced costs, and streamlined asset management across the entire project life cycle, from planning to operations, by connecting digital models with real-world location data. The only limitation at this stage is that this integration is currently exclusive to the Autodesk CDE (being ACC and BIM360) and will not work with any other software.

AI on the other hand has revolutionised the way we do a plethora of things. When specifically looking at road projects, AI has been applied in a variety of ways. A good example is an AI-powered road inspection system that was used in Doha to assess approximately 267.6 km of urban roads. Ordinary vehicles were fitted with off-the-shelf dashcams to collect high-resolution video footage of pavement surfaces at normal traffic speeds, eliminating traffic disruptions and the need for specialised survey vehicles. The collected video was uploaded to a cloud platform where advanced AI models processed every frame to automatically detect and identify road surface defects such as cracks, ravelling, rutting, potholes and settlements. Detected distresses were classified and scored by type and severity using deep learning models trained on global road defect datasets. The system then generated structured defect data and visual dashboards that enabled actionable, data-driven maintenance planning, prioritisation of repairs, and integration with existing asset management systems. This approach accelerated inspection time, reduced manual effort, and

supported predictive maintenance planning compared with traditional manual surveys (RoadVision AI 2025).

Other applications involve the integration of AI with technologies such as BIM applications, CDEs, reality capture, and photogrammetry. In these contexts, AI can be used to automate aspects of the design process, assess road BIM models for compliance with relevant standards, generate reports, and flag areas of non-compliance. AI can also enhance integration with CDEs for enhanced, automated project and information management. In addition, AI can contribute to improved safety management, as-built and environmental monitoring, and proactive maintenance.

The applications of AI on road projects and civil engineering projects are expected to expand as AI's capabilities accelerate. It is further anticipated that the advent of Industry 5.0 (I5.0) and Construction 5.0 (C5.0) will unlock additional benefits and opportunities to innovatively overcome challenges.

CONCLUSION

With BIM technologies and workflows ticking the boxes of economy, sustainability and innovation, its application and implementation across the road project life cycle is essential, promoting resilient, intelligent road infrastructure and paving the route towards digital twinning.

The 'single collaborative model', where all stakeholders work on one model, is now the utopia thought to never be possible (RICS 2020), where design, construction, and maintenance teams collaborate within a CDE. Coupled with AI, I5.0 and C5.0, the industry is bound to unlock a technological ecosystem of opportunities to solve the challenges of the modern world. It can be concluded that the first milestone in this digital journey is BIM.

In South Africa and developing regions there has been a rise of BIM at varying levels of application and understanding, with BIMcommUNITYAfrica playing a pivotal role in advocating for BIM in South Africa relative to ISO 19650. Currently, most companies use BIM only for its technological 3D modelling component. However, some incorporate a CDE, with larger companies having documented standardised processes of their BIM and CDE ecosystem. More digitally mature companies are BIM ISO certified or in the process of becoming certified.

There are numerous factors that contribute to the above, particularly in developing countries and regions. These include resistance to change, limited understanding of BIM and its value proposition, upfront investment costs, concerns regarding business scalability, shortages in skills and education, limited access to guidance and support resources, and the absence of a national BIM mandate. A BIM mandate serves as a legislation or framework governing the implementation of BIM on projects, outlining subjects like processes and procedures, roles and responsibilities, deliverables, ownership, and liability associated with BIM-enabled project delivery.

To overcome these hurdles, stakeholders across the public and private sectors, including professional institutions, educational bodies, companies, and asset owners, need to play an active role in promoting BIM adoption. Increased implementation of BIM can

support improved economic efficiency, service delivery, and the sustainable use of land and resources, ultimately contributing to the development of more resilient infrastructure.

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