BUILDING INFORMATION MODELLING TECHNOLOGIES FOR INTELLIGENT ROAD ENGINEERING DESIGN, CONSTRUCTION AND DIGITAL TWINNING

BY

SHUAIB YUNOS

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DECLARATION

I, **Shuaib Yunos**, hereby declare that this dissertation, except where indicated in the text, is my work and has not been submitted in part, or in whole, at any other University or University of Technology.

This research was conducted at the Durban University of Technology under the supervision of Professor Dhiren Allopi.

--------------------------------	24 July 2023 --------------------------------
Shuaib Yunos	**Date**

APPROVED FOR FINAL SUBMISSION

Prof. Dhiren Allopi: Supervisor

DTech (Civil Eng) (MLST); MDT (Civil Eng) (TN);

Postgrad Dip Eng (Natal); Dip Datametrics (cum laude) (UNISA);

PrTech Eng; FMSAICE; MIPET; MSAT; MCILT

ABSTRACT

Roads form an integral part of civil infrastructure, providing safe and reliable access from a point of origin to a destination. With the rapid growth in population, urbanisation, and the pursuit of smart cities, the pressure on effective road design, construction, and maintenance is ever-increasing, with sustainability and innovation being at the focal point to derive better and more intelligent ways to accomplish this infrastructure requirement. With this influx of demand, traditional processes are put under strain, resulting in roads being designed inadequately, impacting the safety and service, exploration of minimal alternative routes due to time pressure or lack of information, material wastage affecting design sustainability and construction cost, and poor maintenance affecting safety and design life.

With the progression in technology, building information modelling (BIM) is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to plan, design, construct and manage buildings and infrastructure more efficiently. BIM has been implemented, adopted, and mandated by many countries across the world, seen as an intelligent, innovative necessity for enhanced civil infrastructure design, construction, and maintenance. This leads to the question of BIM on civil infrastructure projects, with the focus being roads, and how would it compare to the traditional way of accomplishing road projects.

In this regard, an in-depth investigation into the application and impact of BIM technologies across a typical road project had been conducted. This was achieved by describing the processes associated with a typical project when employing a traditional and BIM approach across 9 stages of the project lifecycle. This methodology effectively allowed for a detailed comparison between the two approaches, with the findings collated. The dissertation also expands on what is BIM, its levels, dimensions, benefits, its application on projects across various continents, its role in digital twinning and smart cities, its presence and development globally, its presence and development in Africa, as well as the hurdles experienced in its adoption and implementation and recommendations on how to overcome them.

The conclusion arrived at was that BIM provides a plethora of advantages across the road project lifecycle, resulting in innovative, economical, and sustainable civil infrastructure, paving the way to enhanced operations and maintenance and digital twinning in the pursuit of smart cities, correlating with BIM being mandated by countries across the globe and various literature confirming its positive impact. The BIM approach outperformed the traditional approach across all stages of a typical road project lifecycle, conforming to the MacLeamy curve. The BIM technologies applied to derive and illustrate this conclusion were BIM technologies developed by Autodesk and the Devotech Group of Companies.

It was also observed that whilst BIM has been around since the 1970s, BIM is still seen as a new concept, particularly in the civil infrastructure industry, and whilst professionals acknowledge its advantages, they are resistant to change, overwhelmed by how to become BIM ready, or do not know where to turn to for guidance, particularly in South Africa, Africa, and other developing countries. Other main challenges observed were those of education, training and upskilling, upfront cost, and the absence of a BIM mandate, as well as challenges specific to Africa were unpacked such as infrastructure gaps, skill gaps, digital division, and digital transformation.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

ACC	Autodesk Construction Cloud
AEC	Architecture, Engineering & Construction
AECO	Architecture, Engineering, Construction & Operations
BIM	Building Information Modelling
BOQ	Bill of Quantities
CAD	Computer Aided Design/Drafting
CDE	Common Data Environment
DDR	Detailed Design Report
DoT	Department of Transport
DT	Digital Twin
ECSA	Engineering Council of South Africa
ETW	Edge of Travel Way
GIS	Geographic Information Systems
ICE	Institute of Civil Engineers
IDF	Intensity-Duration-Frequency
IDP	Integrated Development Plan
IoT	Internet of Things
LOD	Level of Development
NASA	National Aeronautics and Space Administration
NTS	Not to Scale
PDR	Preliminary Design Report
PLM	Product Lifecycle Management
QMS	Quality Management System
SABS	South African Bureau of Standards
SAICE	South African Institute of Civil Engineers
SANRAL	South African National Roads Agency SOC Ltd
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

1.1 RESEARCH BACKGROUND

Infrastructure is defined by the Oxford dictionary as "the basic physical and organisational structures and facilities (e.g., buildings, roads, power supplies) needed for the operation of a society or enterprise". Roads form an integral part of Civil infrastructure, providing safe and reliable access from a point of origin to a destination. By the year 2050, Africa is projected to have the highest urban population growth of 3.1% (Autodesk & Statista, 2019), with the United Nations (UN) predicting the number of people on our planet to grow from approximately 7.6 billion today to nearly 10 billion, as displayed in the figures below:

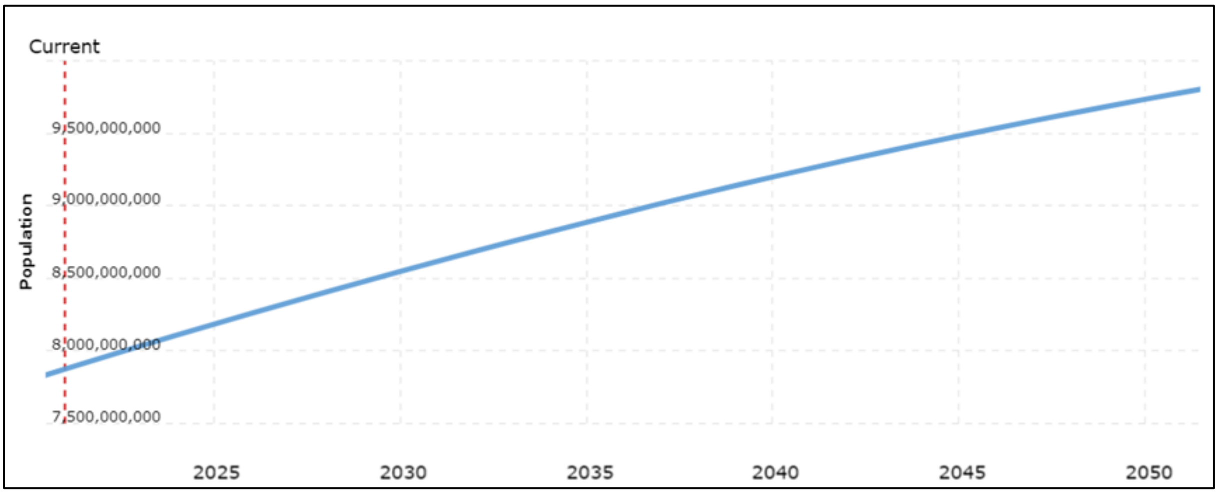


Figure 1.1: United Nations: World Population Prospects Projections Through the Year 2050
Source: Macrotrends, 2021

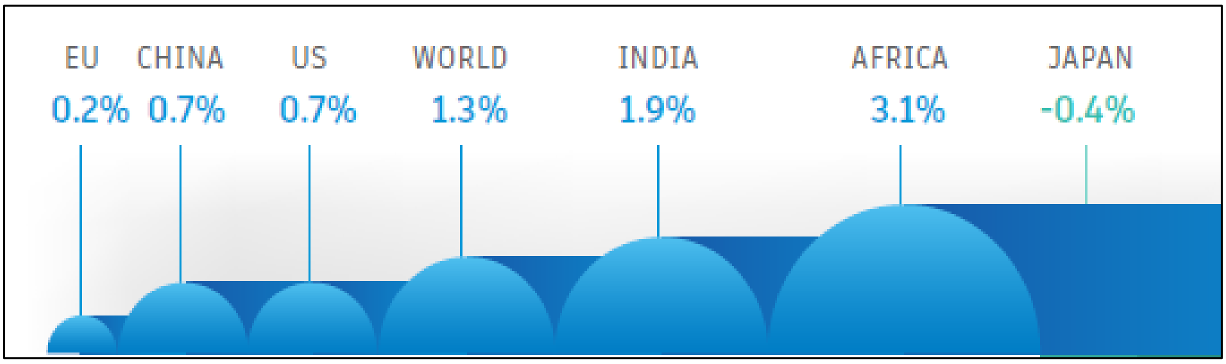


Figure 1.2: World Urban Population Growth Projections Through the Year 2050
Source: Autodesk & Statista, 2019

Population has a directly proportional effect on civil infrastructure demand and delivery, and with a rapid acceleration in urbanisation, resilient infrastructure provision is required sooner than ever. The figures below depict the estimated daily global averages for new roads and highways constructions (Autodesk & Statista, 2019),

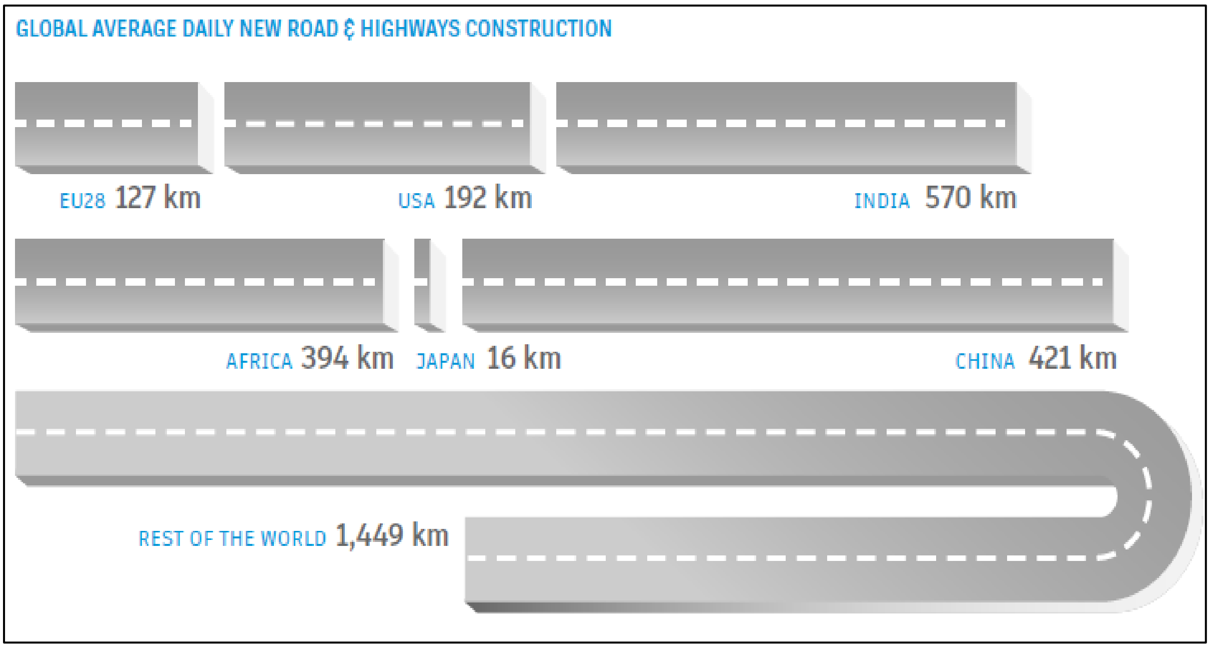


Figure 1.3: Global Average Daily New Road & Highways Construction
Source: Autodesk & Statista, 2019

With this high demand for road construction and infrastructure provision, the traditional methodologies of the past need to be infused with innovative technologies and processes to tackle the increased design complexities of today and the future. BIM affords this innovation to architecture, engineering, and construction (AEC) professionals, serving as an intelligent means of combining 3D modelling technology, cloud computing and engineering standards to provide faster, leaner, and more resilient civil infrastructure.

This dissertation delves into the transformative potential of BIM technologies in solving the abovementioned challenges and demands, revolutionizing road infrastructure within the civil engineering section. It illustrates the power of BIM in not only driving economic efficiency but also fostering insights into road projects, laying the groundwork for digital twinning and smart cities. With a hot focus on digital transformation by many sectors and disciplines around the world, this research seeks to answer critical questions surrounding BIM's profound impact specific to road projects, which are expanded on under the aims and objectives section.

1.2 RESEARCH PROBLEM STATEMENT

As per Stats SA, the population of South Africa (SA) in 2016 was 55.7 million, with the United Nations (UN) projecting the current population of South Africa in 2021 to be just over 60 million, a 1.24% increase from 2020 as displayed in the figure below.

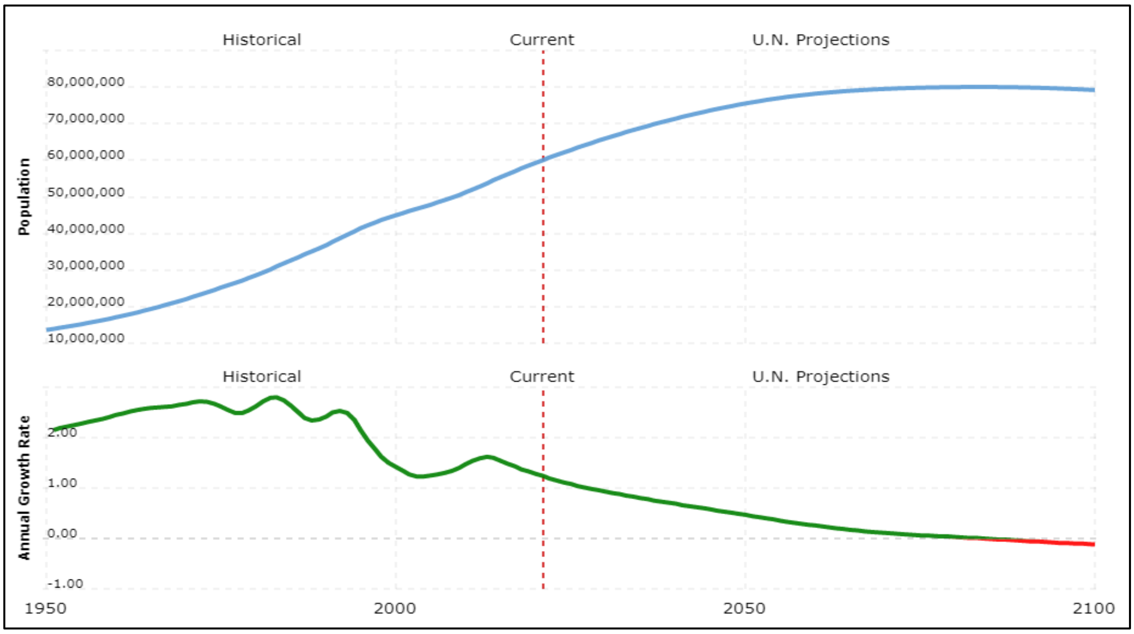


Figure 1.4: United Nations: World Population Prospects Projections Through the Year 2100
Source: Macrotrends, 2019

The civil infrastructure industry must look to smarter, more efficient ways for infrastructure provision, not purely based on population dynamics but also on the smarter utilisation of land and resources. The gold standard for civil infrastructure is that which increases the quality of life whilst fulfilling its function and design life in the most economical, sustainable, and resilient way possible. This is not the norm in the civil industry today, as projects do not see out their design life due to increased design complexity, which in turn results in design errors, which then have a domino effect throughout the project lifecycle, impacting project management, deadlines, deliverables, economy, sustainability, and optimal infrastructure delivery.

Road infrastructure plays a pivotal role in the successful utilisation of accompanying infrastructure components, meaning if no safe and reliable access is provided to, for example, hospitals, schools, housing, malls, and recreational areas those infrastructures will be rendered futile. This poses the opportunity for exploring alternative, newer, faster, leaner, and more innovative methods to tackle road projects, that alternative being BIM.

1.3 RESEARCH AIMS AND OBJECTIVES

The aim of this dissertation is to provide a more intelligent, innovative, and sustainable methodology, process or workflow in the planning, design, construction, and maintenance of roads by incorporating BIM intelligent technologies and processes. By using BIM technologies and processes as an enabler, professionals involved in the design, construction and maintenance of roads are afforded greater insight due to the benefits of reduced time pressure, insightful analysis, and alternative route determination and optimisation. This technological workflow will result in a dynamic, data-centric design, enhanced management, coordination and control, leaner and sustainable construction, and form the foundation for preventative maintenance, as well as digital twinning in the pursuit of smart cities and infrastructure. Should BIM be made a mandatory means of infrastructure delivery here in South Africa, Africa and developing countries (as has been done across many regions globally), it will pave the path to sustainable, well-managed infrastructure. In light of the above, this dissertation addresses the following questions:

- What is building information modelling (BIM), its origin, adoption globally, and relevance in the civil infrastructure industry, specifically the road sector.
- What are BIM technologies and who are the global leaders in developing them
- What does BIM entail, including defining its levels, dimensions, and level of details (LODs).
- What benefits can be experienced applying BIM on a company, project and professional level.
- What does BIM look like for the civil infrastructure industry, including case studies of infrastructure projects that have applied BIM across the world.

- What does the traditional road project process entail and what are the challenges experienced across a typical road project lifecycle.
- What does the BIM road project process entail and what are the benefits experienced a typical road project lifecycle when compared to the traditional process.
- What is digital twinning, its benefits for road networks and how is it different to BIM.
- What role does the BIM road model play in the digital twinning and smart cities, including its integration with the internet of things (IoT).
- What hurdles are faced by developing countries and possible courses of action to overcome these hurdles.

1.4 RESEARCH METHODOLOGY

The nature and purpose of this dissertation are to advocate the necessity for the incorporation of BIM technologies for intelligent road engineering design, construction, and maintenance, ultimately digitally transforming the road sector. The methodology applied in this dissertation to effectively demonstrate the above is as follows:

- Firstly, contextualising the current state of the road industry, the pressures faced and current ways of tackling road projects.
- Secondly, providing a comprehensive explanation of BIM, its relevance in the civil infrastructure industry, its incorporation on road projects across the continents, and the reaped benefits.
- Thirdly, once a detailed understanding of the above two points is established, the methodology applied to effectively illustrate the differences between the traditional and BIM approach is defined, consisting of 9 stages across a typical road project.
- Fourthly, both approaches are expanded upon and scrutinised to their performance across these 9 defined stages, with the findings derived and presented.
- Lastly, exploration to BIM in the digital twining process as well as the hurdles faced in its adoption on a local and global scale are unpacked, with recommendations to overcome these hurdles brought forth.

This methodological approach results in a definitive and balanced research output.

1.5 RESEARCH SCOPE

The scope of this research is limited to the comparison of the implementation of BIM technologies and workflows to that of traditional processes applied in the civil industry across a typical road project lifecycle. With the primary focus being on roadways, stormwater design and digital twinnning will not be looked at in detail but will be touched upon. The points below serve as an indication of the extent of this study:

- Deliver a clear, concise explanation of BIM and its relevance in the Civil infrastructure Industry, zooming in on the phases of a typical road project lifecycle from the project tender stage/inception up to handover and maintenance, and then solution map BIM technologies (Autodesk & the Devotech Group of Companies) and processes to each phase to clearly gauge its impact and benefits within the phases of the project lifecycle.
- Provide solutions to commonly faced challenges across road projects. such as roads designed inadequately impacting safety and service, exploration of alternative routes being minimal due to time pressure or lack of information, material wastage affecting design sustainability and construction cost, as well as poor maintenance affecting safety and design life.
- Highlight real-world applications/case studies of companies that have incorporated BIM in their processes, as well as contextualise its relevance in South Africa and the world over in the pursuit of intelligent design, smart cities/civil infrastructure, and digital transformation within the civil engineering industry.
- Provide use cases of BIM in the role of digital twinning for roads, as well as possible expanded uses of BIM for the future ahead.
- Validate the necessity for the incorporation of BIM technologies for intelligent road planning, design, construction, and maintenance, correlating to BIM being mandated by countries across the world and literature highlighting its benefits.
- Observe the benefits provided by BIM across a road project's lifecycle, as well as the hurdles faced by industry and professionals in its adoption and propose courses of action to overcome these hurdles.

1.6 RESEARCH LIMITATIONS

The following are perceived as or could pose as limitations to this research:

- The workflows proposed and detailed in this research are mainly pivoted around BIM technologies by Autodesk and the Devotech Group of Companies.
- With the constant development in technology, certain software solutions and/or technical components of proposed workflows could be replaced, eliminated, and/or enhanced based on future offerings and functionality.

1.7 RESEARCH OUTCOMES AND POTENTIAL OUTPUTS

This research will serve as a means of proposing a better alternate, holistic approach to the planning, design, construction, and maintenance of roads, with the envisaged potential outputs being as follows:

- Create a deeper, concise understanding of BIM and its positive impact on the civil infrastructure industry, which could be used by related professional bodies to create awareness and mind shift in traditional approaches.
- Be recognised and possibly endorsed by international BIM technology providers and national and international recognition by professional bodies such as Engineering Council of South Africa (ECSA), South African Institute of Civil Engineers (SAICE) and Institute of Civil Engineers (ICE), as well as civil professionals in Africa and beyond as the norm to intelligently tackle road projects.
- Serve as a handbook/guideline to firms, companies, and consulting professionals in the civil engineering/infrastructure industry nationally and internationally involved or interested in adopting BIM on road projects.
- Mobilise and foster an interest amongst the civil engineering and AEC industries in South Africa and the African continent in the compilation of a BIM standard/mandate.
- Peak interest amongst the civil engineering and AEC industries in South Africa and the African continent in economical, intelligent, innovative sustainable infrastructure planning, design, construction, and maintenance.

- Provide insight into world-leading research, processes and workflows, resulting in improved project delivery and construction management.
- Promote the inclusion of BIM in university curriculums to groom innovative professionals here in South Africa and Africa, putting us on the same competitive level amongst the leading countries the world over.
- Foster curiosity and inclusion of industry 4.0 across the engineering fraternity and academic institutions.

1.8 OVERVIEW OF CHAPTERS

To promote a logical flow of information that is understandable and easy to digest, this dissertation is structured as follows:

- **Chapter 1: Introduction**
  This chapter provides context to the research background, problem statement, the aims and objectives, scope of the study and methodology applied, including research limitations, outcomes, and potential outputs.

- **Chapter 2: Literature Review**
  This chapter contextualises road engineering design by detailing how it is mainly tackled currently in the industry using conventional 2D methods, as well as the evolution and increased adoption/implementation of BIM on road projects.

- **Chapter 3: Building Information Modelling (BIM)**
  This chapter provides a clear, concise explanation of BIM, the recognised global leaders/providers in this space, the levels, dimensions and levels of detail associated to BIM, its benefits, including its application in the civil infrastructure industry and implementation on projects across Africa, Asia, Europe, Australia, and the Americas.

- **Chapter 4: Applied Methodology**
  This chapter provides context to the thought process applied to distinguish the effectiveness of BIM on road projects. This methodology defines 8 stages across

the road project lifecycle which will be applied to both methods to effectively compare the 2 approaches.

- **Chapter 5: The Traditional Road Project Process**

  This chapter zooms in on the phases of a typical road project lifecycle and entails the findings when employing a traditional approach, based on the methodology described in chapter 4.

- **Chapter 6: The BIM Road Project Process**

  This chapter zooms in on the phases of a typical road project lifecycle and entails the findings when employing a BIM approach, based on the methodology described in chapter 4.

- **Chapter 7: Data Analysis and Findings**

  This chapter details the findings between the 2 approaches. The chapter also sheds light on the extended use of BIM and its role in digital twinning and smart cities, distinguishing the difference between BIM and digital twinning, the benefits, as well as some literature detailing digital twinning for roads and what is possible.

- **Chapter 8: Closing**

  This chapter brings this dissertation to a close, elaborating on BIM for roads, BIM today and the future, the observed hurdles to BIM adoption, proposed recommendations to overcome these hurdles, and the BIM situation on the African continent.

2. LITERATURE REVIEW

2.1 INTRODUCTION

As more people migrate to urban areas, the need to invest in infrastructure becomes more imperative. Both smart city planning as well as investments in road and public transportation networks are essential. More than 240 000 kilometres of urban roads and 915 000 kilometres of rural roads need to be constructed every year. In total, that is enough to circle the globe 28 times over. With this great demand for road infrastructure, design, construction, and operation of the constructed environment must be fundamentally rethought in the AEC industry. Globally, innovative firms are addressing this issue by bringing in new technologies and processes that improve efficiency and productivity, like BIM prefabrication, modular construction, and robotics. There is a race going on now to meet the need for new infrastructure that will only continue to grow as the industry races to keep up with demand (Autodesk & Statista, 2019).

As of 2015, there were 29 megacities with populations of over 10 million, and by 2030, it is expected that there will be an additional 12, with 10 in Africa and Asia. Polycentric metropolitan regions, which are made up of several connected large urban areas, have gained prominence in recent decades, creating new challenges in transportation planning. Technological innovation is essential for sustainable transport (United Nations, 2016). This is where BIM plays a vital role in better tackling these new challenges and design complexities.

2.2 BIM AND ITS EVOLUTION IN THE CIVIL INDUSTRY

The concept of BIM was envisioned by an American engineer, Douglas C. Engelbart, in his paper published in 1962 titled “Augmenting Human Intellect”, portraying his vision for the future of architecture, which was followed by the first closest documented concept of BIM in the 1970s by a working prototype called ‘’Building Description System’’ by Charles M. Eastman (known as “The Father of BIM”), where several concepts of BIM were mentioned (KORQA, 2015). Since then, BIM has progressed and evolved in leaps and bounds, being implemented, and adopted across the AEC industry, as well as providing a convergence workflow and integration between manufacturing and construction.

BIM has been and still is predominantly championed by architects, which has led to a misconception that the application and implementation of BIM technologies and workflows are exclusively for the architectural industry. Whilst BIM has its origins in architecture and the building environment, BIM applies to everything that is designed and constructed, including roads and highways. By embracing BIM, civil engineers can reap the same benefits as architects (Strafaci, 2010), if not more.

These benefits can be seen in a survey conducted in 2019 by the Institute of Civil Engineers (ICE) and ALLPLAN UK involving 250 ICE members, the objective was to measure the 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 close to half stating it has contributed to increased profitability (35%) and delivery speed (41%), as well as reducing cost overruns (37%) (ICE & ALLPLAN UK, 2019).

2.3 BIM FOR ROADS – A NECESSARY GOOD

In most countries, the design, construction, and maintenance of road infrastructure are critical aspects of the economy. However, it is also a sector lacking in digital transformation. It is characterised by a wide variety of systemic deficiencies and challenges, such as inadequate levels of cooperation, ineffective information management, as well as a lack of investment in technology, research, and development. The lack of consistency in project documentation, along with miscalculated timelines and costs, frequently leads to lower levels of efficiency and higher levels of risk for investors. There is significant potential for improvement through the digitalisation of processes and applications of BIM, a methodology suited to improving efficiency in the road sector (UNECE, 2021).

Currently, most road projects use a 2D model-based methodology for design and construction, which is usually cumbersome and prone to errors. As a result, new innovative approaches to enhance road design, construction, and maintenance are necessary. In this regard, BIM technologies and workflows can contribute significantly to greater quality of infrastructure both during and after implementation (Bazán et al. 2020).

When adopted in either road or railway infrastructure projects for design, construction, and maintenance, BIM would serve to create, manage, and maintain all the critical information pertaining to an asset, such as geographic information, graphics of the transportation system, and resources required for the project, which can be used to achieve a cost-effective design solution and improve communication among project stakeholders (Chong et al. 2016).

BIM for road and highway design facilitates the creation of coordinated and consistent design data that results in a smart 3D model. This allows designers to instantly evaluate the effects of changes to road vertical curves, grades, profiles, etc. in a dynamic, live environment. As an integral part of the design process, civil engineers can utilise the information model to enhance and optimise their road designs in terms of constructability, sustainability, and safety to achieve an economically viable roadway design (Lombardo, 2019).

Throughout the road project lifecycle, BIM provides rich geometric and 3D visual information. A distinct advantage is the integration of BIM with GIS data, providing users with the ability to perform complex spatial analysis, determine the optimum route, and have geographic visualisation (Zhao et al. 2019). Another key benefit of BIM is its user-friendliness when managing and implementing changes, enabling insightful and efficient engineering management (Bozmaz, 2019).

2.4 GAUGING THE IMPACT OF BIM IN THE CIVIL INDUSTRY

One of the most formidable drivers in reviewing alternative approaches and processes is that of economy, and when this is achieved, it is often not quantified, because it is difficult to compare old ways to new techniques. BIM is certainly in this category, as most who adopt it soon realise that there is no turning back, as BIM affords new means and advantages that prior processes cannot match. Although it is difficult to calculate total savings and direct comparisons, incremental savings and anecdotal evidence demonstrate significant cost savings (Informed Infrastructure, 2015).

Most BIM users (87%) report that they see positive value from their use of BIM, whereas nearly two-thirds believe that they are seeing a positive return on investment (ROI) from their use of BIM, with about half of those reporting an ROI of 25% or more. Among the remaining third, well over half simply do not know what the ROI on their BIM investments is, a relatively small percentage say that they are breaking even, and less than 5% report a negative ROI (SmartMarket Report, 2017).

As per the NBS 10th Annual BIM Report 2020, a BIM survey was carried out which involved people from every continent besides Antarctica. It was found that BIM adoption and awareness have grown substantially with a 73% adoption rate compared to 13% in 2011, with 68% of participants saying they have adopted BIM successfully, and 58% saying if they do not adopt BIM they will fall behind (NBS, 2020).

2.5 BIM TECHNOLOGIES

BIM software can be categorised as authoring or simulation, and as the technology matures, single software packages may be used that contain both elements (The Sustainable Built Environment National Research Centre, 2017), including the additional element of validation. Amongst many BIM providers in the AEC industry, one of the leading solutions providers is Autodesk.

Autodesk provides AEC professionals with a variety of BIM intelligent technologies an offering titled the AEC Collection. This collection provides enhanced design and collaboration between architects and engineers using an ecosystem of design tools and a cloud-based document management system. The versatility of this offering has led to its popular adoption globally across the AEC industry. Within this collection, the specific BIM technologies used for road engineering design, modelling, analysis, simulation, automation, visualisation, and collaboration are: Civil 3D, Dynamo Studio, Infraworks, ReCap Pro, Vehicle Tracking, 3D Studio Max and Document Management.

From these applications, Civil 3D and Dynamo Studio are presented as consolidated road design tools, having all the tools and elements to elaborate a complete road infrastructure and provide summary tables of the volumes of excavation, landfill and of pavement layers (Biancardo et al. 2020). All these tools lead to a 3D data-rich road model with BIM being the most efficient and recommended path to digital twinning in the pursuit of smart cities, which involves the integration of BIM, GIS and IoT. For enhanced BIM functionality with Autodesk Civil 3D, this dissertation includes the use of Devotech iDAS by the Devotech Group of Companies, developed in South Africa, which provides further automation for road and pipe network design and modelling. With the pursuit of digital transformation being on the forefront of many industries, BIM is seen as one of these enablers to digitally transform the infrastructure industry.

2.6 BIM AND DIGITAL TWINNING FOR ROADS

The concept of digital twinning and smart cities is a hot topic in the industry, with many countries striving towards achieving this goal. Digital twins have the potential to help us meet many of the grand challenges we are facing today, such as urbanisation, population growth, climate change, escalating infrastructure costs, and sustainable development. Since digital twins are not well-established within the transportation sector, there is an opportunity to use them to propel progress in well-defined areas. Probably the most promising idea is a virtual replica of a city, including its transportation system and population. Ideally, the twin should accurately predict lifetime changes given initial conditions, while being able to respond to changes and interventions like new transport services, new housing developments, or changes in fares as necessary (Arup, 2019).

BIM is not designed for real-time operational response, which is the distinguishing feature of a digital twin. In this way, a digital twin is the next evolutionary step of BIM (WSP, 2020). In the case of roads, digital twins represent a solution to providing constant access to digital representations of physical assets. Sensors that feed into the BIM Model collect digital data in real-time that is used to monitor both the physical environment and unstructured material characteristics data (Meza et al. 2021). This results in preventative maintenance, contributing to sustainable and resilient road infrastructure.

2.7 CONCLUSION

With BIM technologies and workflows ticking the boxes of economy, sustainability and innovation, its application and implementation across the road project lifecycle 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 it was thought never to be (RICS, 2020), where design, construction, and maintenance teams collaborate within a common data environment (CDE), is now possible. With the future heading towards an accelerated progression in technology, further enhancements such as artificial intelligence (AI), machine learning (ML), visual scripting, computational design and analysis, and cloud technologies hold great promise to elevating and expanding the uses of BIM.

With the literature documenting the advantages and application of BIM to digitally innovate and transform the way we envisage infrastructure, the question arises as to why BIM has not been mandated by every region around the world. The factors of upfront cost, skill shortages and process of incorporation into current infrastructure processes are seen as primary factors hindering its mandating. In developing countries and regions, access to critical infrastructure, digital opportunity, reach and literacy, localisation and financial constraints further hinder the opportunity for digital transformation as a whole, not just BIM. There is no doubt that BIM and other technologically innovated processes will benefit the industries they adopted in, but until the challenges above are bridged and remedied, BIM will be seen as nice to have and not a necessity, which it most certainly is to create smarter, sustainable infrastructure.

3. BUILDING INFORMATION MODELLING (BIM)

3.1 BIM: ITS ORIGIN AND EVOLUTION TO TODAY

Building information modelling (BIM) is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to plan, design, construct and manage buildings and infrastructure more efficiently.

BIM was envisaged by Douglas C. Engelbart, who was an engineer, inventor, and computer and Internet pioneer. Engelbart described his vision of the future architect in his paper published in 1962 titled "Augmenting Human Intellect". Just over a decade later, in 1975, the first closest documented concept of BIM was arrived at using a working prototype termed "Building Description System", which had been published in the American Institute of Architects (AIA) Journal by Charles (Chuck) M. Eastman, who was a professor and a pioneer of BIM and computer-aided design (CAD) for the architecture, engineering, construction, and operation (AECO) industry, amongst other fields (KORQA, 2015).

Both Engelbart and Eastman described a future in which architects wielded intelligent technology, enabling parametric and dynamic design. As a result of the great impact of Eastman's documented concept of BIM he has become most well-known in the fields he had been involved in, earning him the title of the "Father of BIM".

In the early 1980s, concurrent research about BIM had been ensuing in Europe and the USA. This resulted in two different concept terminologies, with Europe terming its concept "product information models", and the USA terming its concept as "building product models", which later resulted in both these terminologies merging, thus evolving into "Building Information Model". This then led to the first use of the term "Building Modelling" in relation to BIM in a paper by Robert Aish in 1986. Aish's paper consisted of a case study where he applied a Building Modelling System, illustrating arguments and concepts of the BIM that we know today. The term "Building

Information Model" was first introduced shortly after in 1992 in a paper by G.A. van Nederveen and F. Tolman titled "Modelling Multiple Views on Buildings". This further led to several BIM technology and software providers and developers, amongst them being Autodesk. In 2002, Autodesk released a white paper entitled "Building information modelling", and other software vendors also started to assert their involvement in the field (Quirk, 2012).

Today, BIM has evolved exponentially and is widely known across industries. It can be described as a process supported by various tools, technologies, developers, and service providers involving the generation and management of digital representations of physical and functional characteristics of places, with Connected BIM describing the incorporation of cloud computing and functionality with BIM technologies and workflows. Due to the availability of hardware, BIM is easier to adopt and implement today than earlier applications, which were expensive due to the hardware needed to run them.

BIM provides innovation, intelligence, and smarter ways of achieving tasks and overcoming new challenges. BIM is now popularly adopted across the AEC industry, including providing a convergence workflow between manufacturing and construction. With its plethora of benefits, it has led to many countries around the world mandating its use. The figure below showcases BIM awareness in 2011 versus 2020:

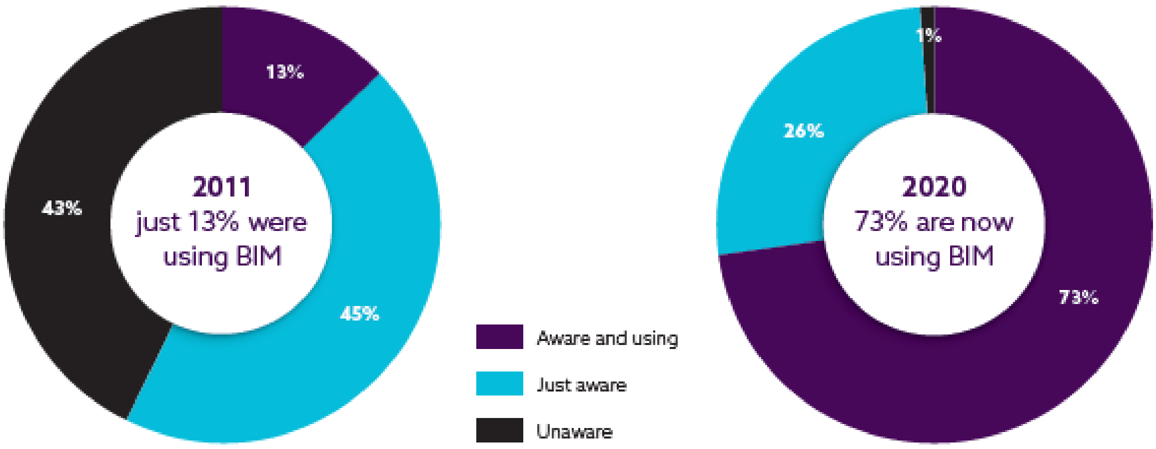


Figure 3.1: BIM Awareness and Use 2011 vs 2020
Source: NBS, 2020

3.2 GLOBAL LEADERS IN BIM TECHNOLOGIES and WORKFLOWS TODAY

The advent of the BIM concept attracted interest in developing a suitable software solution. This led to the development of the first BIM software, Radar CH, which later became, and is currently known as ArchiCAD, developed by Gabor Bojar in Hungary. This was then followed by PRO/ENGINEER by the Parametric Technology Corporation (PTC). Thereafter, Irwin Jungreis and Leonid Raiz, who both worked at PTC and owned the solution architecture of PRO/ENGINEER, left PTC to establish their own software company called Charles River Software. This then led to Jungreis and Raiz developing Revit, which was then sold to Autodesk in 2002 (KORQA, 2015).

The Revit software has grown aggressively, which transformed the architectural market with innovative features such as parametric families, construction phase control, schedules, and a visual programming environment. This popularity in adoption among the architectural field resulted in further development, resulting in the development of Revit Structural and Revit Mechanical in 2004, promoting further collaboration and integration across architectural and engineering disciplines. This put Autodesk on the map to becoming an influential, innovative BIM developer and software provider, which also gave rise to other competitive solution developers forming in the market such as Bentley Systems, Dassault Systems, ANSYS INC and Aveva.

Fast forward to today, Autodesk software and cloud solutions have grown exponentially with a variety of offerings that are being popularly adopted worldwide. These technologies and workflows have been developed for users in architecture, engineering, and construction (AEC), product design and manufacturing (PDM), as well as media and entertainment (M&E) industries. Their solutions also incorporate enhanced cloud computing, design collaboration and document management, which are integrated and connected to the design process, resulting in an effective common data environment (CDE). The flexibility, scalability, and practicality these technologies afford users have subsequently elevated Autodesk to being recognised as a global leader in BIM technologies and workflows.

3.3 BIM LEVELS, DIMENSIONS AND LOD

To create standardisation in the implementation of BIM processes and methodologies, a guiding legislature is required. This legislature is the ISO 19650 series, compiled by the United Kingdom (UK), which is defined as an international standard for managing information over the whole life cycle of a built asset using BIM, with this series described by the British Standards Institution (BSI) below (BSI, n.d.):

- **BS EN ISO 19650-1:** Organisation and digitisation of information about buildings and civil engineering works, including building information modelling - Information management using building information modelling: Concepts and principles.

- **BS EN ISO 19650-2:** Organisation and digitisation of information about buildings and civil engineering works, including building information modelling - Information management using building information modelling: Delivery phase of the assets.

- **BS EN ISO 19650-3:2020:** Organisation and digitisation of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. Operational phase of the assets.

- **BS EN ISO 19650-5:2020:** Organisation and digitisation of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. Security-minded approach to information management.

These legislatures guide by providing standardisation of BIM across projects and can be applied across the globe, with many countries or regions compiling their BIM mandates using ISO 19650 as their crux. The objective of the ISO 19650 series is to usher the construction industry to a full or highly collaborative, progressive digital working environment with distinct and recognisable milestones being defined within that process in the form of levels.

3.3.1 BIM LEVELS

The concept of BIM levels has become a recognised definition of what criteria are required to be considered BIM-compliant. BIM levels range from 0 to 3, and are described by the UK National Building Specification (NBS) (McPartland, 2014) as follows:

3.3.1.1 BIM Level 0

BIM Level 0 denotes that the project promotes zero collaboration and makes use of paper-based 2D CAD drafting techniques. The main goal is to generate production information in the form of paper or electronic prints, or both.

3.3.1.2 BIM Level 1

BIM Level 1 denotes a mixture of both 2D drafting and 3D CAD. 2D CAD is used to create production information and statutory approval documentation, while 3D CAD is used to illustrate conceptual designs. Using a CDE managed by the contractor, data sharing happens electronically at this level, with the CAD standards being governed by British Standards (BS 1192:2007). To achieve BIM Level 1, the Scottish Futures Trust states you should achieve the following:

- Roles and responsibilities should be agreed upon
- Naming conventions should be adopted
- Arrangements should be put in place to create and maintain the project-specific codes and project spatial co-ordination
- A CDE for example a project extranet or electronic document management system (EDMS) should be adopted, to allow information to be shared between all members of the project team
- A suitable information hierarchy should be agreed upon which supports the concepts of the CDE and the document repository.

3.3.1.3 __BIM Level 2__

BIM Level 2 is distinguished by collaborative working and requires an information exchange process that is specific to that project and coordinated between various systems and project participants.

Any CAD software that each party uses must be capable of exporting to one of the common file formats such as IFC (Industry Foundation Class) or COBie (Construction Operations Building Information Exchange). This is the method of working that has been set as a minimum target by the UK government for all public-sector work.

3.3.1.4 __BIM Level 3__

Often termed as 'Open BIM' the scope of BIM Level 3 has not been completely defined, however, the vision for this is outlined in the UK Government's Level 3 Strategic Plan. In this plan, the following objectives are set out to be secured with further funding:

- The creation of a set of new, international 'Open Data' standards which would pave the way for the easy sharing of data across the entire market
- The establishment of a new contractual framework for projects that have been procured with BIM to ensure consistency, avoid confusion, and encourage open, collaborative working.
- The creation of a cultural environment that promotes cooperation, sharing, and learning.
- Training the public sector client in the use of BIM techniques such as data requirements, operational methods, and contractual processes
- Driving domestic and international growth and jobs in technology and construction.

In conjunction with BIM Levels 0 to 3, a certain dimension of BIM needs to be fulfilled and associated per level. These BIM dimensions are explained in the section following.

3.3.2 BIM DIMENSIONS

BIM dimensions are categorised from 3-Dimensional (D) to 8D, with dimension 1 being just along one axis (unlikely), and dimension 2 being a digital geometric model that constitutes an X and a Y axis associated with further information, with 3D to 8D described by NBS (Hamil, 2021) as follows:

3.3.2.1 3D BIM

3D BIM is a digital geometric model that constitutes an X, Y and Z axis associated with further information, affording the following advantages:

- 2D views of geometric information can be derived from the 3D model at different levels of detail.
- Schedules can be generated of different object types comprised in the 3D model.
- Multiple 3D models can be consolidated for review to identify any geometric clashes.

All the above features greatly improve efficiency and accuracy, as well as reduce the risk of errors occurring on projects. The linking of specific information to the 3D model leads to further benefits being achieved.

3.3.2.2 4D BIM

4D BIM involves the adding of scheduling information to model construction sequences, the dimension being time to the 3D BIM model. Adding the dimension of time allows the project team to better visualise how the construction will be sequenced. This enables enhanced collaboration and insight between design and construction teams, providing a means to assess and optimise construction planning and task scheduling.

3.3.2.3 <u>5D BIM</u>

5D BIM is commonly considered to be the addition of the dimension of cost information to the 4D BIM model. It is advised to clearly specify and define the type of cost to be added to the dimension, such as capital or operational costs, pre-tender estimates or a record of as-built costs, as well as who is responsible for adding this information and what method of measurement is to be used. These costs could be inclusive of non-displayed amounts such as temporary work and construction joints. 5D BIM leads to better cost and design estimations with BOQ/BOM (bill of quantities/materials) incorporated with 4D BIM, providing a means to assess and optimise construction planning and task scheduling relative to cost.

3.3.2.4 <u>6D BIM</u>

6D BIM is considered by some to add facility management to the 5D BIM model/information set to support the project life cycle management and operations to drive better business outcomes. However, there is little industry consensus on this, and arguably this is not a ‘dimension’ at all. If discussing 6D BIM, it is strongly advised to set out precisely what is required so that all parties have a clear understanding.

3.3.2.5 <u>7D BIM</u>

7D BIM is considered by some to add sustainability information to the 6D BIM model/information set. As with 6D BIM, it is strongly advised to carefully define the specific information required in terms of data types, such as scope, units and rules of measure.

3.3.2.6 <u>8D BIM</u>

8D BIM is considered by some to the addition of health and safety information to the 7D BIM model/information set. As with 6D BIM, it is strongly advised to carefully define the specific information required in terms of data types, such as scope and units, rules of measure.

3.3.3 BIM LOD

3.3.3.1 <u>AN INTRODUCTION TO LOD</u>

The American Institute of Architects (AIA) introduced LOD by defining five levels of development to define detailing levels in a BIM model in 2008, with the addition of LOD 350, there are now six levels of development, in which most model elements fall. LOD enables the following (United BIM, n.da):

- The LOD specification affords professionals in the industry a means to track how an element's geometry and associated information have evolved throughout the entire process. It provides a benchmark/frame of reference to which teams can ascertain their reliance on element-associated information.

- Designers can utilise the LOD specification to define the inherent characteristics of each element at different stages of development. The clarity in illustration gives depth to a model, effectively conveying to teams the level of reliance per level on a model's element.

- It helps designers, engineers and other professionals better understand the limitations and practical applications of a model. By providing a means of standardisation, the LOD framework serves as a collaborative communication tool for efficiency and effectiveness.

LOD is commonly interpreted as the level of detail instead of the level of development. Though they might come across as similar, there are important differences. level of detail refers to the proportion of detail enclosed within the model element. level of development refers to the degree of development to which the components' specifications, geometry, and attached information have been thought through, defining the degree of information reliance by project team members using the model. In simple terms, the level of detail can be understood as the input to the element, with the level of development being the dependable output.

3.3.3.2 <u>DEFINITIONS ASSOCIATED WITH LOD</u>

Currently, six different levels of development (LOD 100 to 500) are defined by the AIA with the LOD outlining the design requirements at each stage, described by United BIM (United BIM, n.d) below:

3.3.3.2.1 <u>BIM LOD 100 – Concept</u>

At LOD 100, which is the pre-design stage, the model consists of 2D symbols and the masses to signify an element's existence; the objective being to interpret the information on an elementary level. The model element may be graphically represented in the model with a symbol or other generic representation. Information related to the model element can be derived from other model elements. Any information derived from LOD 100 elements must be considered approximate.

3.3.3.2.2 <u>BIM LOD 200 – Approximate Geometry</u>

At LOD 200, the elements are partially defined by outlining their approximate quantity, size, shape, and location. The model element is graphically represented within the model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Any information derived from LOD 200 elements must be considered approximate.

3.3.3.2.3 <u>BIM LOD 300 – Precise Geometry</u>

By LOD 300, the elements are defined with exact dimensions and their relative positions, enhancing precision. The model element is graphically represented within the model as a specific system, object, or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the model element. The project origin is defined, and the element is located accurately with respect to the project origin.

3.3.3.2.4 BIM LOD 350 – Construction Documentation

LOD 350 describes the information about an element precisely and outlines the element's relations and connections with other components. At LOD 350, the model element is graphically represented within the model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the model element. The majority of models fall into this level in the AEC industry.

3.3.3.2.5 BIM LOD 400 – Fabrication and Assembly

The LOD 400 level outlines the basic information about the construction of various elements. At LOD 400, the model element is graphically represented within the model as a specific system, object, or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the model element.

3.3.3.2.6 BIM LOD 500 – As-built Models

By LOD 500, the model begins representing the real-life functions of elements in a real building. At LOD 500, the model element is a field-verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the model elements.

This six-level LOD specification can be used as a point of reference and guide for those involved in a project to convey the appropriate details allowing them to understand the extent of information available and how to base their usability and reliability. The higher the LOD, the more reliable the information is for teams to make informed decisions.

3.4 BENEFITS OF BIM

3.4.1 BIM ON A COMPANY LEVEL

When looking at BIM on an organisational level, a study detailed in the report (SmartMarket Report, 2017) titled "The Business Value of BIM for Infrastructure 2017" highlighted that the main benefits experienced are increased profitability, reduced business risk, higher retention of skilled workforce, as well as being more innovative and having a competitive edge, with the majority (87%) of BIM users in the study saying they are receiving positive value from their use of BIM. The five most prominent benefits were:

- 34% fewer errors
- 22% greater cost predictability
- 21% better understanding
- 16% improved schedule
- 8% optimised design

When it comes to transportation projects, the 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), with the results depicted on the right.

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%. 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 to recruit and retain staff.

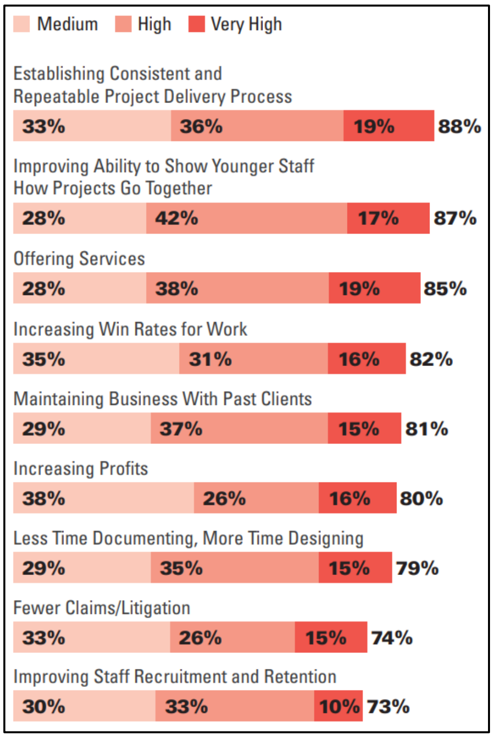


Figure 3.2: BIM Benefits for Transportation
Source: SmartMarket Report, 2017

In another report “The Business Value of GIS for Design and Construction 2020” (Dodge Data & Analytics, 2020), the top internal business benefits of GIS were noted such as improved productivity (61%), establishing consistent and repeatable processes (46%), improved client satisfaction (57%) and offering more services (55%). Organisations can now insightfully tackle projects and win more business with the integration of BIM and GIS. In a white paper “Better Business Results with BIM - Why Striking New Paths for Infrastructure” (Autodesk, 2016), the following business benefits were highlighted:

- Cost and time savings with the advantage of having visualisation as a by-product of the BIM process, and their teams united around one model of truth promoting a streamlined exchange of information with the power of the cloud and an all-digital workflow.

- Enhanced project execution with the use of a shared model to improve project execution on many levels, such as safety, buy-in, conflicts, and liability. Safety plans can be linked to project tasks, identifying areas of risk, with the BIM process contributing towards one collaborative, consolidated model, which can be used for clash detection, achieving reduced liability and conflicts in construction, and portraying a visual model conveying realistic design intent for streamlined project buy-in.

- Value creation beyond design and construction, with BIM data expanding the use of an asset to operations and maintenance, facilities management, virtual design, and construction, as well as value engineering, contributing to sustainable, long-term longevity of an asset, commonly referred to as holistic lifecycle management.

- The points above lead to advancing benefits for a company or organisation, with many reporting a higher ROI, competitive advantage and advantageous expansion of offerings and expertise. This is directly proportional to the bottom line of a company, and by avoiding the bottlenecks typically experienced by traditional workflows and processes, it ensures companies can now wield the insight afforded by BIM for increased profitability.

3.4.2 BIM ON A PROJECT LEVEL

The impact of BIM on a project level could be closely associated with those on a company level, as it has a directly proportional effect on profitability. Besides the points raised in the previous section, the following were noted as highest value project activities below:

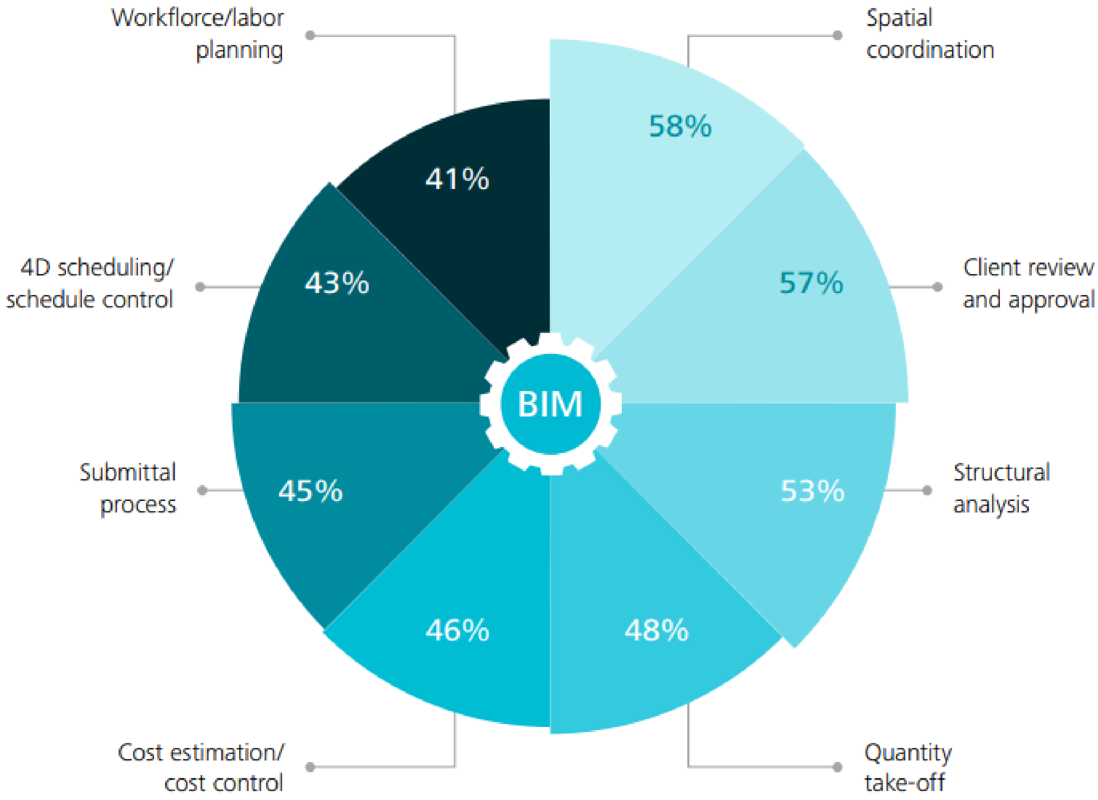


Figure 3.3: BIM Value Drivers
Source: SmartMarket Report, 2017

Integrating BIM and GIS enables project teams to incorporate geospatial information into their AEC designs, resulting in more insightful and contextual designs. Integrating BIM and GIS enables project teams to incorporate geospatial information into their AEC designs, resulting in more insightful and contextual project delivery. The BIM process also affords project teams the opportunity to analyse, schedule and simulate their designs before hitting the ground on the construction site, allowing for errors to be identified and avoided in the early phases of a project. With the advantage of 4D and 5D construction simulation as well as optioneering, teams can now tweak construction sequencing and scenarios and plan more effectively, ensuring projects are executed and delivered on time in the most economical and sustainable way.

With visualisation being an advantageous by-product of the BIM process, teams can now convey their design intent in a non-technically heavy manner, resulting in all teams involved understanding the intent of a project and working towards a common vision. With the added benefit of VR, AR and gamification, teams can now immerse themselves in their projects, providing a realistic, real-world experience to further enhance project planning and approval.

With the advent of COVID-19, the necessity for a collaborative environment where all teams need to be connected had never been more apparent. As a result of connected BIM, cloud collaboration and computing enabled design and construction teams to collaborate in CDE in the cloud to ensure they were on the same page. With the pandemic serving as a catalyst to embrace digital transformation and a collaborative environment, teams have now realised the value of this component for enhanced project delivery. By integrating across disciplines in the AEC industry, teams can now digitally come together to contribute towards a consolidated model no matter where in the world they are situated, as well as raise issues and review models in the cloud.

Another added advantage of the cloud is its secure storage and analytical capabilities. With all the data housed under one roof, the project data can be accessed by relevant teams based on permission rights, allowing for secure project data access information. From a design perspective, teams can now take advantage of revision control and history, as well as run analysis for various elements such as bridges, traffic, watersheds, and energy, including visualisations, using the cloud as a rendering source to create realistic imagery and panoramic VR. This collaborative advantage of connected BIM allows teams to be insightful and connected throughout the project lifecycle.

For construction teams, mobile connectivity that syncs to the cloud ensures that issues raised as well as construction updates are realised as soon as they are submitted. With this pushed connectivity, revisions, change orders, site progress, as well as requests for information (RFIs) can now be resolved as soon as possible with the functionality of attaching this information to a location on the model correlating to that on site including imagery, ensuring problems are resolved as quickly as possible and construction delays are avoided.

3.4.3 BIM ON A PROFESSIONAL LEVEL

With BIM having a significant impact on business and project levels, it also has a positive impact on AEC professionals. BIM enables AEC professionals to be more innovative and creative, combining academic knowledge and technology for futuristic problem-solving and project delivery. The wielding of technology and academia forms the perfect symbiosis, contributing to a holistic professional.

BIM empowers users and professionals to be creative in terms of problem-solving and solution mapping and be the best they can be on a company, region, country and global scale in their respective fields. BIM also, to a certain extent, serves as a means of mentoring, by allowing fresh graduates to apply their textbook knowledge in a technological arena, and gauging the results. This leads to graduates becoming broader-minded in their approach to problem-solving, task achievement and application.

When it comes to the seasoned or mature professional who possesses a wealth of experience, practicality can be incorporated or further interrogated using optioneering and other advantages afforded by BIM. With the younger professionals more open to technology and the older not, in most cases, a balance can be achieved by bridging the gap between technology implementation and project experience and practicality, leading to a mutually beneficial approach to innovatively solving problems of today with the experience and practicality gained of yesterday between new and seasoned professionals, for a better tomorrow.

From a development perspective, BIM opens windows of opportunities for further growth and new career roles. Currently, these new career paths or roles seen in the AEC industry are BIM engineer, BIM technician/modeller, BIM coordinator, BIM manager, digital lead, as well as chief technology officer. Roles headed by those advising companies on people, processes, and technology are occupied by professionals in the technology consulting space, serving as industry leaders/guides in ushering companies and professionals to successful adoption, implementation and training, having the title of BIM technical specialist. They typically have a combination of industry experience and technology certifications.

3.5 BIM FOR CIVIL INFRASTRUCTURE

BIM has been, and still is, predominantly championed by architects, which has led to a misconception that the application and implementation of BIM technologies and workflows are exclusively for the architectural industry. While BIM has its origins in architecture and the building environment, BIM applies to everything that is designed and built (constructed), including civil infrastructure, and by embracing BIM, civil engineers can reap the same benefits as architects, if not more.

BIM is not only for the built environment, but for the civil industry as well, and can be incorporated across the various components of civil infrastructure as depicted below.

Figure 3.4: Core Components of Civil infrastructure
Source: SAICE & Baker Baynes, 2021

BIM for civil infrastructure incorporates and promotes an array of technologies and innovative processes such as the incorporation of reality capture or Scan-to-BIM for terrain and/or as-built capture, integration with Geographic Information Systems (GIS), effective collaboration across civil infrastructure core components/fields, incorporation of CAD design with machine control for automated, precision construction, 4D and 5D construction simulation, clash detection and model coordination, as well as a highly visual, realistic render environment. All these processes occur or contribute towards one collaborative BIM model, with the data feeding to the model at the epicentre of the process, as can be seen below.

Figure 3.5: BIM for Civil infrastructure
Source: SAICE & Baker Baynes, 2021

The ecosystem of BIM technologies is constantly growing and developing, which has led to concern for true, effective collaboration. This has led to many developers and providers in the AEC space striving towards a truly effective means of collaboration, which is vendor-neutral called openBIM, headed by buildingSMART International, of which Autodesk is a co-founder and on the strategic advisory council of buildingSMART, which drives the creation and adoption of open, international standards for infrastructure and buildings.

The definition of openBIM given by buildingSMART International is that openBIM extends the benefits of BIM by improving the accessibility, usability, management, and sustainability of digital data in the built asset industry. At its core, openBIM is a collaborative process that is vendor-neutral. openBIM processes can be defined as sharable project information that supports seamless collaboration for all project participants. openBIM facilitates interoperability to benefit projects and assets throughout their lifecycle.

By adhering to international standards and working procedures, openBIM extends the breadth and depth of the use of BIM by creating common alignment and language. Technical applications developed for openBIM improve the management of data and eliminate disconnected workflows. Independent quality benchmarks ensure reliable open data exchanges, that permit digital workflows based on vendor-neutral formats such as IFC, BCF, COBie, CityGML and gbXML. openBIM enables an accessible digital twin which provides the core foundation for a long-term data strategy for built assets. This provides better sustainability for projects and more efficient management of the built environment. Therefore, the six principles of openBIM recognise that:

1. Interoperability is key to the digital transformation in the built asset industry
2. Open and neutral standards should be developed to facilitate interoperability
3. Reliable data exchanges depend on independent quality benchmarks
4. Collaboration workflows are enhanced by open and agile data formats
5. Flexibility of choice of technology creates more value for all stakeholders
6. Sustainability is safeguarded by long-term interoperable data standards

Striving towards an open BIM collaborative environment and a parametric, dynamic, visual, and cloud-connected ecosystem, BIM is a game changer and plays a pivotal role in intelligent, sustainable civil infrastructure delivery. By using technology as an enabler, civil infrastructure has truly become a technologically opportunistic industry, with a variety of technology, processes and informational data being integrated across the project lifecycle.

With its plethora of benefits, BIM use has increased across the world, which has led to many countries mandating its use. Viewed as a process or methodology that enables innovation, intelligence, economical and smarter ways of achieving tasks and overcoming new challenges, as well as providing a convergence workflow between manufacturing and construction.

With civil infrastructure projects such as those that involve transportation and pipe networks/utilities (also referred to as horizontal construction segments) spanning over great lengths or areas, BIM technologies, processes and workflows are crucial in ensuring the highest levels of coordination, collaboration and transparency are maintained throughout the project lifecycle.

3.6 CASE STUDIES - BIM IN CIVIL INFRASTRUCTURE PROJECTS

BIM has been applied across various core components of civil infrastructure, with this section looks at some case studies dealing with horizontal construction compiled by Autodesk in Africa, Asia, Europe, Australia, and the Americas.

3.6.1 AFRICA

Despite the absence of a BIM mandate and slow adoption of BIM in the civil infrastructure space, the African continent has hosted and produced impressive projects incorporating BIM, most of which are in the vertical construction space. When it comes to civil infrastructure (horizontal construction), a project of great magnitude is that of building Africa's largest (longest and tallest) cable-stayed bridge in Morocco, which involved six companies collaborating across three continents.

Figure 3.6: Bouregreg River Bridge
Source: Autodesk Customer Success Stories Africa, 2015

EGIS JMI applied a 3D-model approach over traditional methods to derive shop drawings, which resulted in zero clashes upon running clash detection based on minimum tolerance between the cables, no rework and only one design submittal. This 3D model approach inclusive of a global collaborative platform prevented the entire project from running into considerable rework, delays, and financial loss during construction, which made a project of this huge magnitude easy.

In South Africa, HHO Consulting Engineers applied BIM to visualise tough engineering challenges in a Bus Rapid Transport (BRT) project. The project consisted of a varying median on which the stations would be positioned, the roadway, as well as a retaining wall of varying elevation to separate the BRT lanes from the general mixed traffic lane.

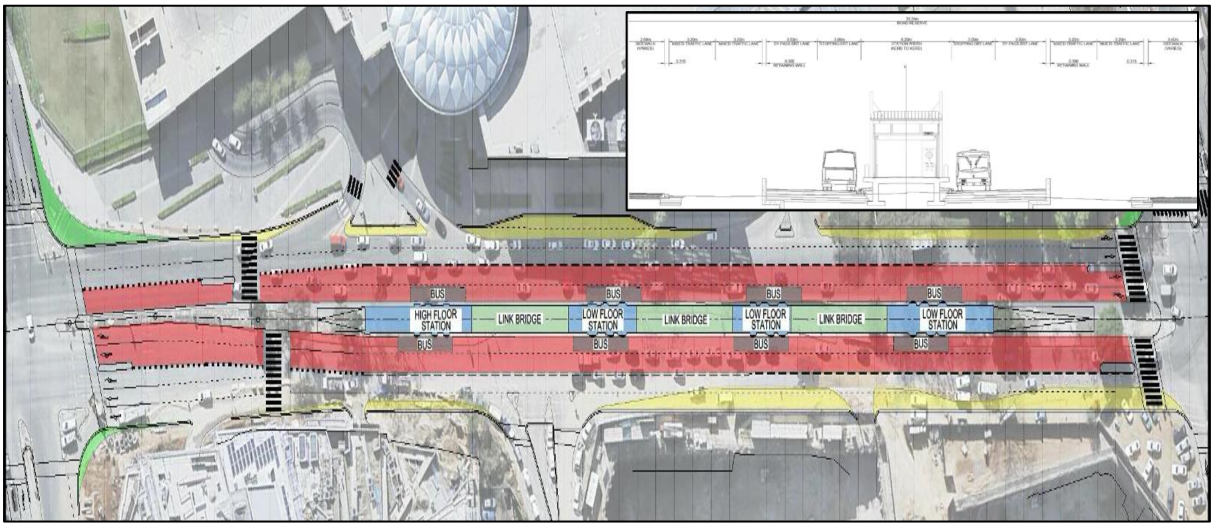


Figure 3.7: Bus Rapid Transport (BRT) Layout
Source: Autodesk Customer Success Stories Africa, 2021

With this much complexity within a tight space of development, the consortium involved could not visualise the project from traditional 2D drawings, which resulted in the project not being approved and moving forward. This led HHO to utilise BIM and upon applying BIM, the technical engineering design was linked and translated to a highly visual platform, realistically conveying design intent, and incorporating the architectural stations which led to the project being approved and moving ahead.

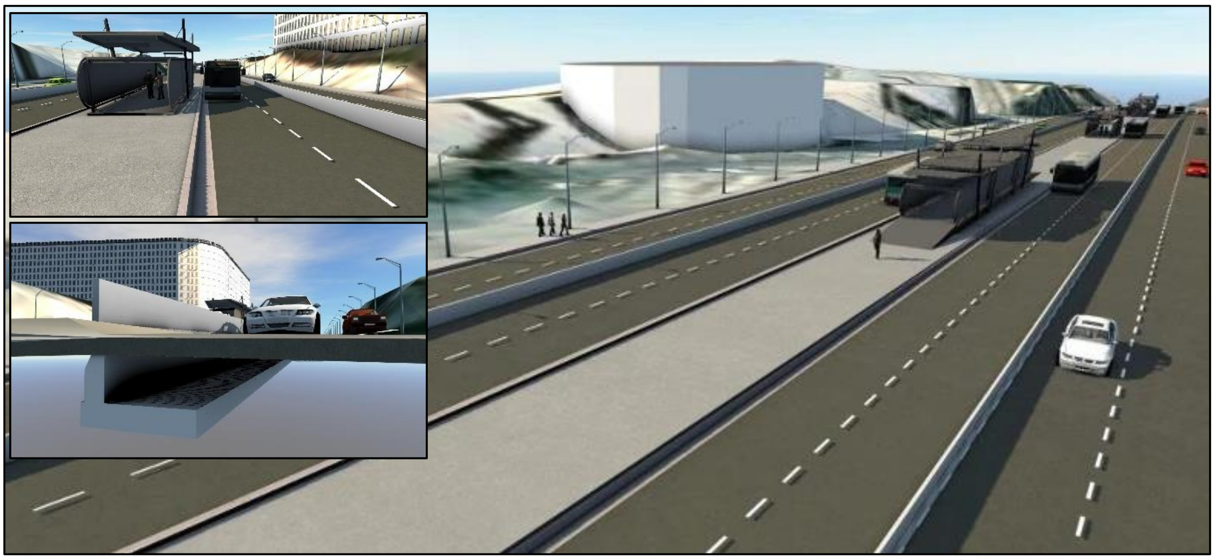


Figure 3.8: BRT Project Visualisation Model
Source: Autodesk Customer Success Stories Africa, 2021

3.6.2 ASIA

In China, the Chongqing Architectural Design Institute of China (CQADI) applied BIM to help speed up a complex interchange project. The project consisted of a variety of complex components, such as the widening of the elevated and underpass main and auxiliary roads, the creation of a viaduct, the demolishing of an existing bridge, the excavation of the underground passage, as well as auxiliary roads to ensure smooth traffic flow on and off the Taohuaxi bridge.

Figure 3.9: Hongshi Avenue Interchange Node
Source: Autodesk Customer Success Stories Asia, 2019a

The highway reconstruction project involved multiple engineering specialities, including bridge, tunnel, traffic, drainage, landscape, and lighting. Using BIM, 3D modelling, clash detection, reality capture and cloud collaboration, CQADI were able to produce a BIM model that met strict environmental regulations and deadlines within budget.

BIM has also been implemented on an impressive wastewater treatment plant (WWTP) project in China. The Shanghai Municipal Engineering Design Institute Co. Ltd. (SMEDI) worked with Shanghai Chengtou Water Group Co. Ltd. to deliver a mega underground WWTP with the aim of making it the most sustainable and intelligent facility of its kind in China. The WWTP consisted of more than 40 tanks, 7 560 facilities, 800 km of pipes, ducts and trays, as well as 600 000 metres of cable laid in a compact space of just 36.84 acres, located 17 metres underground.

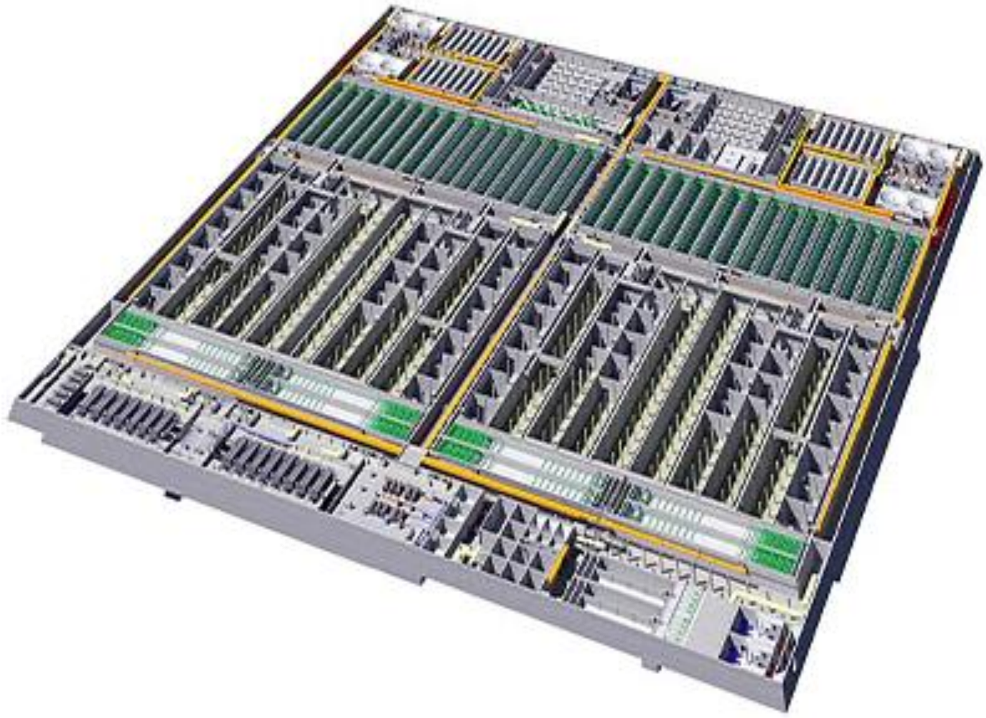


Figure 3.10: A Rational Layout Underground of Shanghai Taihe WWTP
Source: Autodesk Customer Success Stories Asia, 2019b

A team of more than 40 engineers, specialised in a wide range of disciplines, worked together to find optimal solutions for the layout of the underground WWTP. By using BIM software and workflows to design, analyse and simulate all the models and data, SMEDI was able to decide on the preliminary layout in just a few weeks, a task that would have been much more difficult and time-consuming to complete by using 2D drawings alone to envisage spatial arrangements.

BIM technologies and workflows enabled SMEDI to conduct parametric modelling via visual scripting, incorporate GIS and computational fluid dynamics (CFD), as well as integrate all models and run simulations of the entire construction sequence for conflict examination/clash detection and develop immersive visualisation experiences.

This resulted in the team being able to spot more than 1 200 collisions among 800 km of different types of pipes, ducts, and cable trays, thereby reducing mistakes, minimising the environmental impact of the project, and ensuring construction safety. Moreover, the construction efficiency was greatly improved, speeding up construction by three months.

In Malaysia, WDI Studios Pvt Ltd based in India had just three weeks to interpret raw survey data, model civil works and visualise improvements to reduce site development costs. They integrated BIM into their workings for this 100-acre township project consisting of luxury housing and schools, as well as amenities and attractions, including hotels, restaurants, and amusement parks.

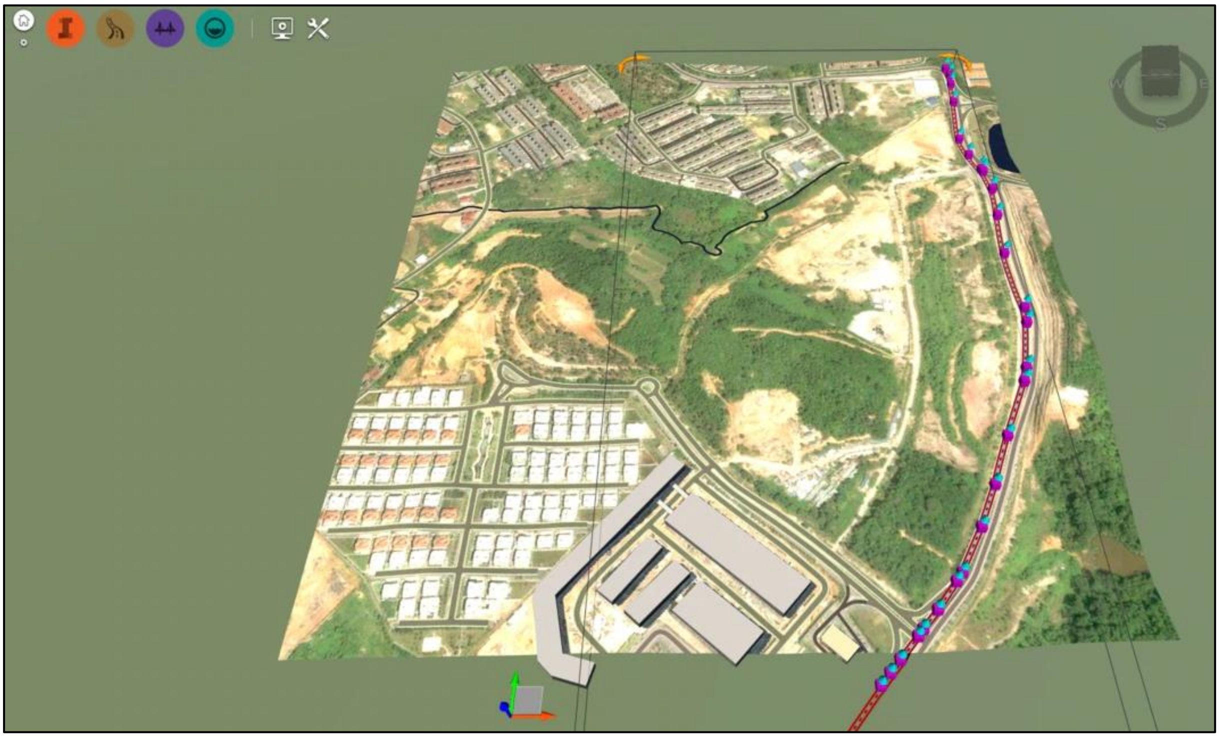


Figure 3.11: BIM Model of 100-Acre Township in Malaysia.
Source: Autodesk Customer Success Stories Asia, n.da.

By allowing the owner to see various site development options early in the design process, WDI Studios helped to predict the impact of design changes, avoid unanticipated costs, and lower the costs of preferred options. BIM capabilities saved almost 42.7% of the time in this initial phase compared to traditional methods, streamlined roadway designs, and improved the site development planning process across the board.

In Japan, the Mikusa Tunnel project on the Kinki Highway Kisei Line was the first of many projects to apply construction information modelling/management CIM (a localised term used in Japan's construction industry in place of BIM) for the entire building process.

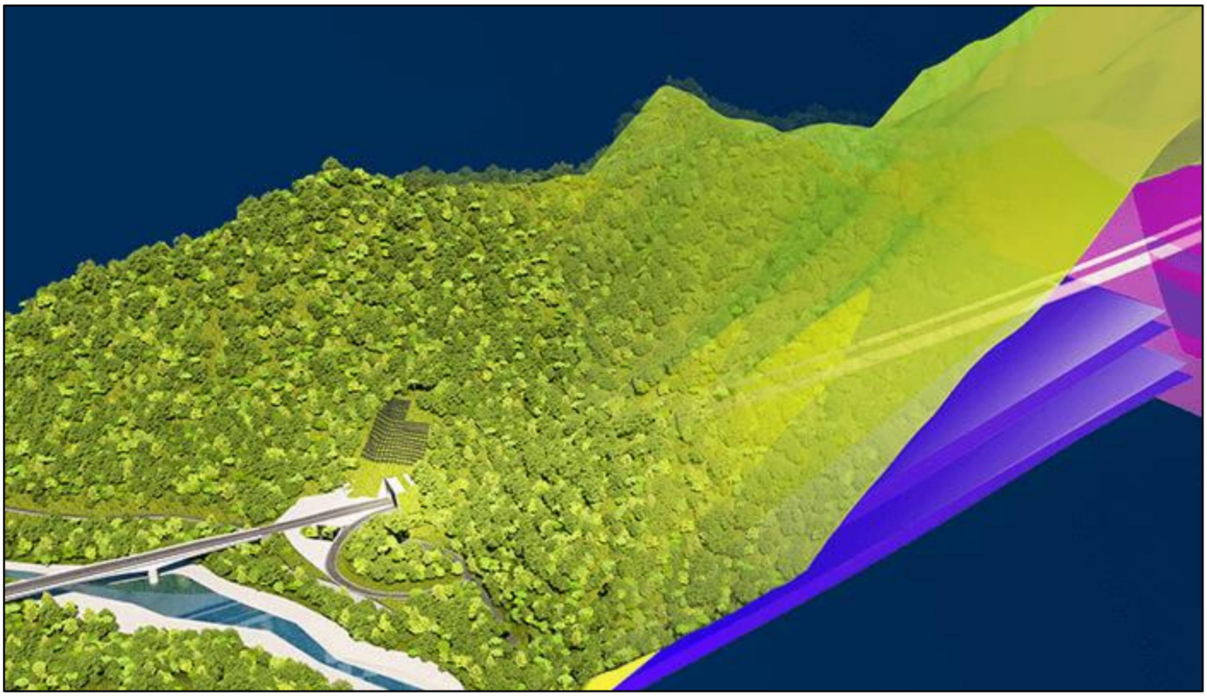


Figure 3.12: BIM Model of Mikusa Tunnel
Source: Autodesk Customer Success Stories Asia, 2018

The Obayashi Corporation completed the construction of the Mikusa Tunnel by using 3D models. Measurements related to tunnel excavation, such as displacement, groundwater level, terrain, and geological information, were continually input as work progressed, with that data shared instantly with the company's headquarters using the cloud. Working with CIM/BIM, the team was able to realise a 35% increase in construction-management efficiency.

Turkey occupies a unique geographic position, with 97% of its territory lying in Asia and only 3% of its territory lying in Europe. Based on the greater extent of Turkey being in Asia, it has found its way under the Asian list of BIM projects in this report.

Yüksel Proje with its head office in Ankara, Turkey, used BIM on multiple large-scale projects, of which two will be mentioned, such as the 3-Deck Great Istanbul Tunnel (when completed, it is going to be the first 3-deck tunnel in the world) and the Yavuz Sultan Selim Bridge (also called the Third Bosphorus Bridge), being the tallest suspension bridge in the world, comprising pylons higher than the Eiffel Tower.

Figure 3.13: 3-Deck Great Istanbul Tunnel - Viaduct Project
Source: Autodesk Customer Success Stories Asia, n.db.

Figure 3.14: Yavuz Sultan Selim Bridge
Source: Autodesk Customer Success Stories Asia, n.db.

Yüksel Proje had switched from 2D design to BIM, resulting in shorter project durations and a significant increase in accuracy saving 20% in project design time. Applying a cloud-based approach allowed them to reduce IT costs and enable fast access to the latest technologies and updates, as well as easy access to a collaborative platform.

3.6.3 EUROPE

With the UK being the global leader in BIM, one would expect BIM to be applied to futuristic projects. One of these projects being the Virgin Hyperloop One which is pushing the boundaries of transportation efficiency. Virgin Hyperloop One's visionary technology features depressurised tubes that carry on-demand passengers or cargo pods at speeds of up to 670 miles per hour, powered by magnetic-levitation and electric propulsion. Its depressurised tube infrastructure eliminates the impacts of air-drag and friction, requiring less energy and cost to operate, and allows travel to occur at exceptionally high speeds.

Figure 3.15: Virgin Hyperloop One
Source: Autodesk Customer Success Stories Europe, 2019

By incorporating BIM technologies and workflows, the project teams collaborate effectively, as well as design, model, analyse, simulate, and visualise in context, resulting in transportation route optimisation and improved digital engineering and construction workflows. They also expressed that tasks that took them nine months to do were now achieved in hours at the same level of detail achieved in nine months.

In Norway, Norconsult used BIM and VR gamification in infrastructure design to help foresee potential design problems on a tunnel project. The interactive game environment it created has set a new standard for streamlining design evaluation, validation, optimisation, and approval.

Figure 3.16: Tunnel BIM & Gamification Model
Source: Autodesk Customer Success Stories Europe, 2017

To tackle the Ulriken Tunnel project's complex design and construction challenges, Norconsult's use of BIM helped the company coordinate across disciplines more efficiently. BIM models and intelligent coordination for the tunnel project and station upgrades were used to collaborate with construction teams. With gamification, the idea was to incorporate the BIM models with virtual reality to create a game environment that would allow train operators to "drive" on the future tracks before they were built. The team achieved this by animating the 3D models and augmenting them with laser scans of real-world data, such as the layout of the train cockpit, for enhanced realism.

In Switzerland, Hunziker Betatech AG's engineering team was tasked with not only renovating two aged wastewater treatment plants located in the canton of Zurich, Switzerland, but also combining them at a single location in order to meet new requirements. The particular challenges the team had to tackle were that of space constraints, stringent regulations that led to tripling purification output, compliance with new environmental laws, and the need to carry out the project without interrupting the service. The ARA Zimmerberg association decided on a large-scale plant designed at the Thalwil site, which will be able to treat 800 litres of wastewater per second, serving up to 78 000 inhabitants. This is the approximate predicted load for 2050. The engineering firm Hunziker Betatech AG was commissioned for the project. The engineering team used digital modelling with BIM workflows for the feasibility analysis.

Figure 3.17: ARA Zimmerberg: Construction Phase
Source: Autodesk Customer Success Stories Europe, 2021

With traditional 2D planning methods, it would have been impossible to plan and build this wastewater treatment plant in the long term. Only with digital 3D planning tools are we able to efficiently use every centimetre of the construction area and approach the project from technical and legal angles. With a combination of BIM, VR, reality capture and cloud collaboration, the team were able to find joint solutions to over 300 coordination tasks and carry out intelligent engineering design. The engineers were able to conduct a shading study to ensure that residents would not miss out on daylight and lake views due to construction. The planned canopy and exhaust air purification via biofilters ensured there would be no noise and odour emissions. And to make sure the building did not look like a wastewater treatment plant, the facade was finished in Swiss wood, to blend in discreetly with its surroundings.

This resulted in a more sustainable and cutting-edge treatment plant in Switzerland, with a unique combination of all energy sources. Construction is planned to start in 2022, and ARA Zimmerberg will be commissioned in 2027.

In the Netherlands, the Arup team utilised the dynamic nature of BIM, visual scripting for design automation, structural analysis, and visualisation on the Tsuhoff Bridge near the Rotterdam area. This allowed the team to connect workflows between highway design and existing site conditions with the overall structural bridge design.

Figure 3.18: Tsuhoff Bridge
Source: Autodesk Customer Success Stories Europe, 2020a

In Germany, the A10/A24 Availability Model project is the first German public-private partnership (PPP) pilot project in which the BIM approach will be integrated from planning to execution and maintenance. The section of the A10/A24 Havelland Autobahn is an important and busy trans-European transportation axis, with a project completion date in the year 2022.

The clients are the German federal government and the State of Brandenburg, represented by DEGES Deutsche Einheit Fernstraßenplanungs- und -bau GmbH. 2020 is the year earmarked in the German federal government's digitalisation strategy by which it wants to make BIM the new standard for transport infrastructure projects and this section of the autobahn is among the BIM pilot projects that make up the government's 2020 road map.

The A10/A24 Autobahn is the main thoroughfare between Berlin and Hamburg. The infrastructure along the entire route can no longer keep up with the growing volume of traffic and the road surface is showing signs of wear. The route will be widened and modernised to cover six lanes while traffic will continues to operate.

Figure 3.19: A10/A24 Havelland Autobahn
Source: Autodesk Customer Success Stories Europe, 2020b

The BIM contract covers a 5.5 km section of the autobahn. This section of the A24 will be comprehensively renovated and a hard shoulder will be added at various points between the Fehrbellin and Kremmen exits and will be opened to traffic when needed. Construction will include two rest and service areas, two traffic sign cantilevers, a replacement bridge, a noise barrier, and wildlife protection fences along the route.

Wayss and Freytag engineers used BIM as the single source of truth (SSOT), incorporating a common data environment (CDE), as well as using BIM technologies for the context model, earthworks, subsoil (including soil layers and groundwater level), interim measurements of the road section, equipment for the temporary openings of the hard shoulder, landscaping, and the digital terrain model. With visual scripting, visualisation and construction sequencing, the team were able to identify and rectify errors at an early stage in the planning and construction process, resulting in a successful BIM pilot project in road construction.

3.6.4 AUSTRALIA

In Australia, Cardno was working on a proposal for an urban development project south of Sydney, New South Wales. With multiple stakeholders involved in this large urban development project, the team needed a solution that would streamline communication and impress the client.

Figure 3.20: Urban Development Project Model
Source: Autodesk Customer Success Stories Australia, 2019

The team chose to develop a data-rich, 3D model of the project using BIM technology. This technology enabled the development of compelling visualisations, flythroughs, and live navigation, which greatly enhanced Cardno's ability to clearly communicate design intent. Using interactive 3D models allowed Cardno to easily get all stakeholders on the same page, effectively communicating design intent to all parties involved.

The result for Cardno and the developer was a streamlining of the engagement process, expressing that what may have taken two or three stakeholder engagement meetings was reduced to a single walkthrough, which allowed the team to be cost-effective while quickly responding to changes in the design.

3.6.5 THE AMERICAS

Los Angeles International Airport (LAX) is the second busiest airport in the US and the third busiest in the world. With a growing influx of passengers from across the globe, the governing body of LAX - Los Angeles World Airports (LAWA) - issued a request for proposals for the design and construction of a new Automated People Mover (APM) train system in 2017.

Figure 3.21: APM Project
Source: Autodesk Customer Success Stories, The Americas, n.da.

At a value of USD2-billion it is one of the largest active airport construction projects in the US, expected to carry up to 87 million passengers per year. The APM features a 2.25-mile elevated guideway that passes through five stations and links the Consolidated Rental Car Facility with the LAX Central Terminal Area. When operational in 2023, it will also connect travellers to regional bus and light rail systems.

As one of the largest BIM projects in the nation, the APM involves more than 180 design models created and maintained by 300+ BIM designers. The design incorporates the train guideway, stations, elevators and escalators, elevated passenger walkway structures (with moving walkways between stations and airport terminals), parking structures, roadway, and landscape improvements, and a maintenance and storage facility for the system's electric trains.

Figure 3.22: APM Project Model
Source: Autodesk Customer Success Stories, The Americas, n.da.

The project incorporated BIM and embraced a CDE in the cloud to unite horizontal and vertical teams, with the project relying on 180+ actively maintained design models used for 3D clash detection, 4D phasing, visualisation, and 5D estimating.

Awarded South Carolina's highest honour for engineering excellence, the Think Energy Positive project achieved multiple milestones for Horry County Schools. Horry County Schools embarked on an endeavour to design and construct five new state-of-the-art schools in 21 months to alleviate overcrowding.

Figure 3.23: Horry County Schools Think Energy Positive Project Overview
Source: Autodesk Customer Success Stories, The Americas, n.db.

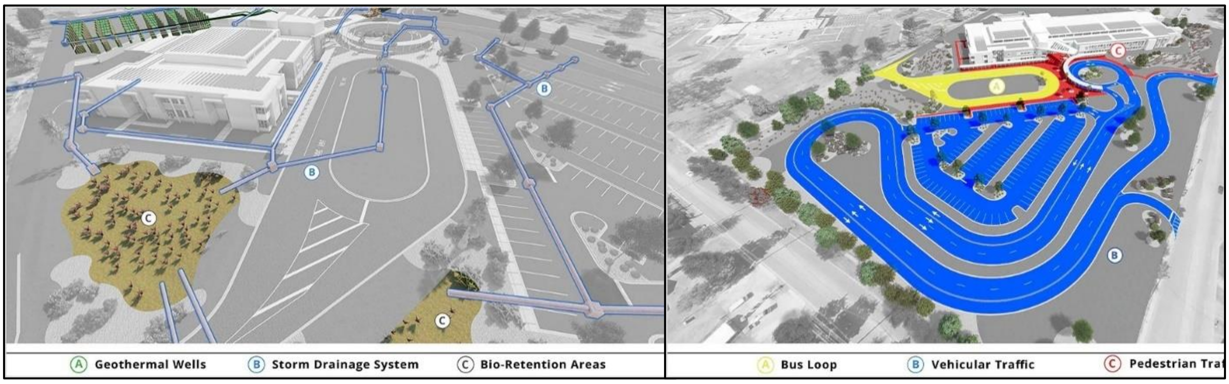


Figure 3.24: Horry County Schools Think Energy Positive Project Roads and Stormwater
Source: Autodesk Customer Success Stories, The Americas, n.db

Thomas and Hutton laid the groundwork for energy efficiency with site planning, civil design and landscape architecture services that involved extensive energy modelling. By integrating BIM and GIS, the team was able to evaluate sustainable land development scenarios, early-stage design concepts for energy efficiency and safety, analyse vehicle paths in relation to emergency equipment, bus traffic and stormwater runoff, as well as pinpoint utilities, soil types and other site characteristics that would affect the design. This resulted in a time saving of about six months on the overall schedule as well as green and sustainable construction comprising solar and geothermal energy sources, with all five schools opening on schedule and under budget.

In New Mexico, the New Mexico Department of Transportation (NMDOT) adopted BIM workflows and technologies for the design and construction of a transportation network.

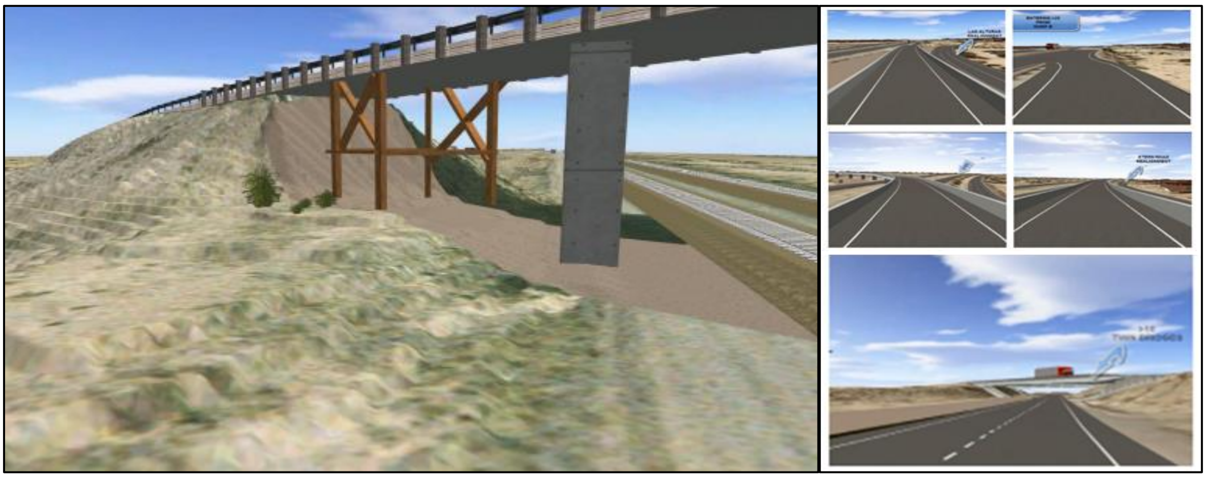


Figure 3.25: Cambray Bridge & Roadway
Source: Autodesk Customer Success Stories, The Americas, 2014

By adopting BIM, NMDOT was able to effectively synchronise road and bridge teams, affording benefits such as ease of performing what-if analysis, dynamically linking design models and materials quantities, the automatic updating of drawings and other documentation when design changes are made, the visualisation of project context and scenarios, as well as cost and time savings.

In the year 2021, realising the challenges facing the East Side Access project, the New York Metropolitan Transit Authority (MTA) asked LiRo's VDCO group to demonstrate how it used BIM on the Number 7 subway line, a previous project engagement. After that meeting, MTA hired the group to transition the entire East Side Access project to BIM.

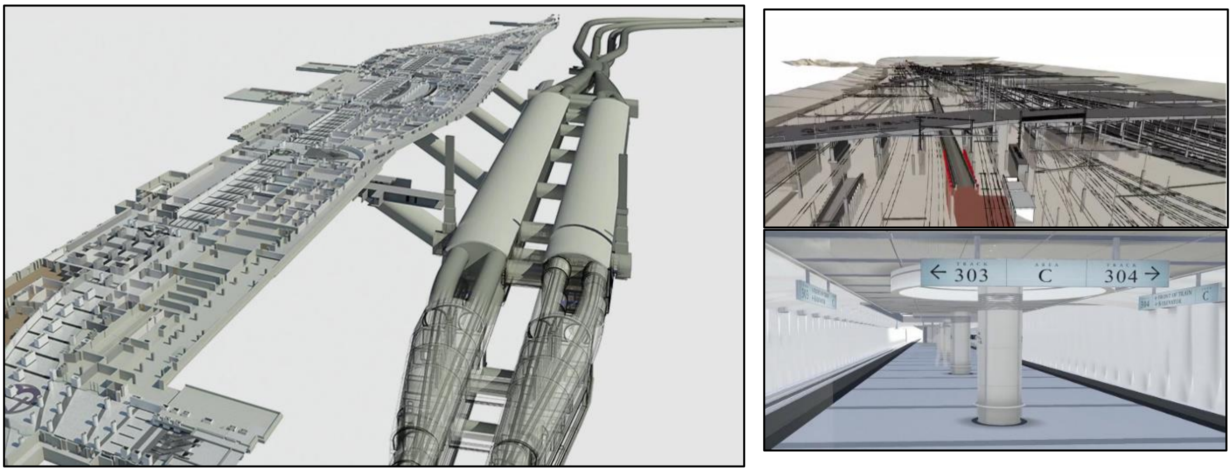


Figure 3.26: New York City's East Side Access Project
Source: Autodesk Customer Success Stories, The Americas, n.dc.

The project includes over eight miles of new tunnels and an eight-city-block long concourse with multiple train platforms 150 feet below Grand Central Station. The project required taking original construction 2D drawings and converting them to a BIM model, developing over 125 interconnected models. To maximise the accuracy of their models, LiRo scanned some existing facilities, such as the Madison Yard, which will house a new passenger concourse. The design intent model was created by just four people in two years, an impressive accomplishment considering the scope of the project of 100 000 drawings, 25 contracts, thousands of workers, and a USD12-billion cost. With BIM and reality capture, the team had identified close to 400 issues that needed to be addressed before construction, saving MTA a massive amount of rework time and money.

Arcadis harnessed cloud collaboration and 3D modelling to complete a USD50-million infrastructure project, providing a resilient water system for the city of Toledo, Ohio, which started with a toxic Harmful Algal Bloom (HAB) in the Midwest and ended with a pandemic that swept the world.

Figure 3.27: Toledo's Collins Park WTP Before the $50 million Expansion and Modernization Project.
Source: Autodesk Customer Success Stories, The Americas, 2021

With the threat of HAB rendering the water undrinkable and producing a deadly toxin called microcystin, the city engaged Arcadis to modernise and expand the aging system. Toledo's Collins Park Water Treatment Plant had six existing water basins at the time of the algal bloom. Built in the 1940s and 50s, the facilities needed more capacity to handle contamination and to remain operational during repairs and maintenance.

Arcadis was charged with designing and overseeing the construction of two new water basins, adding 40 million gallons of capacity per day, while coordinating other system upgrades and keeping the facility operational during construction. The timeline for the project was aggressive, with two years of design work starting in 2016, out for bid and construction beginning in 2018, and two new water basins operational ahead of summer 2020.

Figure 3.28: WTP Project Model
Source: Autodesk Customer Success Stories, The Americas, 2021

Arcadis was able to meet its deadlines by saving thousands of hours, and remotely during the COVID-19 pandemic by adopting BIM, GIS, augmented reality (AR), reality capture and a cloud CDE and connecting a range of disciplines including architectural, structural, mechanical, HVAC, electrical, I&C, and civil site work for enhanced collaboration with the data all in one place.

The expansion of the Panama Canal, a 48-mile-long passageway that connects the Atlantic and Pacific oceans, is one of the largest and most ambitious construction projects in the world. When it first opened a century ago, the Panama Canal transformed international trade by providing a shortcut between the Atlantic and Pacific oceans. But today, in the age of ever-expanding megaships, almost half the world's container vessels are too large to fit through it. In 2009, engineering firm MWH Global began redesigning the canal, evolving it from concept to construction and setting new standards for how massive, multinational civil infrastructure projects are designed, managed and built.

MWH Global's new design will increase the capacity of passing ships from 4 600 containers to 12 800. It is a quantum leap. The project will use the equivalent of 26 Eiffel Tower's worth of steel, and enough concrete (190 000 tons) to construct the skyline of a major city.

The project comprised of expanding existing channels (Widen 21.3m / 70ft, Deepen 5.4m / 18ft, Lengthen 121m / 400ft), creating a new channel, with three new lock chambers on each side and raising the maximum operating level of Gatun Lake, the primary water source for the locks, involving over 3.5 billion cubic feet of earth excavated and over 400 engineers.

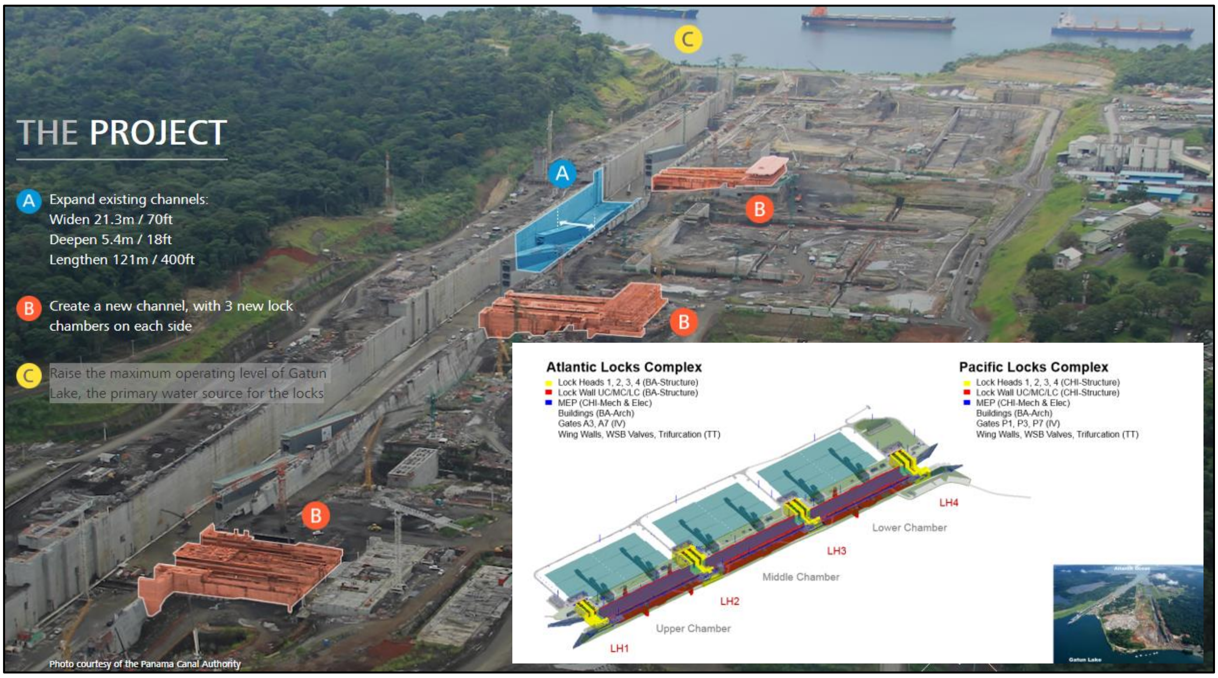


Figure 3.29: Expanding the Panama Canal Project
Source: Autodesk Customer Success Stories, The Americas, n.d.

MWH Global used BIM to map sites and perform critical clash detection, build intelligent databases of key project components and systems and overlay electrical, mechanical, architectural, and civil/structural elements to identify and prevent conflicts as well as the production of civil and structural backgrounds for use by electrical and mechanical designers to lay out their systems, saving thousands of re-work hours and millions of dollars.

The project also boasted cost-effective lock wall designs incorporating foundation drains that reduce the hydrostatic and hydrodynamic loads, seismic design using state-of-the-art seismic analysis techniques as well as water-saving basins, the largest in the world, which aims to reuse 60% of the freshwater consumed for lockages.

4. APPLIED METHODOLOGY

This chapter provides an understanding to the thought process applied in successfully gauging the effectiveness of BIM on a typical road project lifecycle. This was done by first defining the stages across a typical road project, with the stages being as follows:

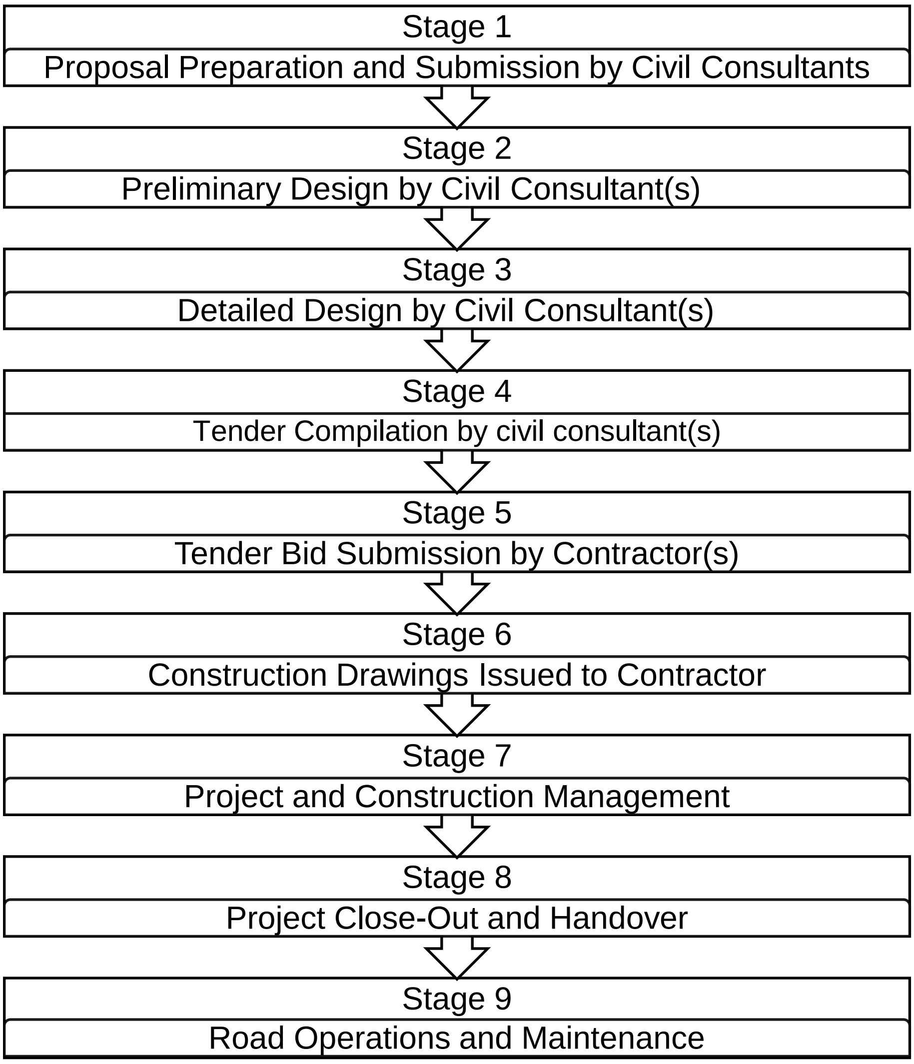


Figure 4.1: Stages Applied in Methodology
Source: Shuaib Yunos

The traditional road process and the BIM road process were then demonstrated and analysed across these 8 stages. Each stage is described in the respective process and how each phase is tackled when employing a traditional and BIM approach. With this methodology, challenges and benefits experienced are systematically diagnosed, and the findings between the 2 approaches summarised, illustrating an effective comparison between the both approaches.

5. THE TRADITIONAL ROAD PROJECT PROCESS

This section provides a contextual overview of how tasks are accomplished on new road projects using traditional/conventional processes still adopted and implemented in the industry. This is achieved by examining the effectiveness across the 9 stages defined in the applied methodology chapter of this dissertation.

5.1 PROPOSAL PREPARATION AND SUBMISSION BY CIVIL CONSULTANTS

A governmental or municipal organisation will require the services for the design and construction of a road that forms part of the Integrated Development Plan (IDP) present in that region or municipality. This then leads to the advertisement of this service, known as a Request for Proposal (RFP), which is open to civil consultants to bid for and is generally accompanied by a compulsory tender briefing. During this briefing, consultants can raise questions relative to the project at hand, which could also be followed by a site visit.

Civil consultants are then required to tender for this project based on the information and deliverables supplied and stipulated in the tender document, including that shared in the tender briefing, arriving at a consulting fee. This fee is typically arrived at from an educated guess, experience and guidelines specified by the Engineering Council in that country/region. At this stage, the following challenges arise or are noted:

- There is no survey data available.
- There is no GIS data available providing the location of services and other surrounding infrastructure
- An aerial/site layout may be supplied in the tender document, but there is no digital format/file

The above challenges make it difficult for consultants to arrive at a reasonable and competitive fee, with consultants (especially those who are just starting off) bidding with fees that are too high or too low. This is due to two causes:

- The consultants who bid too high are doing so to cover any unforeseen circumstances (despite having a contingency, the rates are inflated), with their fees being more conservative than reasonable.

- The consultants who bid too low are doing so to win the bid at all costs and have the conception that the bid would be awarded to the lowest-priced bidder. This conception is typically adopted by emerging consultants who want to make a name in the market. This is a great misconception, as price/fee makes up one of the many components of the bidding/proposal process.

Those consultants that arrive at a reasonably competitive fee are those who have adequate experience or specialise in the field of service. However, due to the lack of data available at this stage, they too are not as certain as they would want to be. Therefore, consultants usually do the following in order to put some form of technical information together in their proposals:

- Acquire aerial imagery of the site as well as an elevation profile along the road centreline typically from Google Earth, with a polyline normally sketched denoting the centreline.
- Geological information and terrain data from a reliable source of their choice on the internet informing material, rainfall, water table and soil conditions.
- Propose a pavement structure informed by the TRH4 catalogue of design.

Despite providing the above technical information, there still is no digital, reusable data, creating a silo effect. The RFP is then compiled, completed, and submitted by the consultant with their proposed fee, after which a public tender opening could be held declaring the bids received, with the awarded consultant declared after the review process has been completed. This now leads to the successful needing to prepare a preliminary design report.

5.2 PRELIMINARY DESIGN BY CIVIL CONSULTANT(S)

At this stage, the awarded consultants are tasked with preparing a preliminary design report (PDR). This report highlights the envisaged technical and financial cash flow (depending on fee structure) for the duration of the project. With regards to the technical engineering aspects, the following should typically be included in the report:

- Topographical, cadastral, survey, geotechnical and environmental data
- Traffic data
- Geometrical design to a conceptual level
- Stormwater design to a conceptual level
- Location and information of existing/pertinent services and infrastructure
- Possible alternatives/options
- Design standards and legislation used

Due to the silo effect created during the RFP stage, that being of no reusable, intelligent digital data, consultants are left at the mercy of receiving the survey data as soon as possible, compounding the silo effect at this juncture. This results in further challenges:

- With no digital survey data available immediately, or in most cases, received quite late in this stage, consultants are put under pressure to get their PDRs out as soon as possible, with their focus being the deadline rather than the project/infrastructure to be designed.

- This results in reusing the data supplied in the RFP process (copy and paste) in the PDRs due to the lack of digital files/information, forming the information for the geometric design of the road.

- Depending on whether the route is defined or not, there is no intelligent way of providing design alternatives or options (optioneering). Should there be a need/desire/ requirement to provide one, the consultants revert to the initial steps highlighted in the previous stage, that being Google Earth, which comes back to the same challenges highlighted, reinstating or even further compounding the silo effect, creating a challenge loop.

- The lack or absence of survey data further creates a challenge to proposing a stormwater solution, even at a concept level, with the majority of consultants drawing the perceived catchment on Google Earth and providing a snapshot or leaving this portion out of their PDR completely. The computation of preliminary quantities is also a challenge and is typically not included at this stage.

- Traffic data can be sourced or informed by the municipality (should they have the counts and vehicle characteristics) or from the experience of knowing the area and providing an estimation. When it comes to roads being constructed in rural or remote areas, this can be quite a challenge to estimate, with consultants using standards and experience to inform their estimation.

- From a drawing's perspective, most consultants use Autodesk AutoCAD to create their layouts, despite other more suitable design software options available in this era. This is due to a resistance to change and comfort, as AutoCAD was released in 1982 (40 years ago) and was the technology responsible for taking the industry off the technical drawing board and onto the first digital draughting environment. Therefore, consultants at this stage typically use the aerial imagery acquired from Google Earth which generally is not to scale (NTS) as it is generally saved as an image and not in a tagged image file format (TIFF), accompanied by another standard department of transport (DoT) detail drawings bordered by a drawing title block containing the consultant's/company's information.

Upon the arrival of the deadline submission, the PDR is submitted to the municipality/client for comment and approval. Once approved, the consultant now arrives at the stage of compiling the detailed design report (DDR).

5.3 DETAILED DESIGN BY CIVIL CONSULTANT(S)

At this stage, the survey data would be received by the consultant from the surveyor. The actual design of the road can only commence now since the design is informed by accurate survey data representing the present site. The late receival of the survey data is typically due to the late appointment of the surveyor to the project, thus resulting in a late survey of the site and acquirement of the survey data by the consultant, or due to the surveyor, depending on the site extent, technology/method used and location (remote or not), publishing and sharing the data upon arriving back from the site due to connectivity issues or sheer extent of site and time taken based on the method applied.

This puts immense pressure on the consultant at this stage, keeping in mind that the challenges listed previously are still pertinent, as the detailed design will inform the bill of quantities (BOQ). A summary of the BOQ, detailing the headings/sections of a project and the associated totals, as well as the total estimated cost of construction (bottom line), is required to be included in the DDR, including detailed, accurate information on the topics highlighted in the previous stage. With the design technically now only commencing at this stage, all deliverables need to be arrived at in half the time allocated, with the following processes and challenges typically occurring:

- The consultants are required to reinforce and substantiate the data provided in the PDR, which could be way off based on the actual survey data received, resulting in amendments, and troubleshooting at the DDR stage, which is immensely difficult.

- With most consultants still using AutoCAD or 2D conventional draughting design technologies, the road alignments, profiles, cross sections, labelling, earthwork, and structural pavement quantities are arrived at manually, containing no intelligent metadata and dynamic links. This is a major, if not the biggest, negative contributor in this process, as should a change, even the smallest of nature affecting elevation be made, everything has to be adjusted manually in the drawing, often resulting in missing something due to the cumbersome nature of the task. This is further compounded by the fact that the survey data being worked off is in an AutoCAD 2D file format, exported as 2D contours, due to consultants not being able to import the raw triangular data into AutoCAD as it does not have the functionality. In this case, the data provided is usable but unusable by the technology being adopted, resulting in working off 2D contours. Other geometric elements such as superelevation, stopping sight distances, passing sight distances and edge of travel way (ETW) elevations will also need to be computed and drawn manually.

- Stormwater runoff, road sheet flows, catchments/tributary areas and flow paths among other factors will need to be analysed and arrived at to compute analysis values (normally by using the rational method) to provide a suitable, adequately sized stormwater pipe network, with the associated pipe diameters, lengths, and structure quantities. As consultants face time pressure, they typically achieve this by using experience and legislation, but with no innovation or economy, the result is a very conservative and overly designed stormwater network.

- With the compulsory technical design aspects being very time-intensive, consultants have no choice or room to look at or provide an alternative design option, committing fully to the one selected, irrespective of whether errors are detected, or elements could be optimised, as it will result in the restarting of the entire process, due to a lack of a digitally dynamic and intelligent process.

With all this prevalent messiness, the consultants create at a detailed geometric design, with the drawing documentation complete that informs the BOQ and is attached to the DDR or shared as a transmittal. The design and construction costs are then reviewed, commented upon, and approved by the municipality or client. The detailed design now becomes the final design, with consultants either interpreting it as such or associating it to another stage based on their company's quality management system (QMS) as the final design.

With the DDR approved, the road now goes out to tender, facilitated by the municipality, in search of appointing a suitable contractor to construct the road, resulting in the consultants being required to compile the tender documentation.

5.4 TENDER COMPILATION BY CIVIL CONSULTANT(S)

At this stage, the civil consultants are tasked with compiling the tender document required by the municipality/client. This will include the tender drawings from the consultant with the necessary information required for contractors to bid for the project. Depending on the confidence of the detailed/final design drawings, consultants, in some cases, are still finalising and reviewing their designs during this stage, and should any errors be detected that require adjustments to the design, an addendum would be required to be sent out to all contractors that have purchased the tender document and attended the compulsory tender briefing.

This is something that all consultants dread and wish never to find themselves in that situation, as it leads to revisiting their BOQs, arriving at another estimate, and thus coming across as sloppy and unprofessional. Once the tender documentation is complete, the municipality/client will review the document, and approve it should it be satisfactory. Thereafter, the project will be advertised to contractors to bid for the project.

5.5 TENDER BID SUBMISSION BY CONTRACTOR(S)

A compulsory tender briefing will be held with all interested contractors in attendance at this stage. Questions and concerns are raised during this meeting based on the items listed in the tender document and highlighted during the meeting. Upon completion of the tender briefing, contractors are tasked with compiling their construction programme and BOQ and bidding their price to construct the road. At this stage, contractors face some challenges, such as:

- No CAD/digital files/data to get a better understanding of the tasks at hand
- No 3D representation and visualisation present on layouts

As highlighted previously, this also results in contractors bidding either too high or too low, and those with adequate experience bidding at a competitive, reasonable rate.

Once contractors have completed their bid, it is submitted. The municipality typically has a public bid opening, and after the review, a suitable contractor is appointed.

5.6 CONSTRUCTION DRAWINGS ISSUED TO CONTRACTOR

At this stage, the consultant and contractor are both appointed and introduced, with the consultant providing the contractor typically with three sets of construction drawing hardcopies. These drawings will be used by the contractor to construct the road, ensuring it complies with the details present on the construction drawings supplied by the consultant. It is worthy to mention that at this stage, the contractor still does not have any form of CAD/digital files.

5.7 PROJECT AND CONSTRUCTION MANAGEMENT

At this stage, the contractor progresses with the project at the stipulated start date, with the goal of finishing the construction of the road as soon as possible before the stipulated project end date. Site meetings and inspections will be carried out by the consultant, ensuring that everything being constructed is design compliant as per the drawings supplied and that the project is running smoothly.

Despite the best efforts of both the consultant and the contractor, at this stage, the following arises on most projects:

- Due to the pressure faced by the consultant in the earlier phases, errors or items that are ambiguous in nature are identified or raised by the contractor. This generally results in the submission of a variation/change order, which comes with its own additional cost and time additions.

- With the absence or lack of GIS information, services are identified whilst construction is going ahead, resulting in further variation/change orders, including the relocation or replacement (should a service such as a pipeline be destroyed/damaged) of services, thus hindering project progress. The clashing of services is also a big issue at this stage, as design levels, cover and other issues did not cater for such occurrences. Due to a non-dynamic process, and in desperation, the consultant must revise their designs and issue drawing revisions, and everything must be adjusted manually, or accommodations must be made on the site itself, which may be functional, but not ideal.

- Depending on the time invested and the methodology used by the consultant in determining construction quantities, ambiguity is generally faced when required to approve claim certificates submitted for work carried out by the contractor. The ambiguity faced by the consultant is that the truth or reliability of the quantities submitted by the contractor is directly proportional to that of the quantities estimated by the consultants themselves. Where there is an unreasonable mismatch between estimate and claim, a dispute ensues between consultant and contractor, which results in a delay in the project or the project coming to a complete standstill.

- With a flurry of back and forth between the consultant and contractor, revision tracking, requests for information (RFIs) and documentation control become issues. This results in ineffective project management and ensuring that both parties are working off the latest drawing revision becomes a challenge. This is usually done using hard copies and with no digital means or processes.

Following through to the construction phase, the project now reaches its peak of pressure. This results in the contractor and/or consultant filing for an extension of time on the project, which could be granted as is, or granted with the inclusion of a penalty, depending on the extent of the items to be accommodated. These compounded effects negatively impact the bottom line of the project, resulting in eroding profit margins or the project running into a loss for both parties involved. This could also result in the replacement of the consultant and/or contractor on the project depending on the gravity of the situation.

With all of these challenges, the quality of the project from a construction perspective becomes a non-priority, resulting in shoddy construction workmanship and overall project constructability quality. Once these challenges have been overcome, the project reaches completion and is required to be closed out and handed over.

5.8 PROJECT CLOSE-OUT AND HANDOVER

At this stage, the construction of the road or project is now complete, with the consultant required to inspect the completed construction site and prepare a project close-out report detailing the construction aspects and relevant information. In conjunction with this report, the consultant is required to produce as-built drawings for the road which serves as a means to provide accurate information about the constructed asset.

The surveyor provides the consultant with the elevation data of the road that has been constructed, which is then taken by the consultant and incorporated to produce the as-built drawings. Based on the deadline stipulated for the close-out report, consultants typically edit the original construction drawings to say as-built on the title block and submit that as their as-built drawings. This practice is unethical and incorrect, and resorted to purely out of desperation and not having enough time.

By using 2D non-dynamic processes, consultants have no option but to create the as-built drawings from scratch, which can be equated to the time taken to complete two design projects, further impacting profitability and allocation of resources.

Upon completion of the as-built documentation and close-out report, the consultant submits these drawings and the report, which can be shared as hard copies and/or PDFs. With the road having been completed and handed over to the municipality/client, the operations and maintenance of the road need to be implemented to ensure the road fulfils its function and design life, with a retention percentage released to the consultant/contractor upon the functioning of the road past certain time periods.

5.9 ROAD OPERATIONS and MAINTENANCE

At this stage, the municipality/client is responsible for ensuring the efficient operation and maintenance of the road are upheld. This is usually informed by the community on which the road serves, with the community typically reporting any form of damage, deformation, deterioration, hazards, or potholes.

This process or methodology can be described as reactive rather than proactive; waiting for the road to deteriorate to the point of being an endangerment to life or unusable and then only taking the correct reactive actions to remedy the situation, which is not ideal. Depending on the effectiveness of this methodology or the capacity of the municipality/client, this process could prove to be manageable. However, in most cases, it is seen as an area that is lacking in terms of the effective upkeep of civil infrastructure.

This results in the neglect of roads over their design life, which results in the road not achieving its full design life and level of service, which translates into the ineffective use of the taxpayer's money and non-resilient infrastructure. Over time, the road may serve out its designed life or not. Depending on the operations and maintenance plan implemented, a roadway will be required to be upgraded or rehabilitated. This then results in the municipality/client advertising for a proposal from suitable consultants and the process restarts itself.

6. THE BIM ROAD PROJECT PROCESS

This section will highlight the adoption of BIM technologies across the project lifecycle, and how BIM processes, workflows and technologies revolutionise the way road projects are approached and implemented. This is achieved by examining the effectiveness across the 9 stages defined in the applied methodology chapter of this dissertation.

6.1 PROPOSAL PREPARATION AND SUBMISSION BY CIVIL CONSULTANTS

6.1.1 MODEL CREATION

BIM technologies can be applied as early as the proposal stage, affording consultants intelligent, dynamic data. With the road location and characteristics defined in the tender briefing, model creation can now begin. At this stage, the BIM technology used is Autodesk Infraworks. Autodesk Infraworks has a feature called Model Builder, which allows the consultant to define a project area and create a 3D intelligent, highly visual model in minutes, with a maximum model area size of 200 square kilometres. A sample output is depicted in the image below.

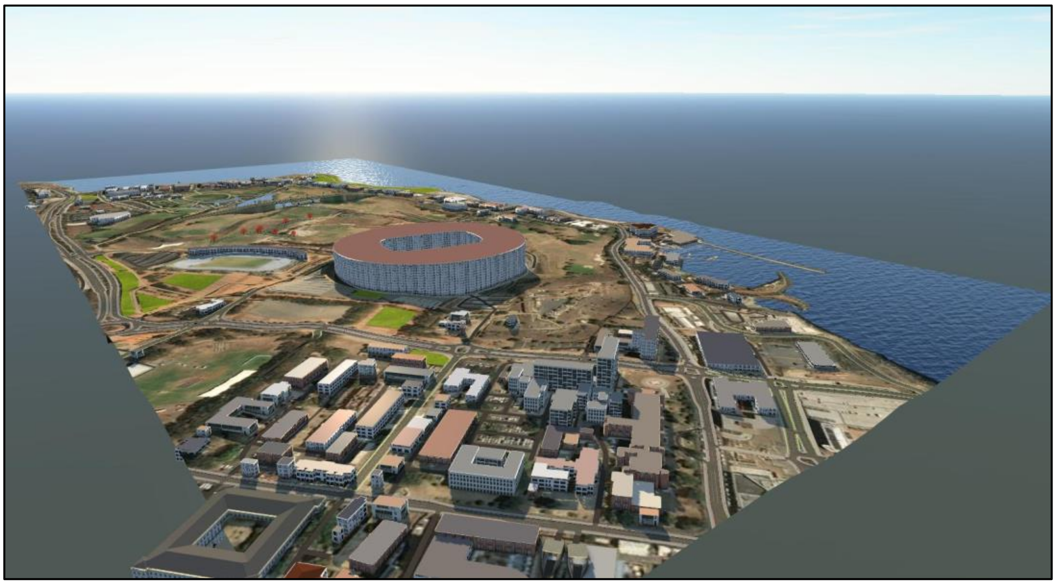


Figure 6.1: Site Model of Area Around Green Point Stadium in Cape Town, South Africa
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

Upon model completion, consultants have the following main advantages at their disposal:

- A geolocated site with the associated aerial imagery derived using Bing Maps.
- A preliminary survey/terrain surface of the site extents from which elevation data can be obtained.
- Relative positioning of roads, buildings, rivers, streams, water areas and associated site features and infrastructure within the site extent/vicinity.

6.1.2 ROAD ALIGNMENT/PROFILE

Depending on work capacity and time constraints, consultants typically try to complete and submit their proposals as soon as possible, based on the scale and comprehensive nature of the road project. Should the project consist of a single or a few strips of the road with a simple cross-section such as those found in residential areas, consultants can utilise the planning roads feature in Autodesk Infraworks.

This approach is the quickest, as it affords the consultant or designer the opportunity to provide a conceptual visualisation of the road to be constructed with minimal effort, including intersections, roundabouts, lane markings and widenings. The output of this approach is that of the road modelled contextually within the site vicinity. Planning roads are used when required to quickly pitch an idea of how a road will look, comprising no parametric nature.

The cross-section style assigned to a planning road is purely for visualisation and is preconfigured or created at set dimensions. It cannot be edited directly on the road model but rather only by updating the style itself, with no vertical alignment/profile or engineering data available. This approach has seen many consultants across the world pitch ideas and impressively convey designs, resulting in them winning more bids and having a competitive edge in their market. Road components such as lanes, lane markings, medians, kerbs, sidewalks, trees, light posts and other associated road furniture and model components can be included into a style, as depicted in the sample below:

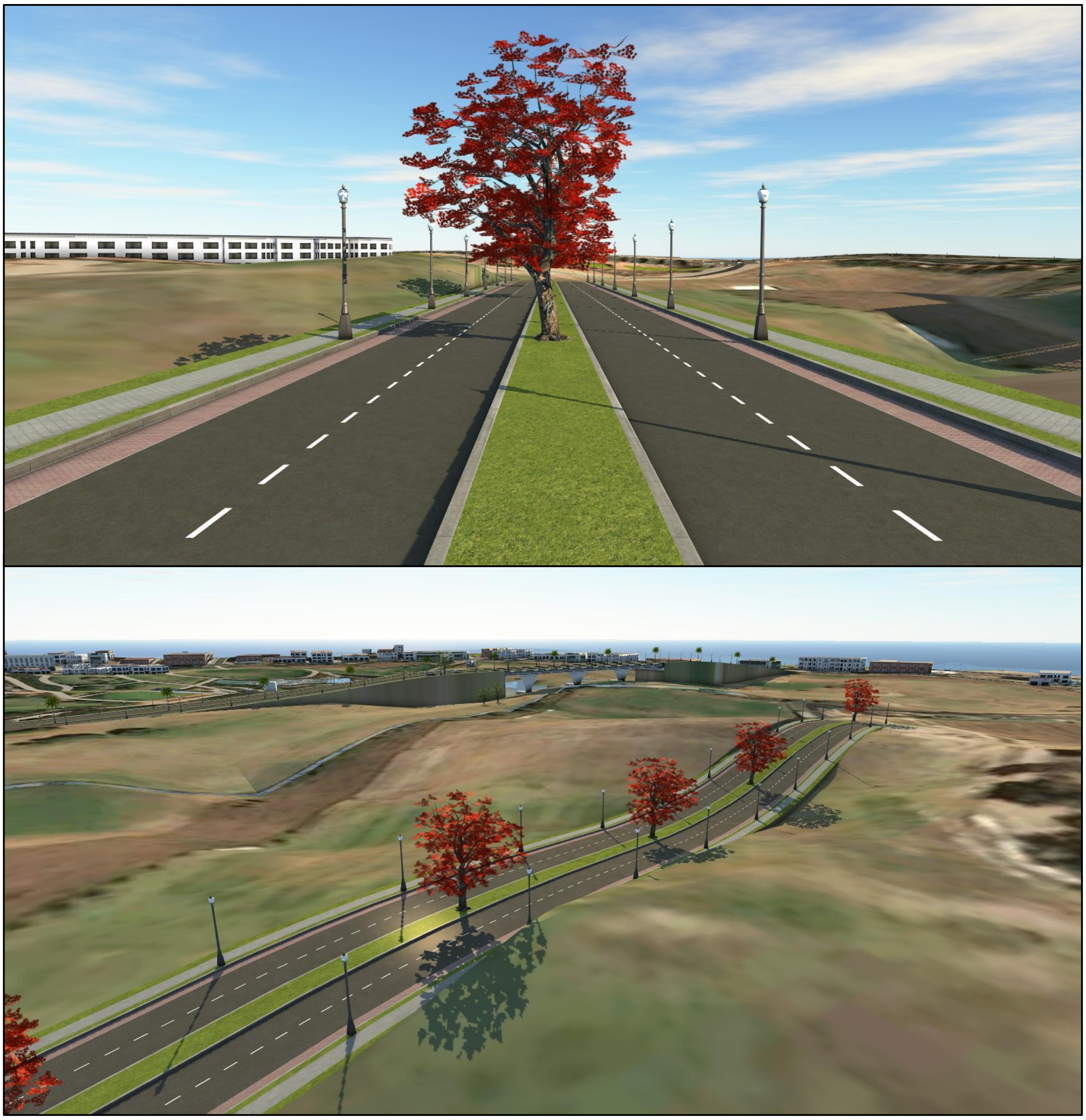


Figure 6.2: A Road Style Assigned to a Road Horizontal Alignment
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

Should the project be of a large scale or complexity, consultants are afforded the BIM functionality in Autodesk Infraworks called component roads. Component roads consist of a parametric nature and a vertical alignment/profile, allowing the designer/consultant to have greater control over the road elevation data as well as be able to edit, replace, remove, or add additional components such as lanes, medians, and sidewalks to the existing design. Component roads are typically undertaken by consultants during the preliminary phase, but can be undertaken at this phase as well, depending on consultant's or designer's proficiency, or project requirements, with the sample outputs depicted below.

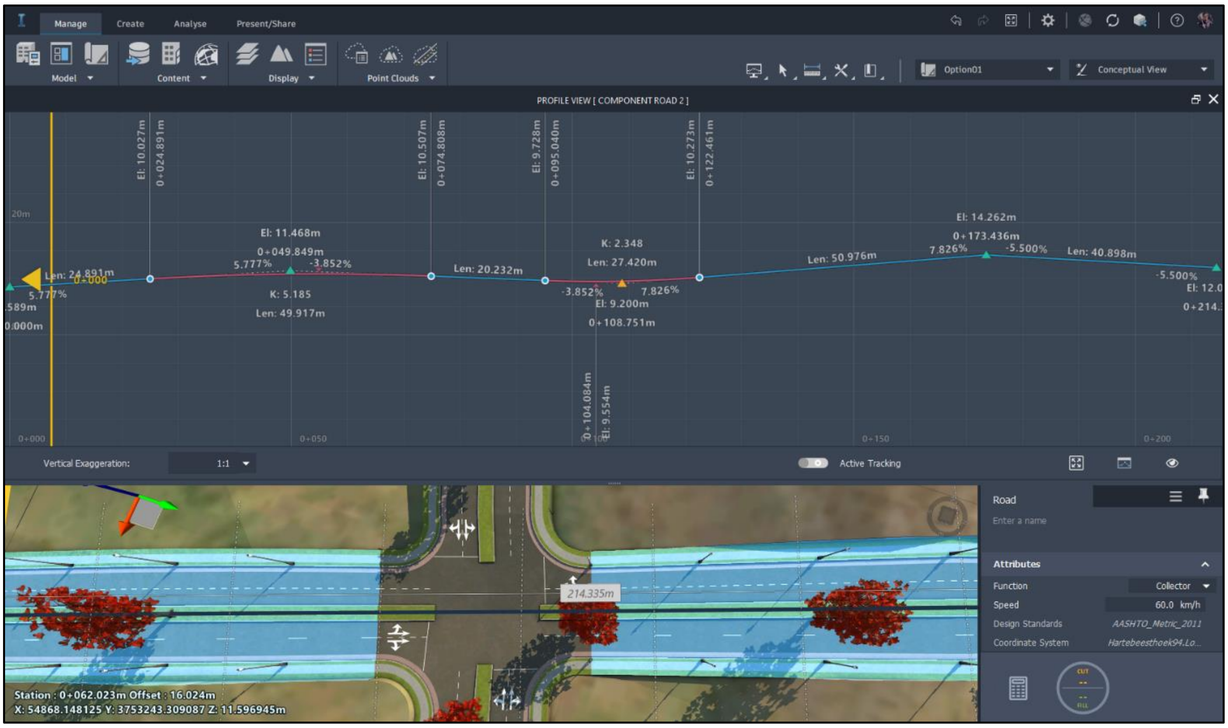


Figure 6.4: Road Vertical Alignment
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

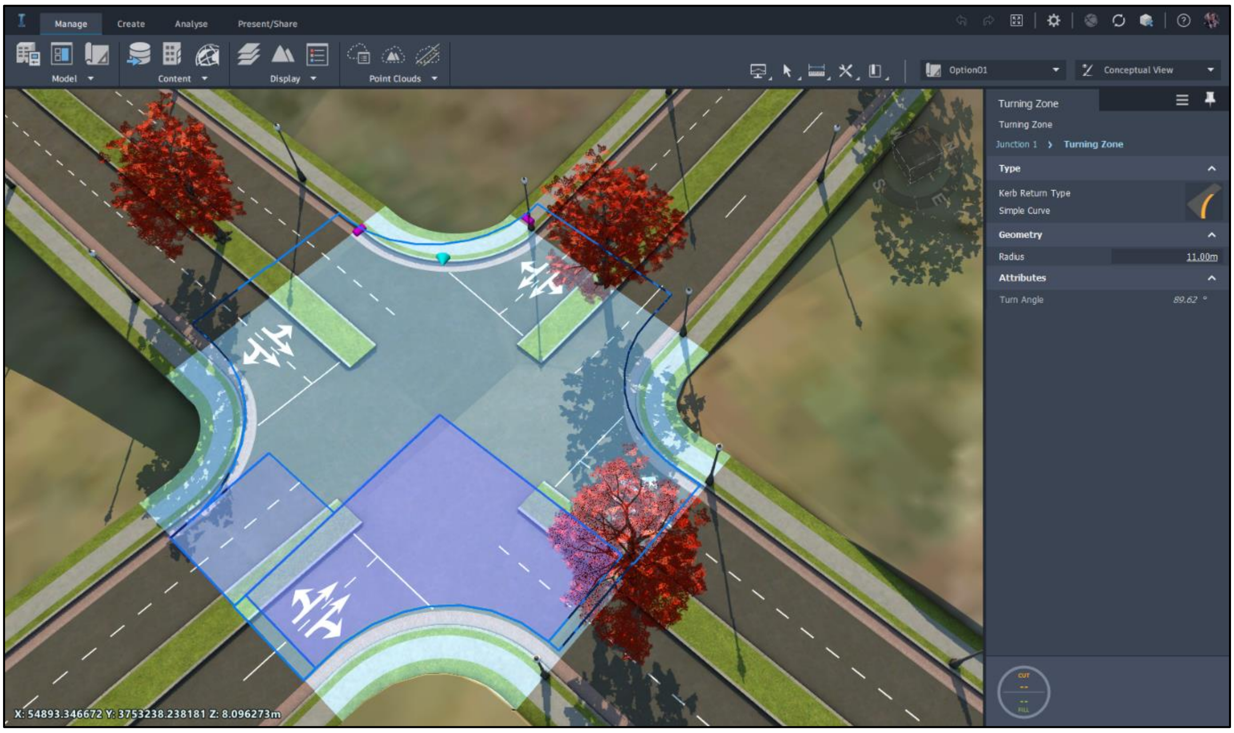


Figure 6.3: Individual Road Parametric Components of an Intersection Which Can be Modified
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

Component roads will be investigated in greater detail in the next phase, with planning roads having the ability to be converted to component roads easily, breaking the data silo effect.

6.1.3 ROAD OPTIONEERING

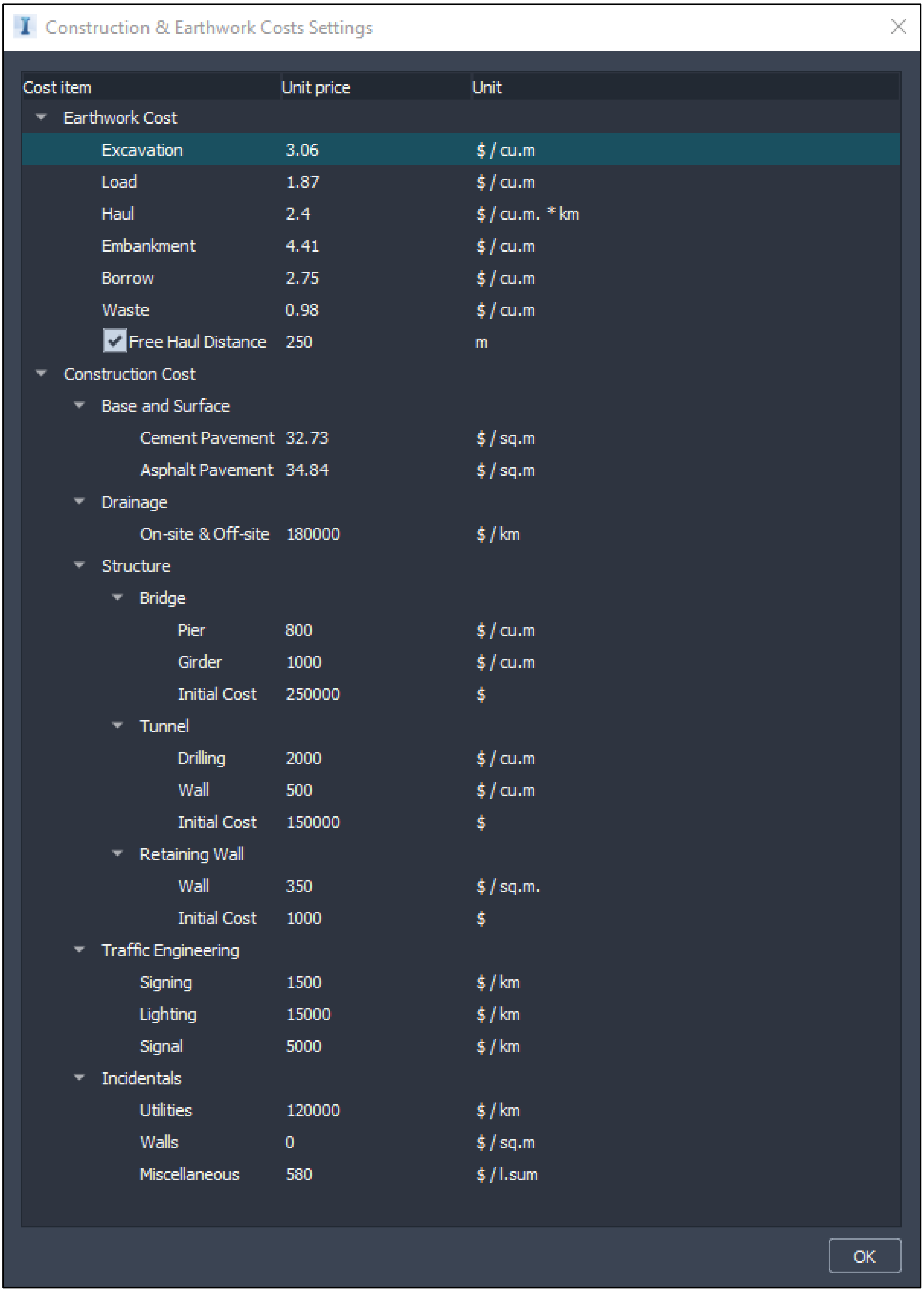
Another great possibility afforded to consultants, especially on large-scale road projects, is that of providing route alternatives. This is relevant when the start and end point of the road is given/fixed, but the route is not defined. Consultants can make use of two options to compute the most suitable route using BIM and/or GIS functionality as follows:

6.1.3.1.1 BIM

The BIM approach utilises the corridor optimisation function in Autodesk Infraworks, which is computed in the cloud. This involves specifying the start, critical points of intersection (PIs) and end location of the horizontal road alignment at a specified design speed. The consultant/designer is afforded a number of options, specifically the geometric design of the road such as:

- Being able to specify the type of road cross-section;
- To automatically include/insert bridges and tunnels at specified maximum and minimum fill heights and cut depths;
- Set a grading limit distance as well as cut and fill slope ratios for daylights/roadside embankments, and
- Set a minimum radius and maximum grade for the horizontal and vertical alignments.

Once the above is specified, the consultant/designer can create avoidance zones, which must be bypassed by the routing computation, areas which are seen or derived as being unsuitable or not an option, such as swamps, wetlands, heritage sites and vegetation. These zones can be drawn manually or derived by importing CAD and or GIS data to define these coverage areas. Suitability maps can also be created based on weighted averages to guide the computation, including the allocation of cost to construction activities, such as earthworks, bridges, and tunnels. Upon specification of the above elements, the road routing computation will select the best option, with examples of the above functionality depicted below (units are only available in dollars but can be treated at whichever currency when working).



Construction & Earthwork Costs Settings

Cost item	Unit price	Unit
Earthwork Cost		
Excavation	3.06	$ / cu.m
Load	1.87	$ / cu.m
Haul	2.4	$ / cu.m. * km
Embankment	4.41	$ / cu.m
Borrow	2.75	$ / cu.m
Waste	0.98	$ / cu.m
Free Haul Distance	250	m
Construction Cost		
Base and Surface		
Cement Pavement	32.73	$ / sq.m
Asphalt Pavement	34.84	$ / sq.m
Drainage		
On-site & Off-site	180000	$ / km
Structure		
Bridge		
Pier	800	$ / cu.m
Girder	1000	$ / cu.m
Initial Cost	250000	$
Tunnel		
Drilling	2000	$ / cu.m
Wall	500	$ / cu.m
Initial Cost	150000	$
Retaining Wall		
Wall	350	$ / sq.m.
Initial Cost	1000	$
Traffic Engineering		
Signing	1500	$ / km
Lighting	15000	$ / km
Signal	5000	$ / km
Incidentals		
Utilities	120000	$ / km
Walls	0	$ / sq.m
Miscellaneous	580	$ / l.sum

OK

Figure 6.5: Cost Items Available to Derive Preliminary Cost using Autodesk Infraworks
Source: Autodesk Infraworks 2022

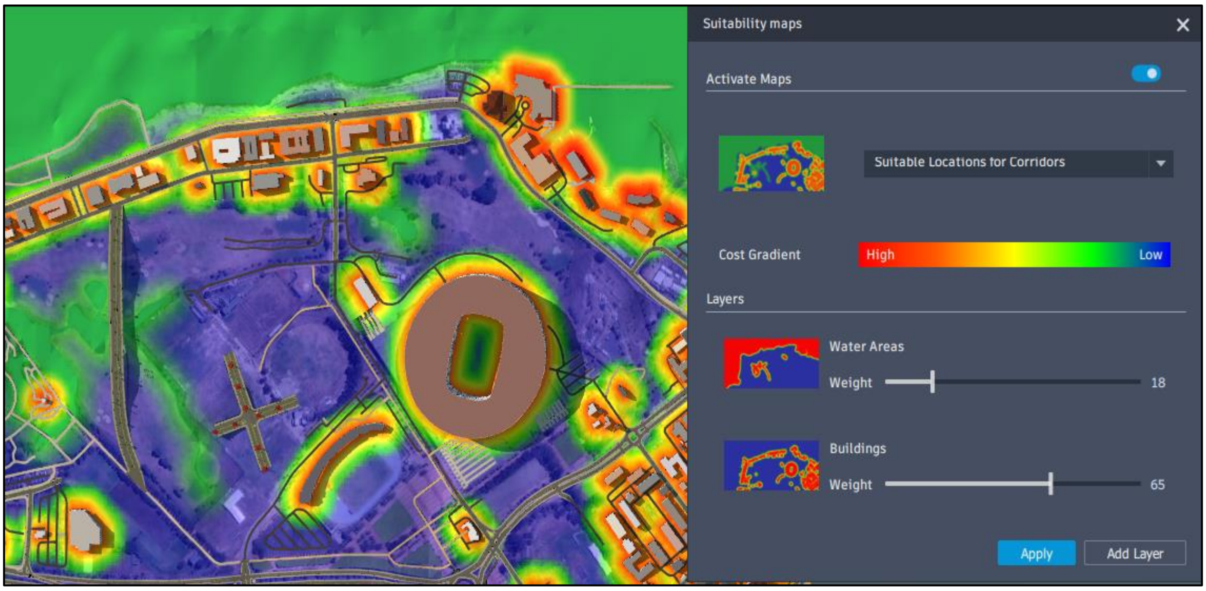


Figure 6.6: A Suitability Map Created on a Weighted Average
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

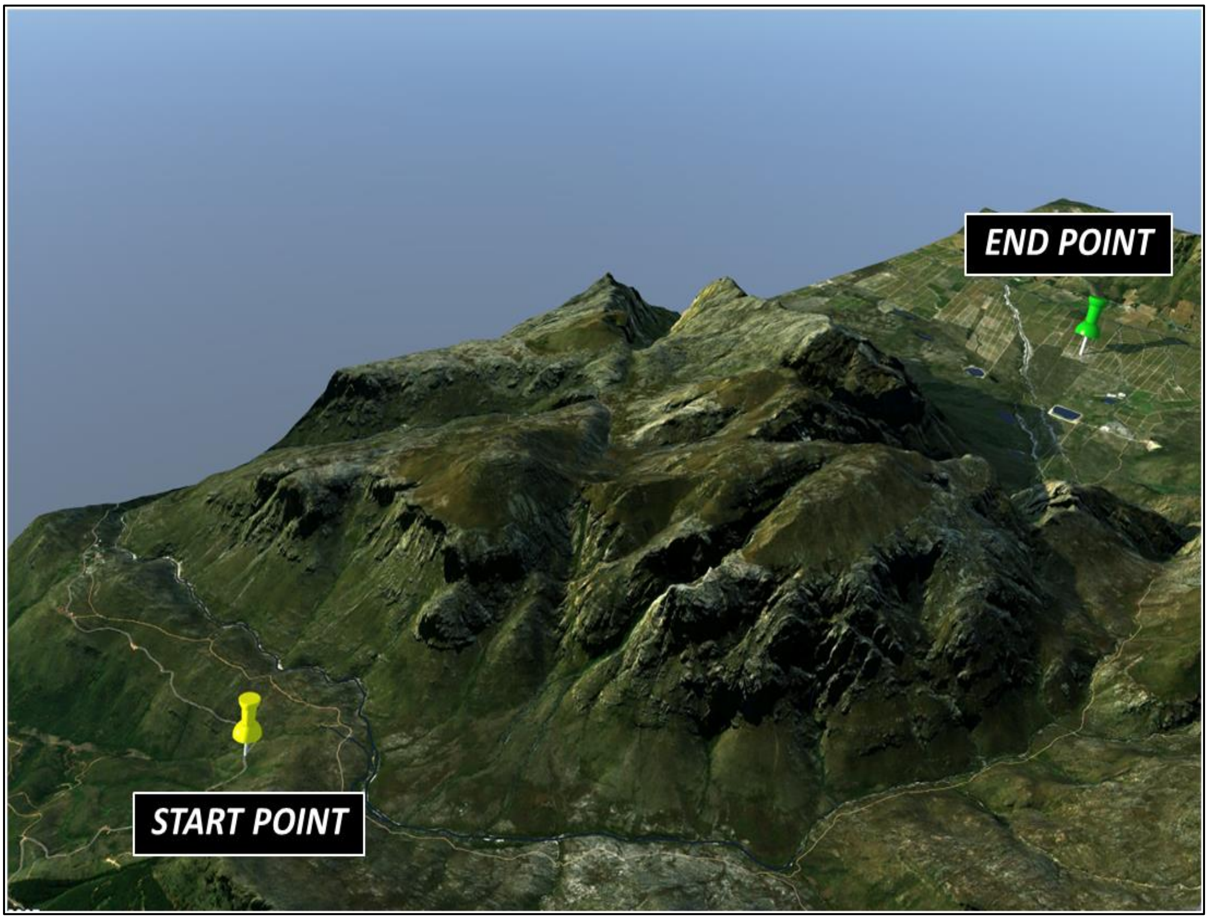


Figure 6.7: Start and End Locations of Road
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

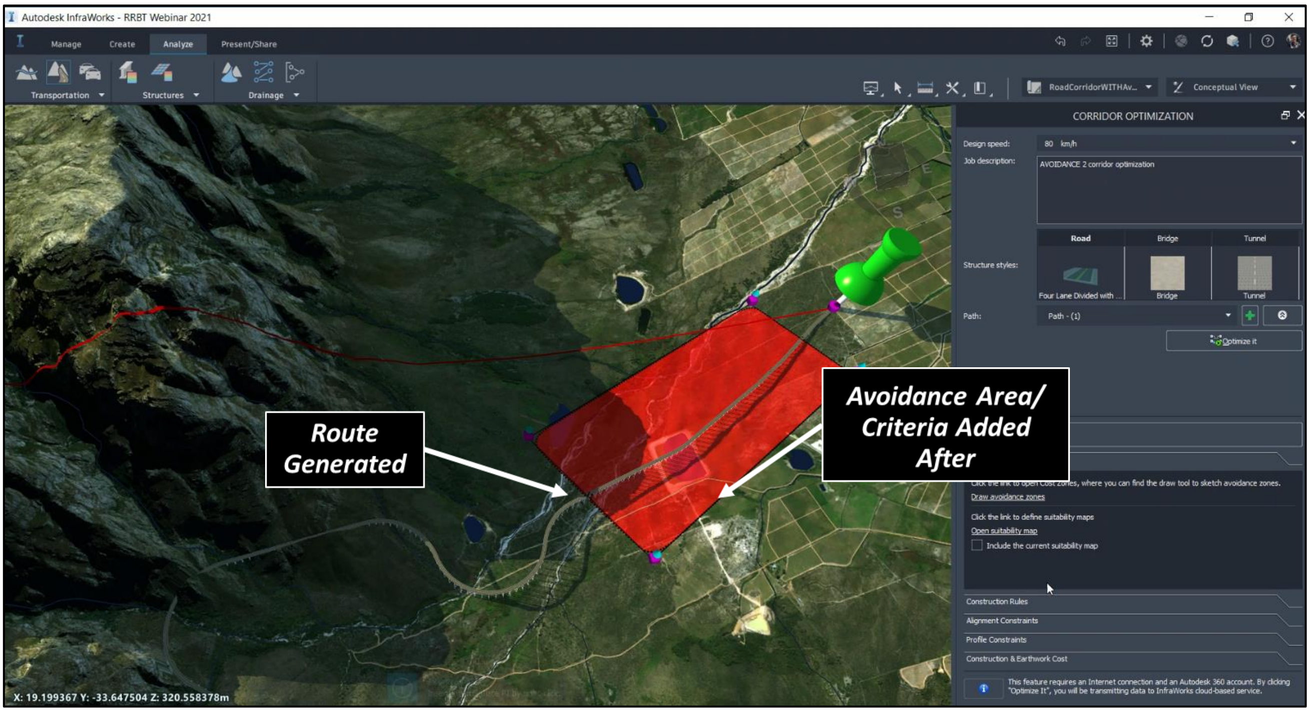


Figure 6.8: An Avoidance Zone (Red) Added Along a Created Roadway
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

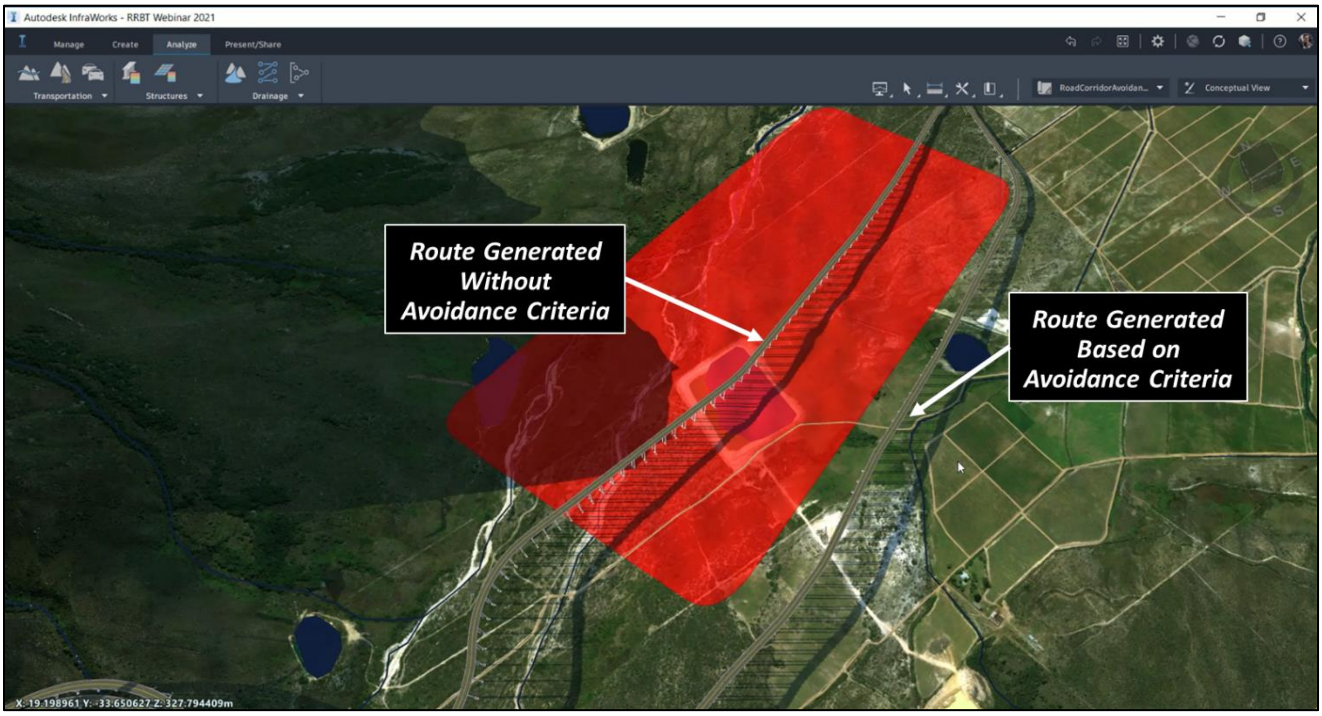


Figure 6.9: An Avoidance Zone (Red) Added Along a Created Roadway
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

Figure 6.10: Automated Insertion of Parametric Bridge Based on Specified Maximum Fill Height Along Computed Route using Corridor Optimisation
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

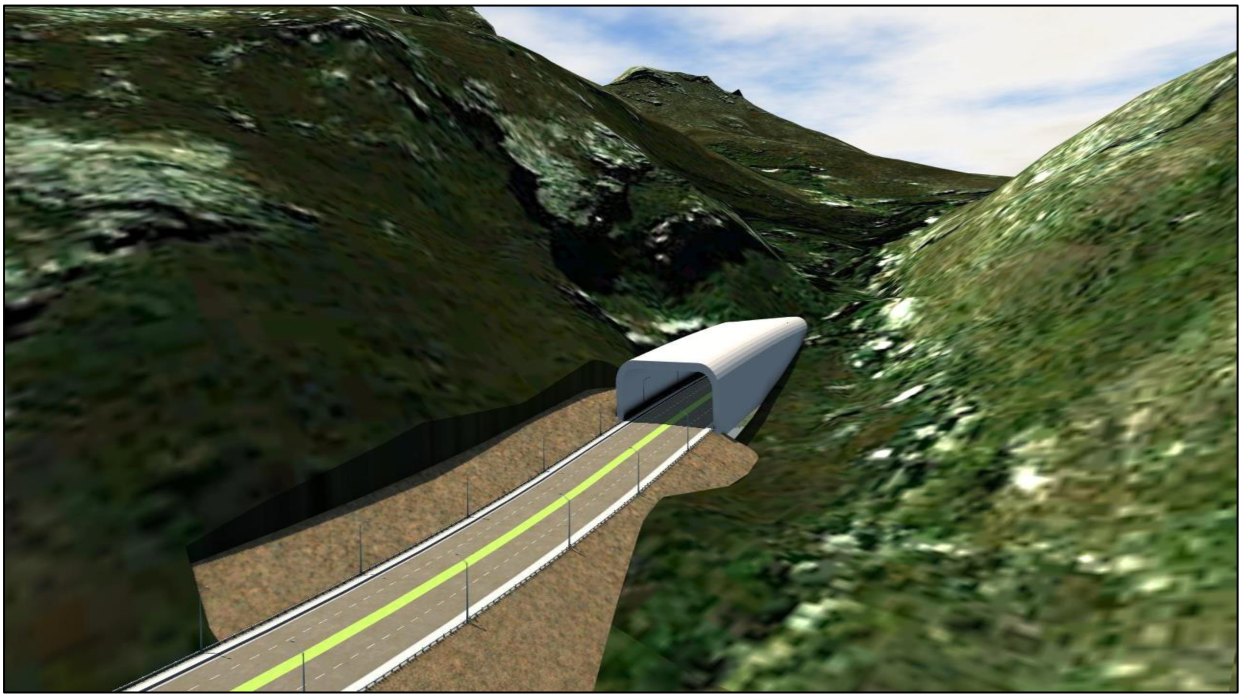


Figure 6.11: Automated Insertion of Parametric Tunnel Based on Specified Minimum Cut Depth Along Computed Route using Corridor Optimisation
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

With the availability of such BIM functionality, consultants and designers can compute multiple options based on different inputs all in one model, without the need to duplicate the model multiple times and start afresh, a functionality called Proposals in Autodesk Infraworks.

Should the route be defined, consultants and designers are afforded the functionality to optimise the vertical profile of the horizontal alignment by specifying the following:

- The design speed and type of road cross-section to be used.
- The maximum road gradient, minimum spacing and frequency of the points of vertical intersection (PVIs), PVIs to be anchored, as well as the required drainage surface gradient.
- Whether to allow the automated placement of bridges and tunnels.
- The location of borrow pits as well as costing functionality as previously highlighted.

Upon input of the relevant data, the BIM functionality in Infraworks will optimise the vertical alignment/profile along the defined route, after which edits, and tweaks can be made. As mentioned previously, this BIM functionality enables consultants/designers to compute multiple options based on different inputs all in one model, without the need to duplicate the model multiple times and start afresh, saving these options as differently titled alternatives/proposals in Autodesk Infraworks.

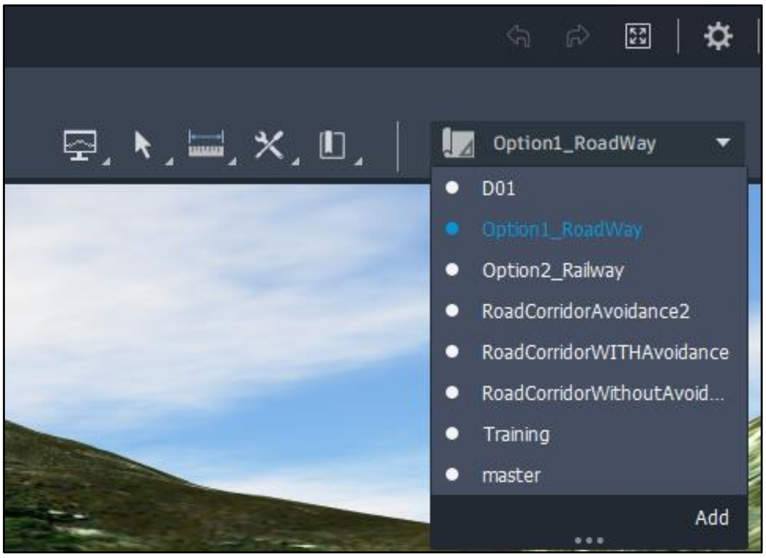


Figure 6.12: Different Design Proposals/Options Saved in One Model
Source: Created by Shuaib Yunos in Autodesk Infraworks 2022

6.1.3.1.2 GIS

Route computation can also be done using ESRI ArcGIS. The start and end of the road is defined, with a combination of weighted factors used in determining the most suitable route, as depicted below.

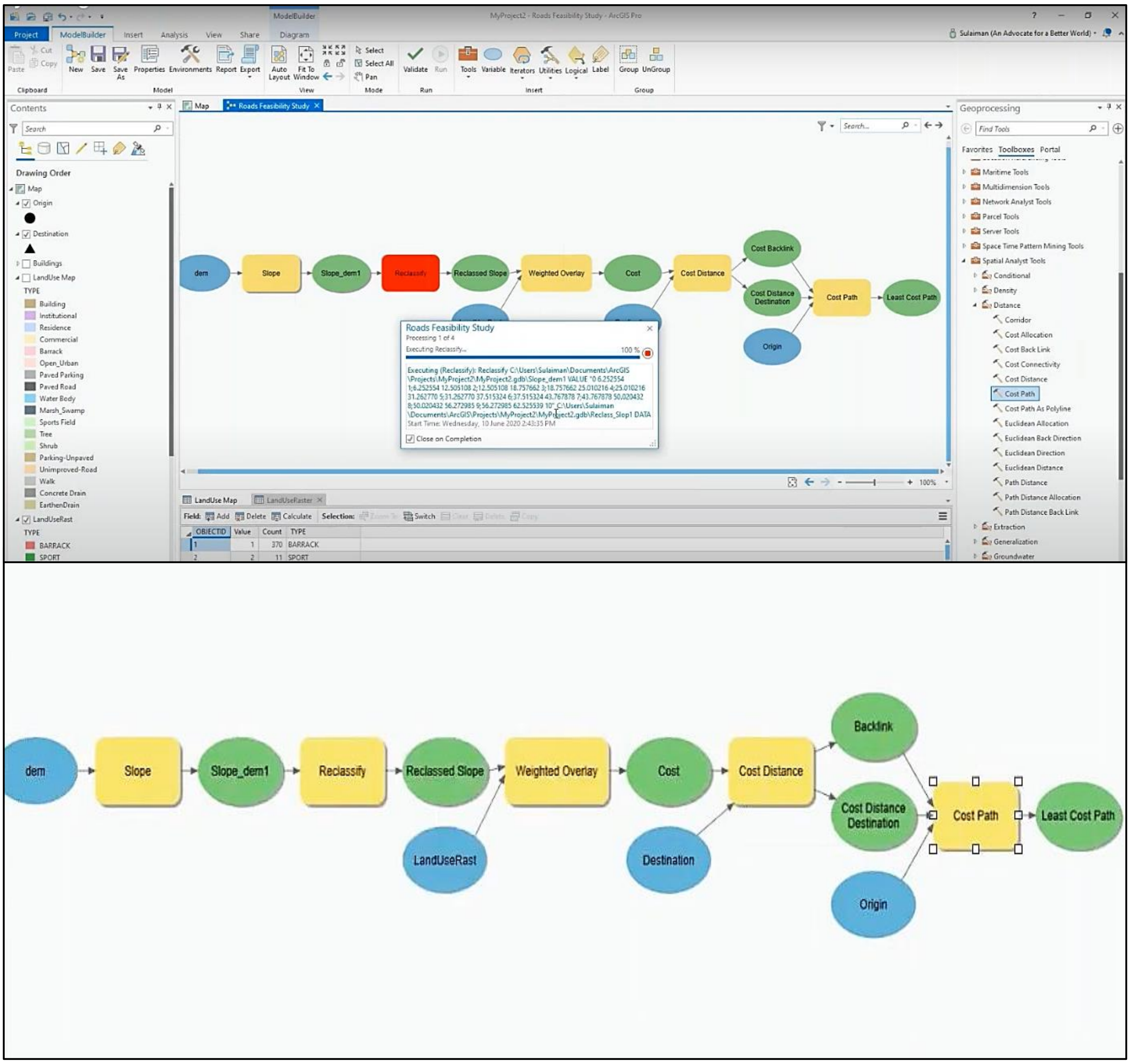


Figure 6.13: Computation of Suitable Route using Weighted Averages of Various Factors in ESRI ArcGIS Pro
Source: Baker Baynes, 2021

Once the route has been computed, the route and suitability map/GIS data can be published to ArcGIS Online and can be shared with the consultant/designer by the GIS professional online or exported to .shp format. This data can then be imported into Autodesk Infraworks as a .shp file or by connecting to ESRI ArcGIS Online.

The method usually applied is the creation of the suitability map in ESRI ArcGIS, which is then published to ESRI ArcGIS Online and shared with the civil consultant/geometric designer. Once published and shared, the consultant/designer imports the GIS data into Autodesk Infraworks and thereafter uses a profile or corridor optimisation as it provides more road-specific functionality, with the weighted averages computed using the suitability map derived from the GIS professional.

6.1.4 OTHER AVAILABLE CAPABILITIES AND FUNCTIONALITY

With the powerful BIM and GIS capabilities above afforded to consultants as early as the first stage of the road project lifecycle, consultants still have the following additional options and capabilities at their disposal, which can be applied at this stage if warranted, but will be delved deeper into in the next project phase.

- Depending on the scale of the project, Survey (LandXML) and reality capture data may be available or supplied during the tender briefing. These data sources are also supported in Autodesk Infraworks and should they be applied in the proposal stage, would result in accurate positioning from the onset.

- A conceptual stormwater network can be created using the automated BIM capability of Autodesk Infraworks, after which the consultant/designer can then include snapshots of the conceptual stormwater network in their proposal.

- Parametric bridges and tunnels can be modelled to convey design intent in a highly visual and realistic manner, affording consultants/designers the opportunity to impress and showcase their innovative flair in their proposal.

With this wealth of options provided by BIM and GIS technology, the consultant has the power and flexibility to govern which aspects or areas are required, or how they wish to invest and focus most of their time and resources, including the visualisation element, which can be incorporated into their report for a rock-solid proposal submission.

6.2 PRELIMINARY AND DETAILED DESIGN BY CIVIL CONSULTANT(S)

Once consultants are awarded the project, the model created during the proposal stage is reusable and can be extended into the preliminary design phase. This eliminates the silo effect that is experienced using the traditional approach, where consultants are left at the mercy of receiving the survey data and still waiting to start the design. Due to this game-changing advantage provided by BIM technologies and workflows, consultants typically reach the detailed design level at this stage, a progressive transition between preliminary and detailed design that has led to the discussion of these stages as combined rather than separately, as portrayed by the MacLeamy Curve below.

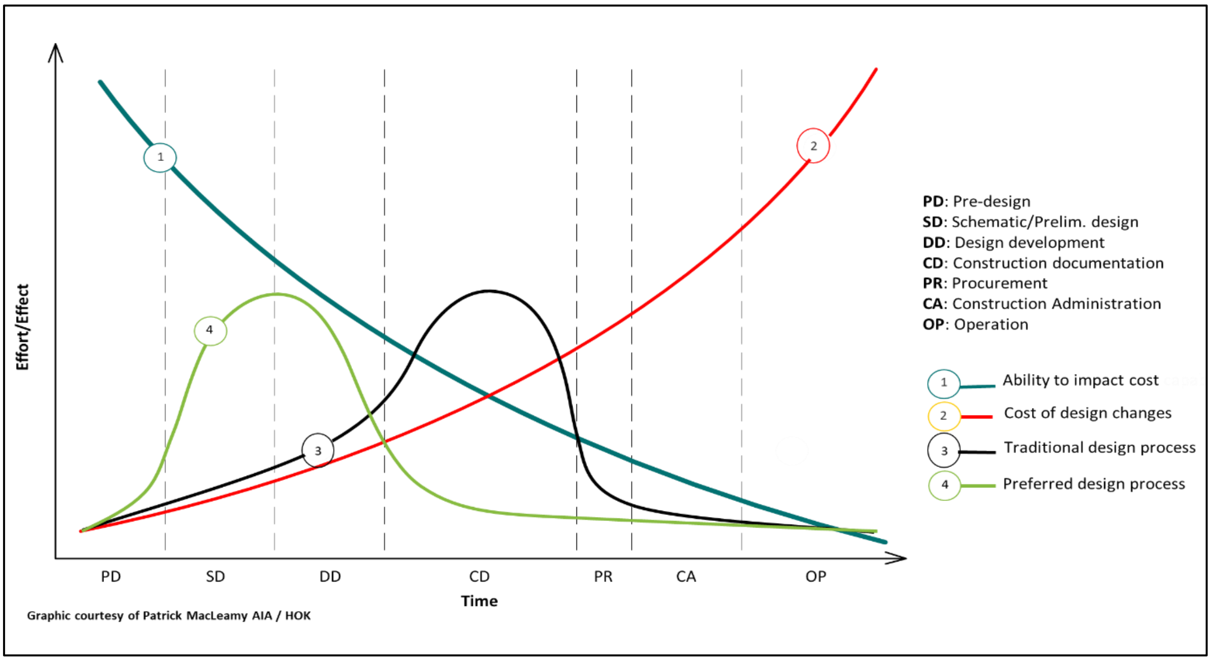


Figure 6.14: The MacLeamy Curve
Source: Walaseka D & Barszczb A, 2016

The MacLeamy Curve compares traditional versus preferred approaches against the ability to impact cost and the cost of design changes. BIM concurs with that of the preferred design process, as most of the heavy lifting is done at the transitional phase (the peak of graph 4) between preliminary and detailed design, due to the insight and intelligence afforded to the project lifecycle from the onset, enabling consultants and designers to troubleshoot, compare and analyse their designs before construction.

For CAD drawing outputs and data, the Infraworks model integrates with Autodesk Civil 3D. The challenge of receiving the survey data on time or as per schedule could still be experienced during the BIM approach, but it does not hold back the entire road design process. The design elements created in Infraworks can be imported into Autodesk Civil 3D, including the preliminary survey. This is extremely beneficial, as the road can be designed and modelled in detail, using the preliminary survey as a reference, which can be swapped to the actual, accurate survey data when received from the surveyor.

Upon replacement or swapping of the preliminary survey data, minor adjustments will be required based on how similar the preliminary surface is to the actual survey data. With Autodesk Civil 3D already being efficient, it is made even more robust and automated with the incorporation of Devotech iDAS. iDAS is the acronym for Infrastructure Design Automation Suite, developed by the Devotech Group of Companies in South Africa. iDAS is an add-on to Civil 3D, providing much more control and automation in Civil 3D for roads and pipe networks. The advantages for road components/elements with these powerful BIM technologies are elaborated on below.

6.2.1 TERRAIN DATA

As a result of the Infraworks model builder, consultants are able to create contextual models based on a preliminary survey of surface and terrain, as well as the relative positioning of buildings and infrastructure around the area.

Critical infrastructure and services impacting the road are highlighted during the tender briefing but are denoted on hard copies. This can be inputted into the model manually for relative positioning as well. Depending on the scale of the project, GIS and reality capture data may be available or supplied during the tender briefing or upon the appointment of the successful constancy. These data sources are also supported in Autodesk Infraworks, including LandXML survey data, resulting in accurate positioning should they be applied in the proposal stage.

Should that data not be available, it can be incorporated as soon as it is received, and design adjustments made accordingly. GIS data can be imported directly into the model from files supplied or from ESRI ArcGIS Online. With the integration between Autodesk and ESRI, who are recognised as global leaders in BIM and GIS, consultants can search and import freely available GIS data, create their own, as well as access data that could be available as a paid service. This advantage results in more practical and contextual design, as the GIS data would inform the road design early in the project lifecycle, rather than encountering challenges when already in the construction phase. As with survey data, GIS data can be incorporated as soon as it is received, and design adjustments can be made accordingly.

Point clouds can be imported into Autodesk Infraworks and Civil 3D for reality capture. The use of unmanned aerial vehicles (UAVs) to capture road strips and sites is becoming increasingly popular. This data can then be imported and a terrain surface extracted to provide much more accurate elevation and site data, thus enhancing design confidence.

Upon receival of the reality capture/scan files, consultants can process this data in Autodesk ReCap Pro, outputting to a .RCP file (consultants typically receive the file already processed and output to .RCP from service providers), which can then be imported to Autodesk Infraworks and/or Civil 3D. When it comes to existing roads, in which elevation data/profiles are required for linking into or rehabilitation, the .RCP file can be imported to Autodesk Infraworks. Autodesk Infraworks has the ability (depending on the quality of the processed scan data) to extract linear features for roads such as the edge of lane and road centrelines automatically, a feature titled Automatic Linear Extraction.

This feature requires the consultant/designer to define two points along the path they wish to extract, after which the entire path will be extracted by Autodesk Infraworks, which can be edited if or where required. These paths can then be converted to a component road in Autodesk Infraworks so that a vertical profile may be derived, and/or exported to .shp files that can be imported to Autodesk Civil 3D. This automated BIM functionality for roads, therefore, permits the consultant to get existing elevation data for existing roads to inform the design process, with the option to extract linear features both automatically and manually as depicted below:

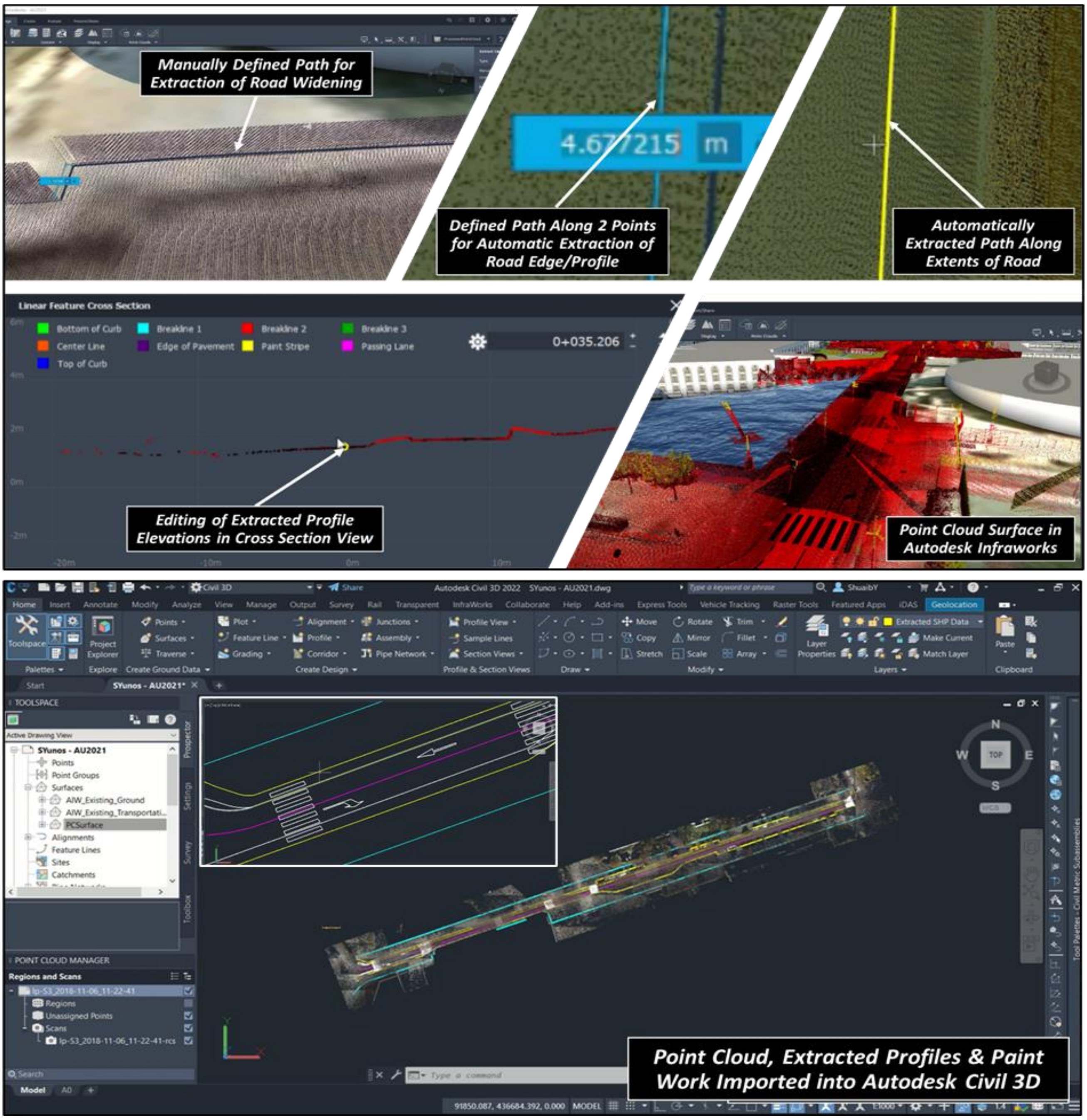


Figure 6.15: Point Cloud Linear Extractions of a Roadway Generated in Autodesk Infraworks and Imported to Autodesk Civil 3D 2022
Source: Created by Shuaib Yunos using Autodesk Infraworks & Civil 3D 2022

Should the design be for a new road and only a terrain is required, a terrain surface can be extracted in Autodesk Infraworks or Civil 3D from a point cloud as portrayed below:

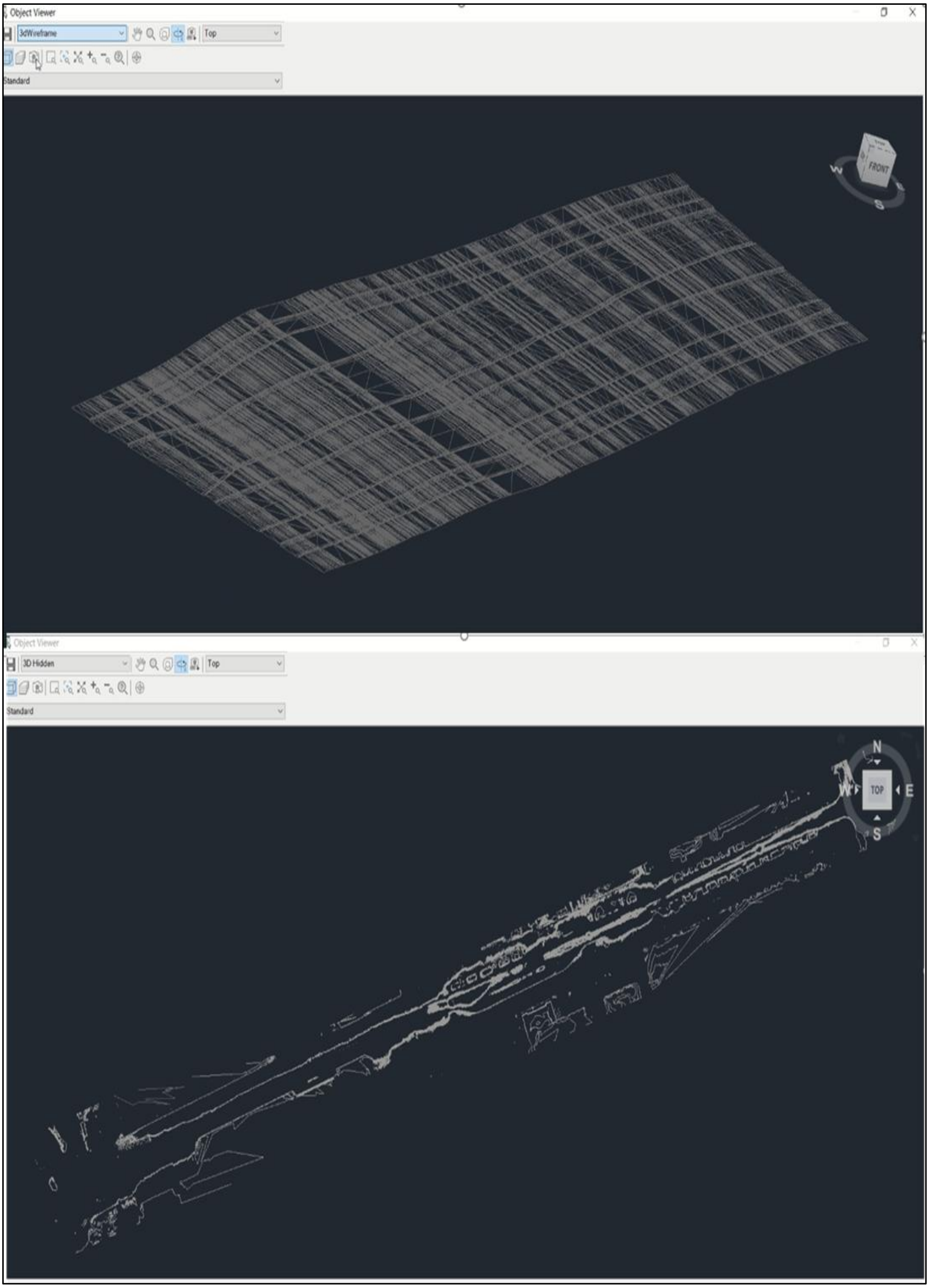


Figure 6.16: Terrain Extracted from Point Cloud Displayed Using Different Visual Styles
Source: Created by Shuaib Yunos in Autodesk Civil 3D 2022

Whichever method is used to derive and compute the terrain, consultants/designers have the flexibility to incorporate the preferred or available option with BIM technologies. With Autodesk Infraworks used for conceptual and/or preliminary design, all design data can be imported to Autodesk Civil 3D, as per the coordinate system specified in Autodesk Infraworks to ensure correct site geolocation.

With most or popular BIM technologies designed in the northern hemisphere, the survey projection/parameters differ from that in South Africa (SA). Despite the current Hartebeeshoek94 and prior SA coordinate systems available in both Autodesk Infraworks and Civil 3D, a slight tweak is required as the X and Y values are swapped or read oppositely in the software, without the negative 1 multiplication factor assigned.

This tweak is quite easy to apply in Autodesk Civil 3D using Devotech iDAS and their created Civil 3D template, with a function to apply this correction with a single click, transforming the terrain/survey data to the correct quadrant position in South Africa.

Should consultants/designers have access to only Autodesk Civil 3D, the correction can be applied by duplicating the coordinate system of the site, thereafter, swapping the coordinate parameters to increase to the North and East. Thereafter, a label style should be created incorporating the swapping of the X and Y values and assigning the negative 1 correction factor, or by using the already created Devotech Civil 3D template that is free for download to all from the Devotech Group of Companies' website.

This report will showcase the application of Autodesk Civil 3D in conjunction with Devotech iDAS and not Autodesk Civil 3D alone, as the combination of both these BIM technologies further aligns with the MacLeamy Curve. Once all pertinent design data is imported into Autodesk Civil 3D from Autodesk Infraworks and other available sources, detailed design of the roadway can commence.

6.2.2 ROAD CORRIDOR MODELLING

6.2.2.1 <u>ROAD CROSS SECTION/ASSEMBLY</u>

Upon import from Autodesk Infraworks, the alignments, including the associated cross sections and profiles, created in the conceptual model can be imported into Autodesk Civil 3D using the Devotech iDAS Civil 3D template. The imported cross-sections (called assemblies in Autodesk Civil 3D) will need to be edited or recreated depending on the complexity, in order to generate the road corridor and associated earthworks and structural pavement quantities correctly and accurately.

This is because the cross-sections generated in Autodesk Infraworks are conceptual and comprise just one structural pavement layer. This can be created easily in Autodesk Civil 3D, with a variety of out-of-the-box parametric road components (subassemblies) available as portrayed below:

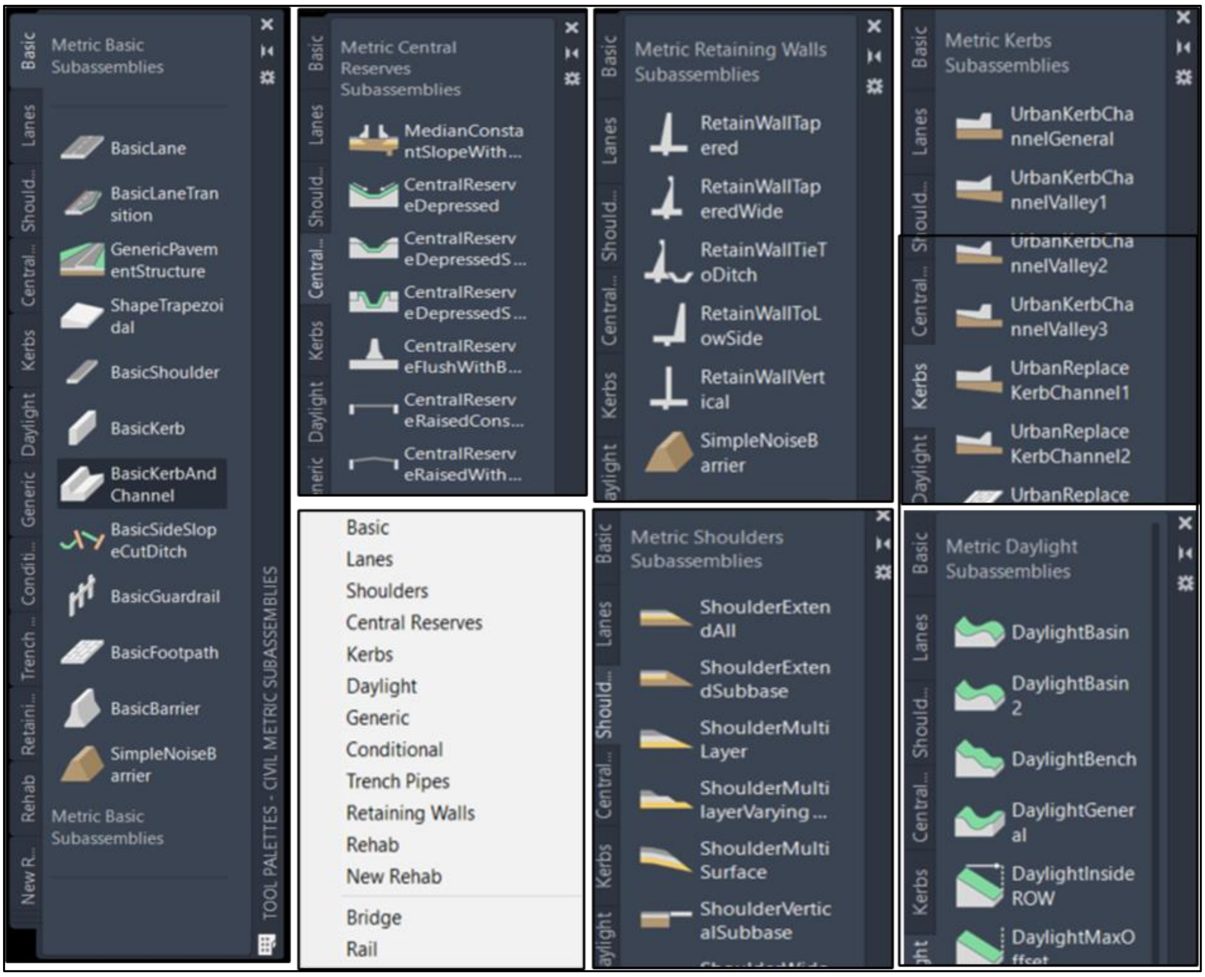


Figure 6.17: Parametric Road Components (Subassemblies) Available
Source: Autodesk Civil 3D 2022

In the case where custom road components are required, these components can be created via two methods:

- The component, for example, a kerb, can be drawn using a polyline, thereafter, converting it to an assembly using the polyline to subassembly feature in Autodesk Civil 3D and assigning the relevant code set. An example is portrayed below:

- The second method for generating parametric road components is that of using the Autodesk Civil 3D subassembly composer. This method enables consultants/designers to create parametric road components, allowing for the editing of dimensions when inserted into a cross-section/assembly, which cannot be done in the first method. An example of the subassembly composer is portrayed below:

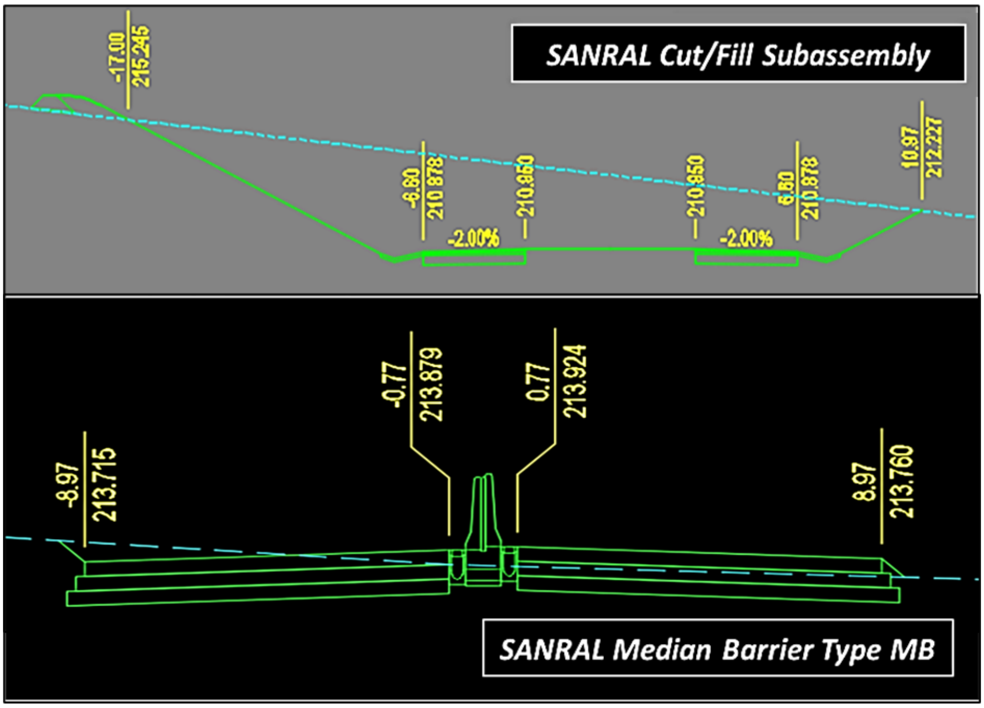


Figure 6.18: Sample of SANRAL Cross Section/Assembly Components
Source: Devotech Group of Companies, n.da.

For SA standard road components such as South African Bureau of Standards (SABS) kerbs, including subassemblies for road layers and conditional cut and fill daylighting as per SANRAL has already been created by the Devotech Group of Companies which can be downloaded from their website and applied to the designs of SA consultants.

There is a range of SA assembly components (as per the South African Bureau of Standards (SABS) and the South African National Roads Agency SOC Ltd (SANRAL)) available from the Devotech Group of Companies` website such as:

- Road Kerbs
    - Barrier kerb SABS (Fig 3)
    - Rectangular kerb SABS (Fig 5)
    - Semi-mountable kerb SABS (Fig 7)
    - Mountable kerb SABS (Fig 8B)
    - Mountable kerb SABS (Fig 8C)
    - Rectangular kerb SABS (Fig 10)
    - Rectangular kerb SABS (Fig 12)
- Stormwater channel on the low side
- Advanced Lane
- SANRAL Cut Fill
- SANRAL Median Barrier with Retaining Wall
- SANRAL Median Barrier with Wall and U-Channel
- Conditional Road Edge Beam or Channel

Once the cross sections/assemblies are created accordingly, they can be assigned to their respective alignments for road corridor generation.

6.2.2.2 <u>Road Corridor Generation</u>

Upon import from Autodesk Infraworks, the consultant/designer is presented with an option to tick the data they wish to import into Autodesk Civil 3D. With the incorporation of Devotech iDAS in Autodesk Civil 3D, consultants/designers are afforded the impressive BIM functionality of the Corridor Wizard.

This functionality requires the centreline(s) to be drawn as a polyline or an alignment itself, thereafter, assigning a cross-section and creating the corridor, including the creation of the datum and road finish surface, and associated horizontal and vertical alignments/profiles. This automation dramatically streamlines the road corridor creation process.

Upon corridor generation using the Corridor Wizard, consultants/designers can then edit and modify the horizontal and vertical alignments/profiles as required, with all design data updating instantly due to the dynamic nature provided by Autodesk Civil 3D, as well as the added dynamic nature provided by Devotech iDAS for the edge of road profiles.

When it comes to geometric design checks and safety, design criteria as per AASHTO standards are built into this BIM environment, affording consultants/designers to visually check their design compliance for elements such as minimum radius, K values, sight distance and tangency points that are unsuitable. These design criteria are monitored automatically in real-time to ensure that design compliance is met, with an example of horizontal curvature illustrated below:

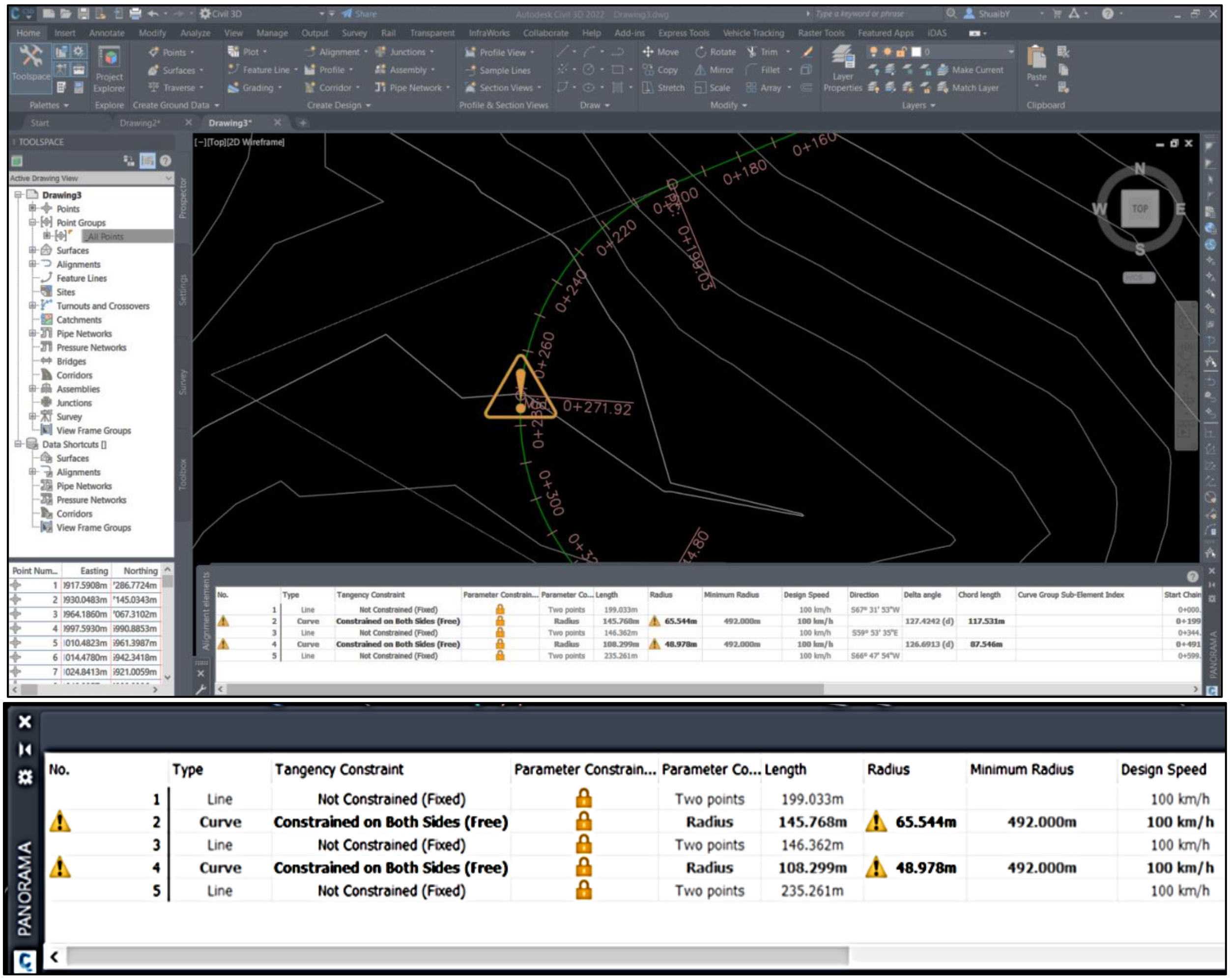


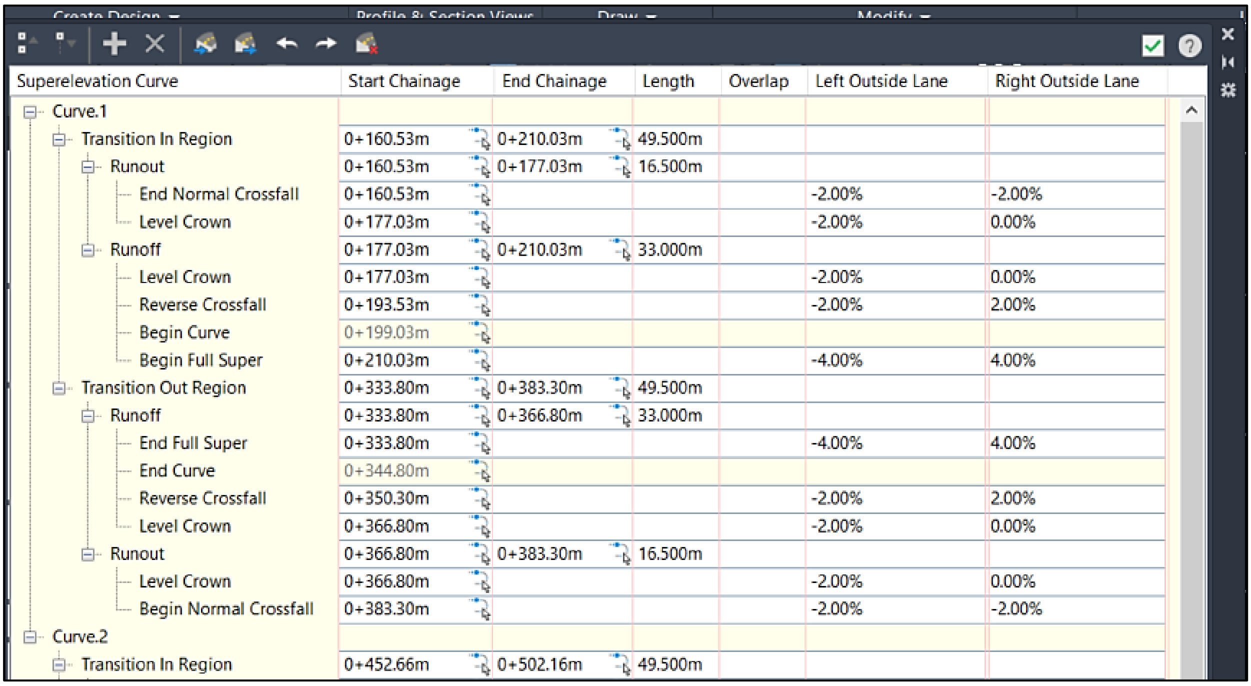
Figure 6.19: Curve Radius Automatically Flagged to be Non-Compliant for Design Speed
Source: Derived by Shuaib Yunos using Autodesk Civil 3D 2022

These elements can be modified or corrected graphically in the interface by editing the alignments/profiles or by using the panorama window, providing an option to input exact values. Other design standards can be created and saved for future projects, ensuring flexibility and versatility.

In the Corridor Wizard, the consultant/designer has the option to slope the road with or against the natural ground level, with the latter used in urban areas to assist in effective stormwater runoff. This can be edited or modified using superelevation, which plays a critical role in road safety and stormwater design.

Autodesk Civil 3D comprises a Superelevation Wizard, which enables the consultant/designer to input design criteria required such as design speed, road configuration, number of lanes, lane widths, lane slopes, pivot points, eMax percentages, as well as attainment method, based on AASHTO standards, which can be modified and saved as different design criteria for future use if required.

Upon input of these design criteria, the superelevation wizard will compute the values and points of superelevation, displayed in a tabular format, which can be edited, with a sample provided below:



Superelevation Curve	Start Chainage	End Chainage	Length	Overlap	Left Outside Lane	Right Outside Lane
Curve.1						
Transition In Region	0+160.53m	0+210.03m	49.500m			
Runout	0+160.53m	0+177.03m	16.500m			
End Normal Crossfall	0+160.53m				-2.00%	-2.00%
Level Crown	0+177.03m				-2.00%	0.00%
Runoff	0+177.03m	0+210.03m	33.000m			
Level Crown	0+177.03m				-2.00%	0.00%
Reverse Crossfall	0+193.53m				-2.00%	2.00%
Begin Curve	0+199.03m					
Begin Full Super	0+210.03m				-4.00%	4.00%
Transition Out Region	0+333.80m	0+383.30m	49.500m			
Runoff	0+333.80m	0+366.80m	33.000m			
End Full Super	0+333.80m				-4.00%	4.00%
End Curve	0+344.80m					
Reverse Crossfall	0+350.30m				-2.00%	2.00%
Level Crown	0+366.80m				-2.00%	0.00%
Runout	0+366.80m	0+383.30m	16.500m			
Level Crown	0+366.80m				-2.00%	0.00%
Begin Normal Crossfall	0+383.30m				-2.00%	-2.00%
Curve.2						
Transition In Region	0+452.66m	0+502.16m	49.500m			

Figure 6.20: Computation of Superelevation
Source: Derived by Shuaib Yunos using Autodesk Civil 3D 2022

Consultants/designers are also afforded the option to manually create the superelevation for a road, especially for those roads which are purely linear and require superelevation for stormwater design.

Once the superelevation is complete, the data is displayed within the superelevation band in the long section/profile, as well as the option to produce the superelevation diagram for the given road as portrayed below:

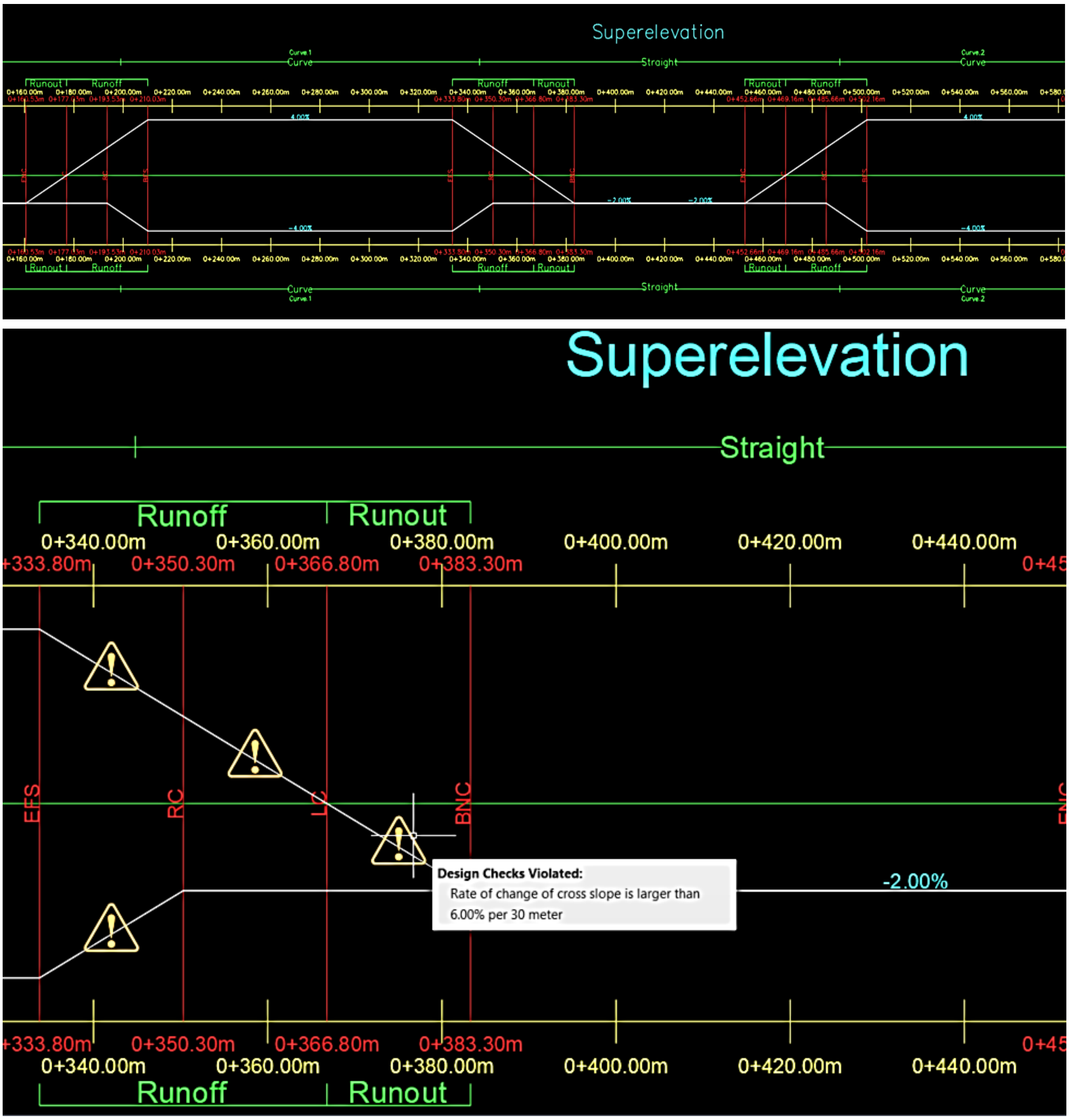


Figure 6.21: Superelevation Diagram Including Design Check
Source: Derived by Shuaib Yunos using Autodesk Civil 3D 2022

6.2.2.2.1 Intersections

Intersections form a critical component of road design, and are governed by the intersecting alignments/roadways, their associated cross sections/assemblies, as well as their turning radii based on the type of vehicular traffic.

Devotech iDAS provides the functionality in Autodesk Civil 3D to generate the intersection (2-way and/or 4-way) using the bellmouth and intersection wizards. This BIM functionality affords the consultant/designer to create the intersection along with the bellmouth/curve alignments/profiles, whilst tying in the alignments at either the intersection point or edge of road elevations of the main/priority road.

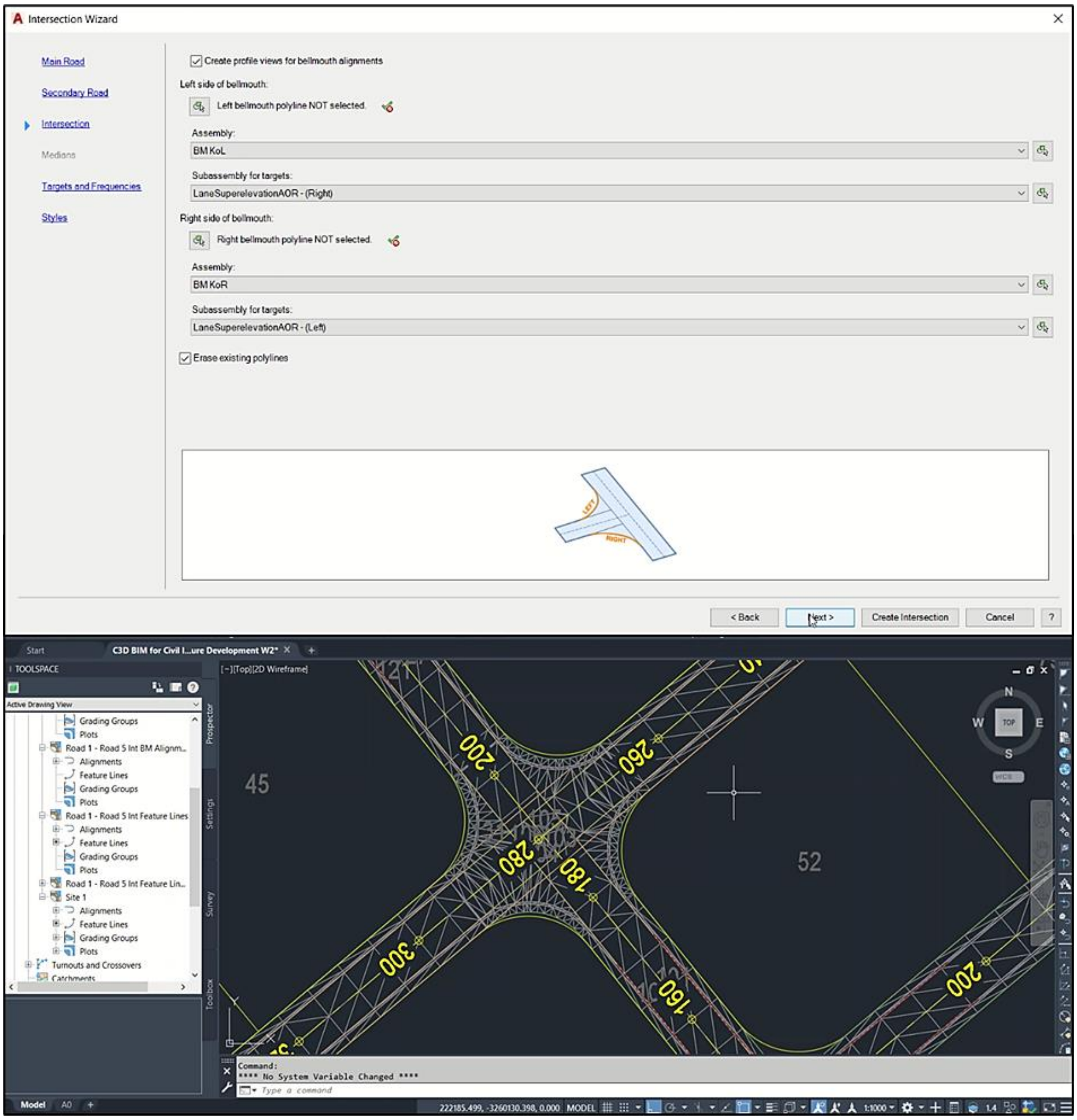


Figure 6.22: Road Intersection Corridor Including Vertical Alignments/Profiles for Bellmouths
Source: Created by Shuaib Yunos using Autodesk Civil 3D & Devotech iDAS 2022

Once the intersection has been generated, either by using the bellmouth and intersection wizards or by manual targeting (to be covered under section 5.1.2.2.5) based on configuration and/or complexity, Autodesk Vehicle Tracking can be used.

Autodesk Vehicle Tracking in Civil 3D is used to analyse and review an intersection or road curve in relation to a design vehicle's swept path, to ensure that there is ample space for the design vehicle to manoeuvre and perform a turn comfortably. This BIM technology comprises a library of automobiles, trucks, buses, and aeroplanes (useful when designing airport runways), with the option to add custom vehicles and dimensions. Based on the design vehicle used, the software will compute and simulate the movement of the design vehicle (in 2D and/or 3D) based on the axle movement and display the swept path envelope, enabling designers to check their design relative to suitability/practicality of the design traffic.

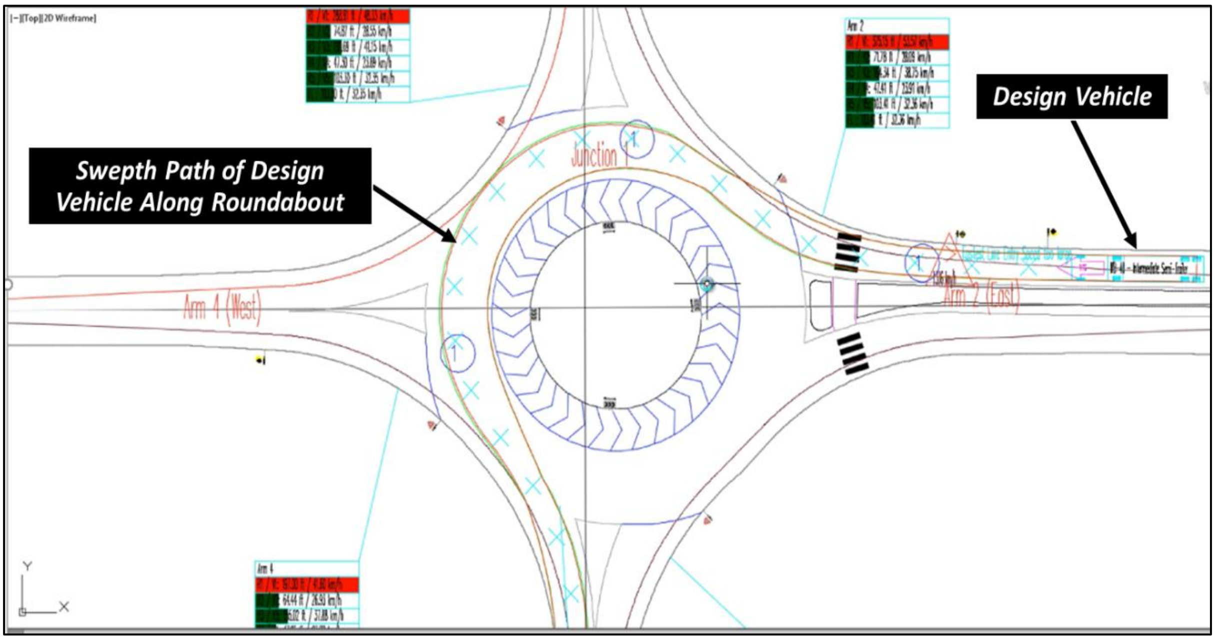


Figure 6.23: Simulation of a Design Vehicle's Swept Path to Check Design Suitability
Source: Created by Shuaib Yunos using Autodesk Civil 3D & Vehicle Tracking 2022

With these BIM technologies, revisions, design flaws/inadequacies and costly mistakes can be troubleshot and avoided way ahead of the construction phase, promoting a smooth transition through the road project lifecycle.

6.2.2.2.2 Roundabouts

Roundabouts serve the purpose to control traffic flow in highly congested areas such as urban, industrial, residential, and educational developments, and are also governed by the factors highlighted previously for intersections.

Autodesk Civil 3D and Vehicle Tracking provide consultants and designers with design-based automation for generating roundabouts with the option, as previously mentioned, to create their own required design criteria if required. The roundabout wizard is used to generate the roundabout corridor based on the intersecting/approaching alignments/arms relative to the design criteria applied with vehicle tracking used for road markings and vehicle swept path analysis and review.

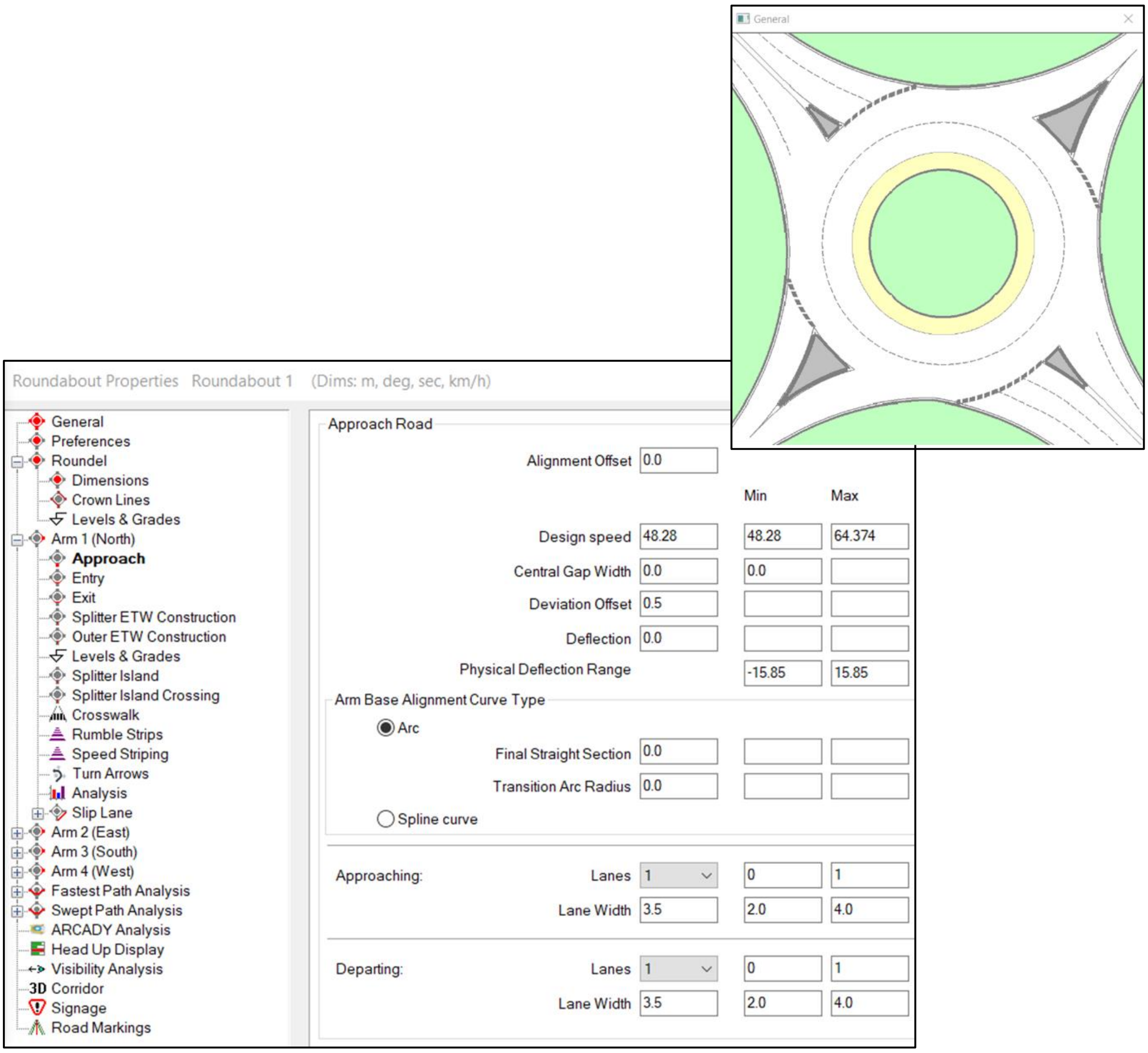


Figure 6.24: Generating a Roundabout with Associated Geometry & Standards using the Roundabout Wizard
Source: Autodesk Civil 3D & Vehicle Tracking 2022

The vertical alignments/profiles can then be derived, reviewed, and modified accordingly, including the geometry of the roundabout based on design criteria and vehicle movement/simulation. Other elements such as crossings and islands can be inserted as depicted below:

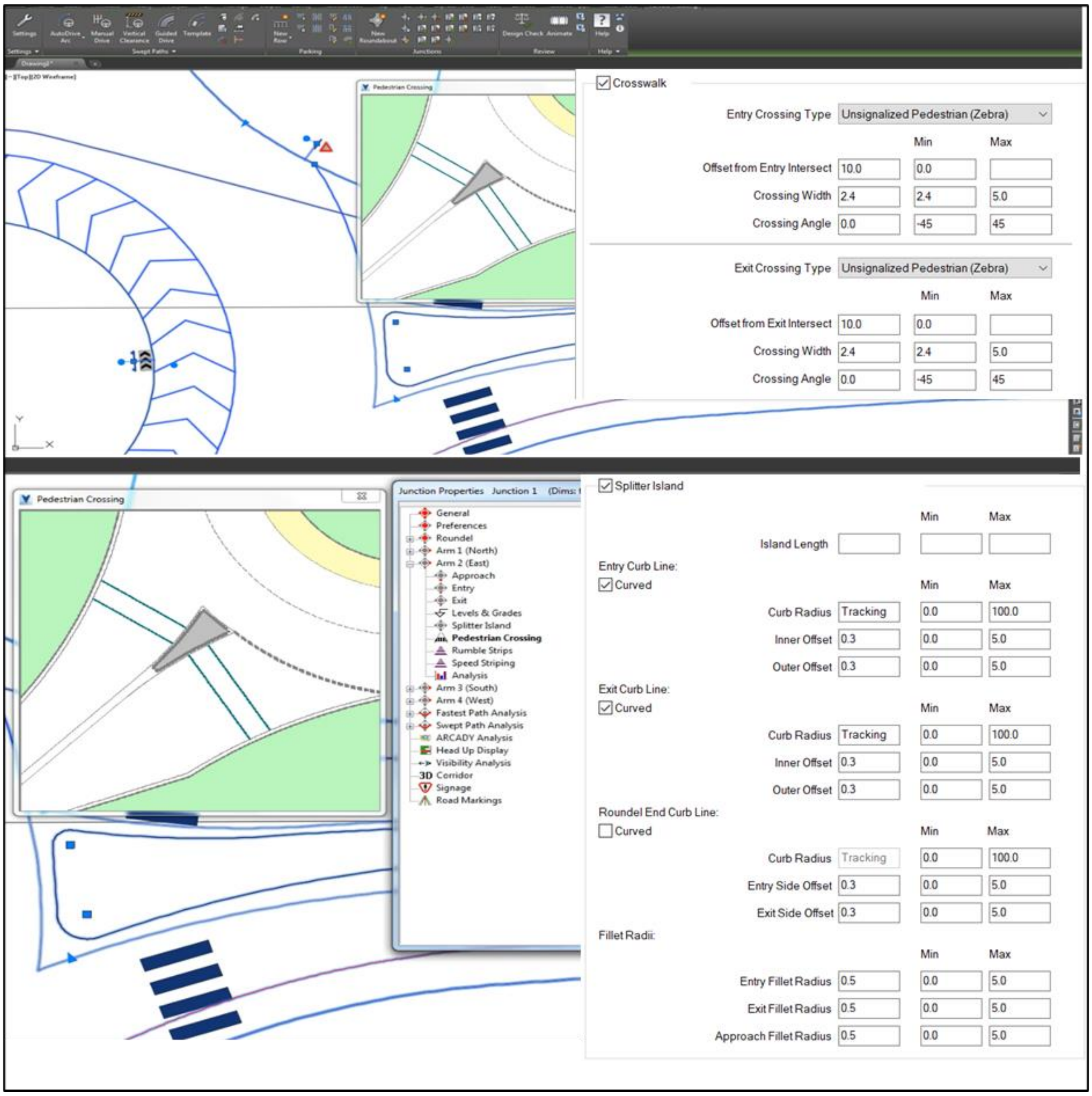


Figure 6.25: Insertion & Creation of Islands & Crossings for a Roundabout
Source: Autodesk Civil 3D & Vehicle Tracking 2022

With these BIM technologies, revisions, design flaws, inadequacies and costly mistakes can be troubleshot and avoided way ahead of the construction phase, including reviewing the roundabout for being over-or under-sized-and-designed, more efficient and economical and promoting a smooth transition through the road project lifecycle.

6.2.2.2.3 Road Interchanges and Widenings

When it comes to high-capacity roadways such as highways, interchanges and widenings are required to accommodate traffic flow and volumes, as well as public transport such as taxis and buses.

The methodology used to design road corridors is that of corridor targeting. This functionality affords the consultant/designer to create geometric designs that are complex and irregular in shape, such as slipways, offramps, bus/taxi bays and tapered turning lanes, by following the defined path created by the consultant/designer by means of an alignment and/or polyline, relative to the governing road alignment/profile.

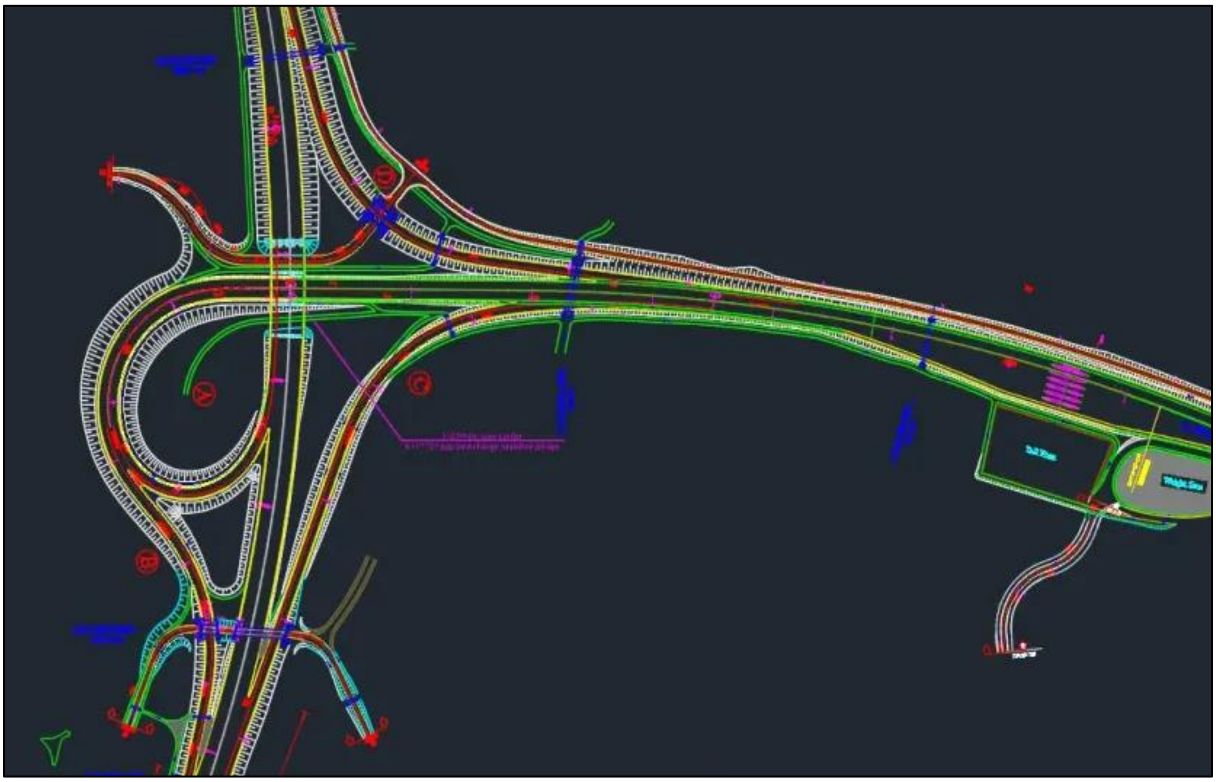


Figure 6.26: Trumpet Interchange Detail Design in Autodesk Civil 3D 2022
Source: Highway Academy, n.d.

This BIM functionality in Autodesk Civil 3D affords the consultant/designer a contextual view of their design corridor, including the location of bridges and alignment tie-in points for accurate road design, whilst ensuring design compliance, economy and horizontal and/or vertical clearances where required.

6.2.2.2.4 Bridges and Tunnels

With high-capacity road networks, bridges and/or tunnels form part of the civil infrastructure deliverables. The coordination between the road corridor and bridges or tunnels is a challenging task, especially between roads and bridge or tunnel design teams. The workflow afforded by BIM technologies such as Autodesk Infraworks, Civil 3D and Revit, synchronisation and parametric intelligence is provided to road and bridge or tunnel design teams.

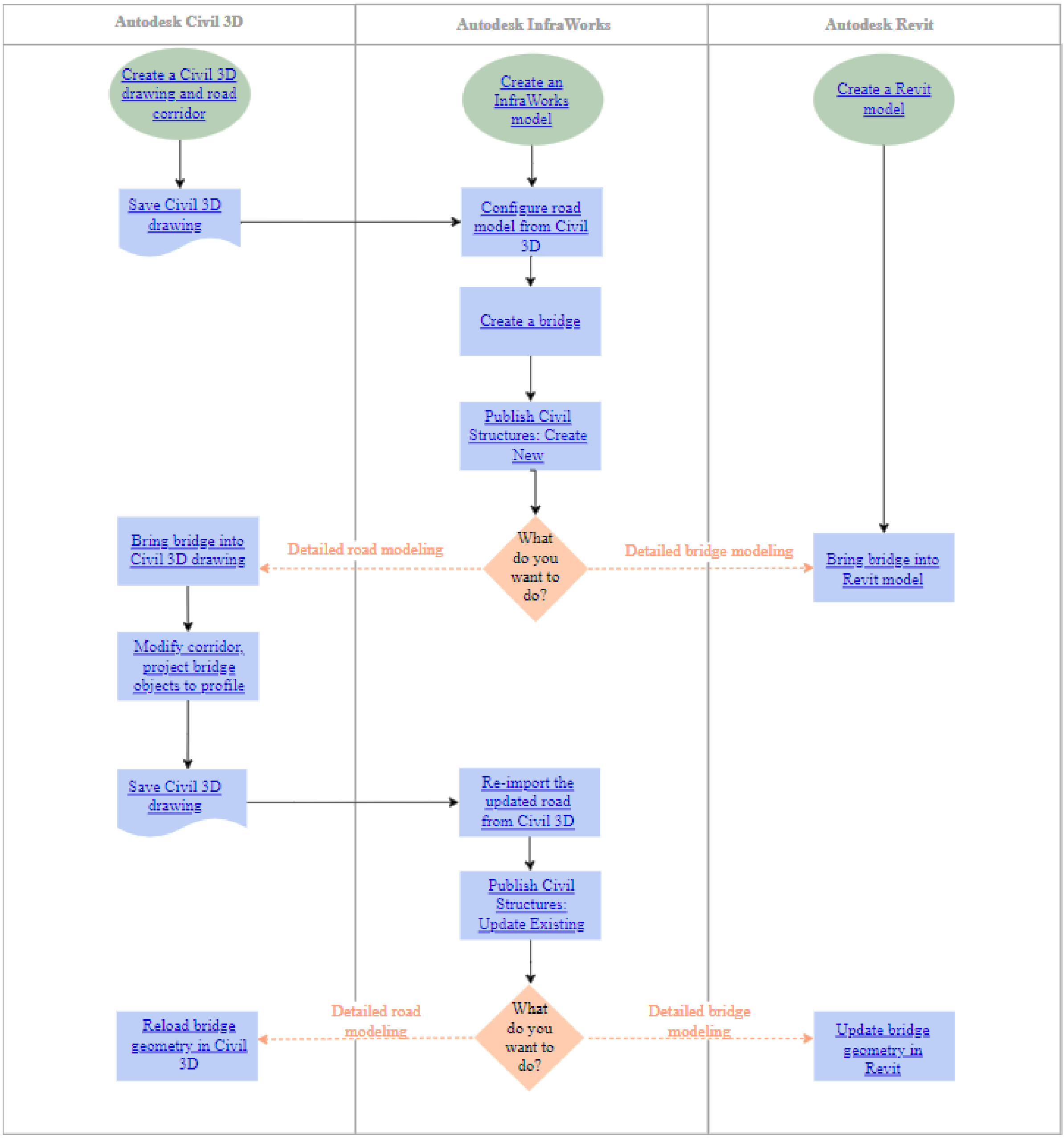


Figure 6.27: Autodesk Civil Structures Workflow 2022
Source: Autodesk, 2021

The workflow consists of modelling the conceptual road in Autodesk Infraworks, thereafter, importing it to Civil 3D for final corridor design. Upon corridor completion, the Civil 3D model is imported into Infraworks, with a parametric bridge and/or tunnel inserted at the desired locations or chainages.

Autodesk Infraworks has a library of common parametric bridge components used in bridge and/or tunnel design such as abutments, bearings, cross frames, decks, diaphragms, field splices, foundations, girders and piers. These parametric components can be edited according to required dimensions as in the example portrayed below.

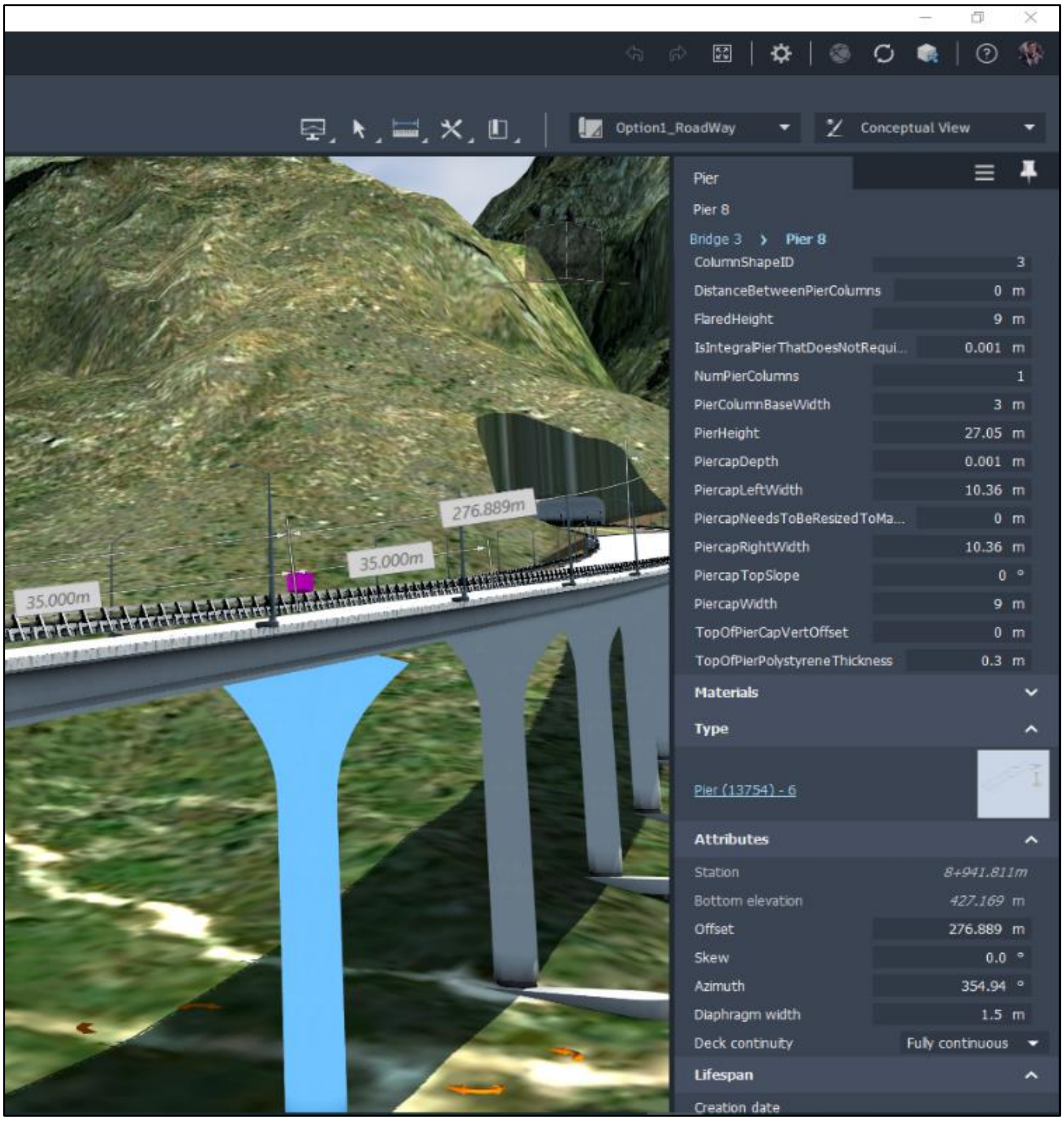


Figure 6.28: A Parametric Pier Selected with Editable Metadata on the Right Asset Card
Source: Created by Shuaib Yunos using Autodesk Infraworks 2022

Should the bridge or tunnel be of a custom, untypical geometry, the consultant/designer is afforded the option to utilise Autodesk Inventor Professional to create custom bridge or tunnel components and export them for use in Autodesk Infraworks. This solution is particularly favourable to those consultants specialising in bridge and/or tunnel design using this workflow, with one person being tasked to create the parametric components in Autodesk Inventor and saving them to a company library for future use in Autodesk Infraworks.

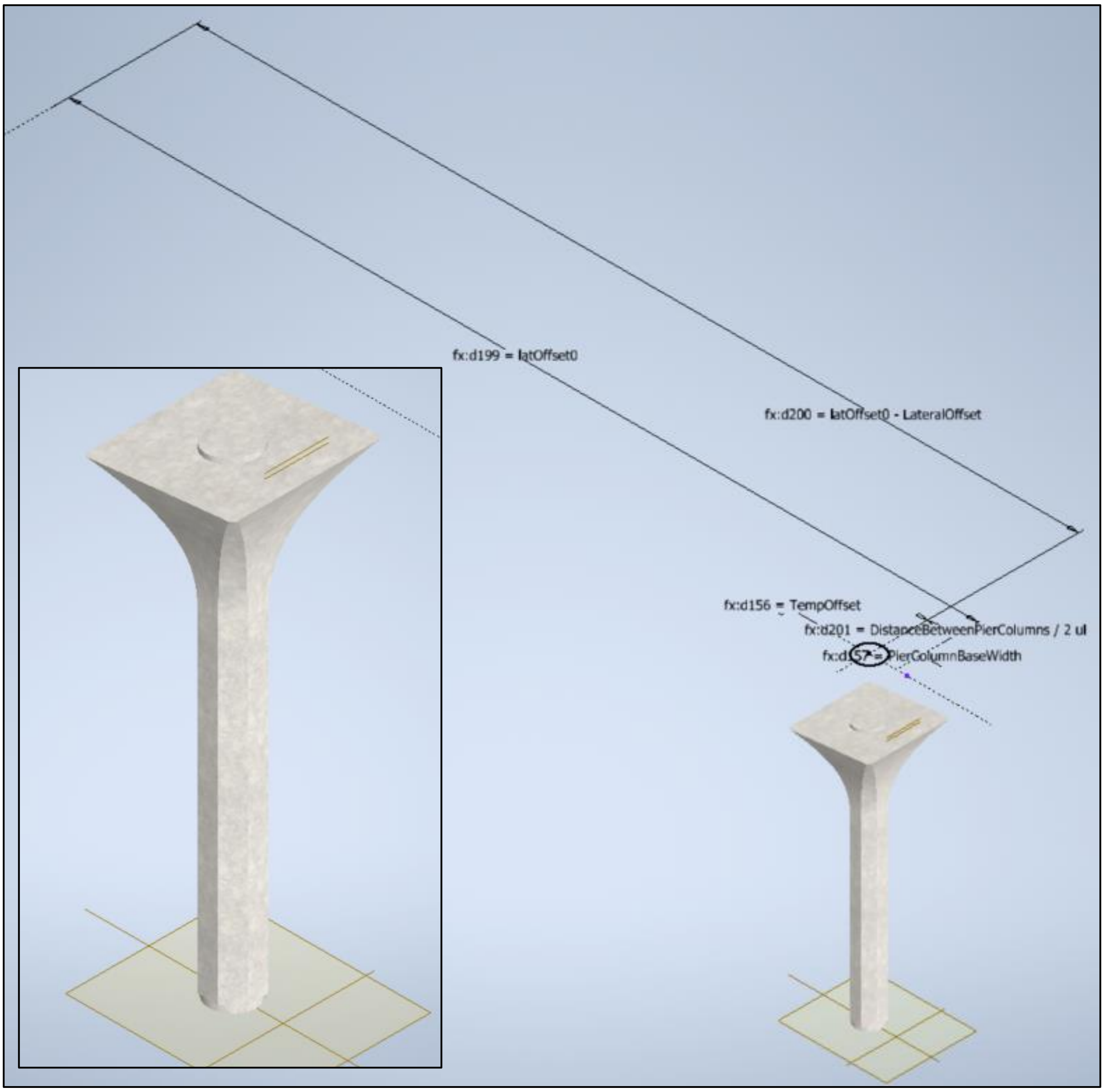


Figure 6.29: A Parametric Bridge Pier Modelled in Autodesk Inventor Professional for use in Autodesk Infraworks
Source: Autodesk Inventor 2022

Autodesk Inventor is currently not included in the Autodesk AEC Collection, and as it is used in the mechanical and manufacturing disciplines, it provides a convergence workflow between manufacturing and construction, a highly beneficial solution applied by consultants that do design and construction, as well as those involved in modular or prefabrication for construction, opening a range of possibilities and business opportunities. Depending on scalability and opportunity, consultants involved in road and bridge and/or tunnel design typically purchase one seat of Autodesk Inventor Professional, with a BIM Modeller tasked with creating the required components for all related projects, with others purchasing more based on service offerings, until a time where Revit capability is introduced into the workflow.

Once the bridges/tunnels have been inserted in Autodesk Infraworks, they can be imported into Autodesk Civil 3D and Revit. This advantage allows the geometry to be locked/non-editable in Revit so that the purpose is for structural detailing and drawings, with the geometry for bridges or tunnels only being editable in Autodesk Infraworks, providing more stringent control. In Autodesk Civil 3D, the bridges or tunnels are also displayed at their respective locations, with the ability to portray them in road long sections/profiles.

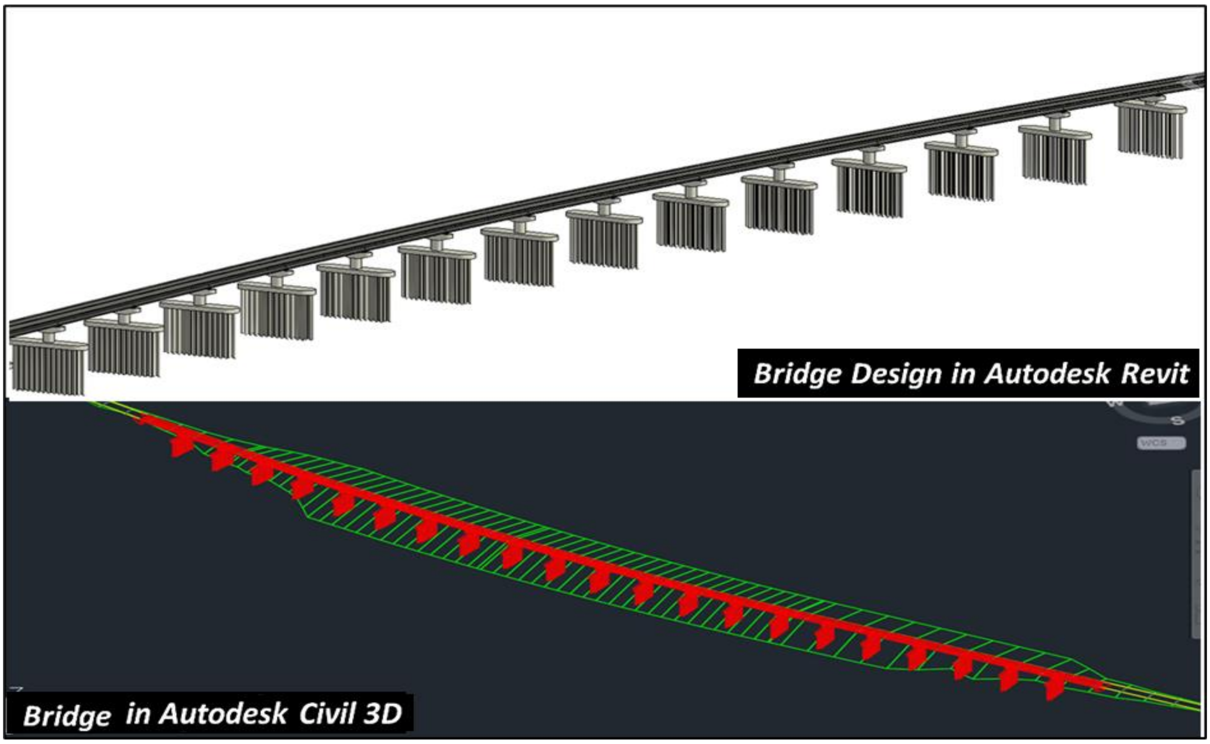


Figure 6.30: Bridge Geometry Imported & Linked from Autodesk Infraworks to Revit & Civil 3D 2022
Source: Autodesk Revit & Civil 3D 2022

The true beauty of this BIM workflow is the dynamic coordination and intelligent linking, in which should any changes be made to the road and/or bridge/tunnel geometry, the consultant/designer will be notified by a pop-up in the software (Revit and/or Civil 3D), ensuring live collaboration as well as efficient linking between the road vertical alignment/profile and the bridge/tunnel.

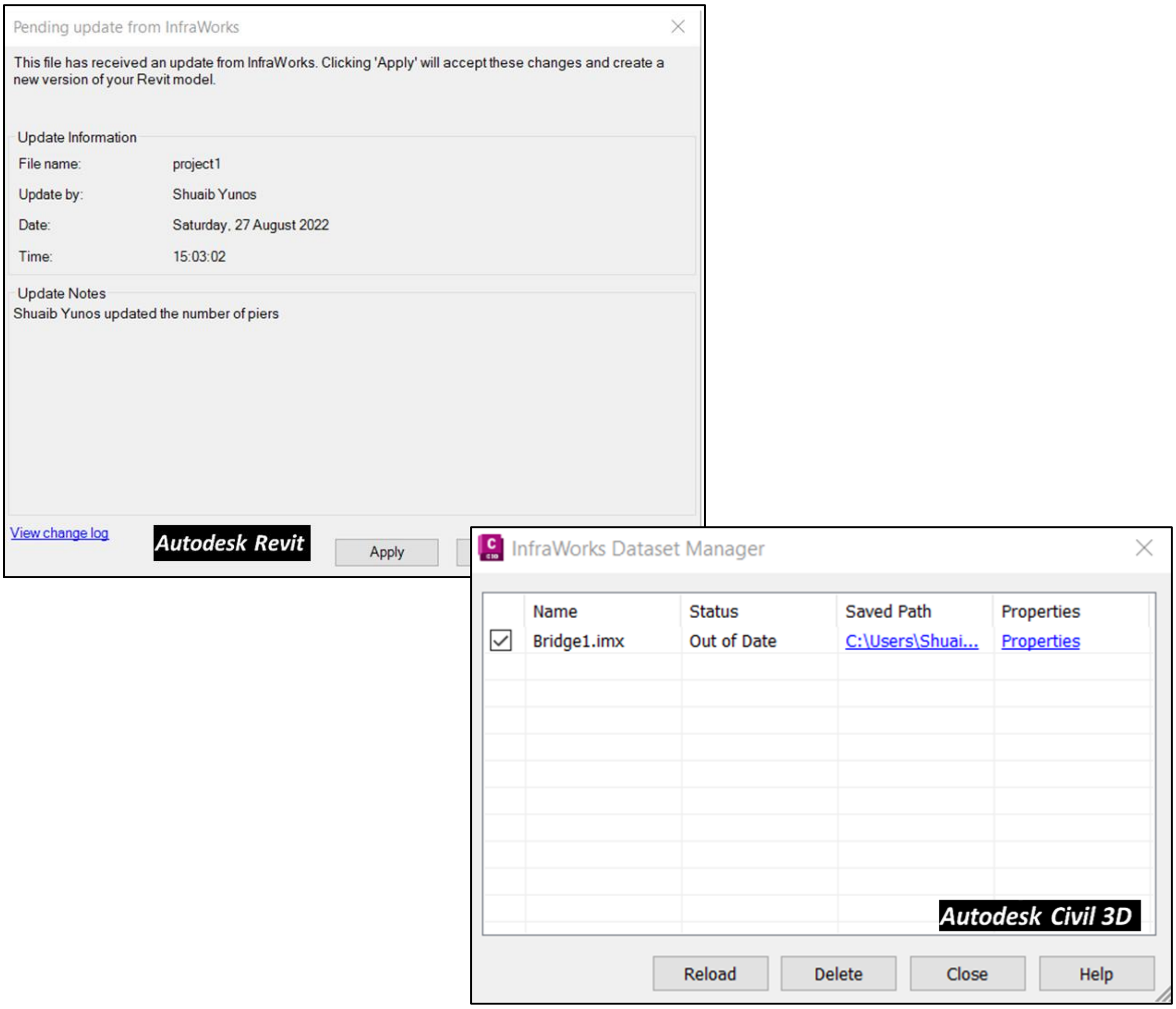


Figure 6.31: Pop-Up in Autodesk Civil 3D & Revit Indicating Bridge Has Been Modified & Reloading of .SMLX File is Required
Source: Autodesk Civil 3D & Revit 2023

Upon updating the file (.SMLX format) prompted by the pop-up (Civil 3D & Revit), all geometry and views update accordingly, saving the consultant/designer from searching, identifying and modifying these changes manually. This avoids clashes and coordination issues during the construction phase, with the tolerance for error being extremely low when dealing with bridges and tunnels.

6.2.3 STORMWATER DESIGN AND ANALYSIS

The safety and design life of roads form an integral part of geometric design, with stormwater design aiding in this pursuit. Depending on the awarded tender, a consultant may be awarded to purely do the road design, or both road and stormwater. Based on company structure and expertise, roads could be designed by a specific designer/department and stormwater another, or both done by the same designer/department. Whichever the case may be, Autodesk Civil 3D and Devotech iDAS allow the consultant/designer to do the stormwater design in the same interface as the roads, without the need to export to a separate software for design and analysis.

This powerful BIM duo of technology enables the consultant/designer to compute a watershed analysis on the site, resulting in the delineation and derivation of catchments and low points, taking into consideration the road finish surface for optimal stormwater design, as portrayed below:

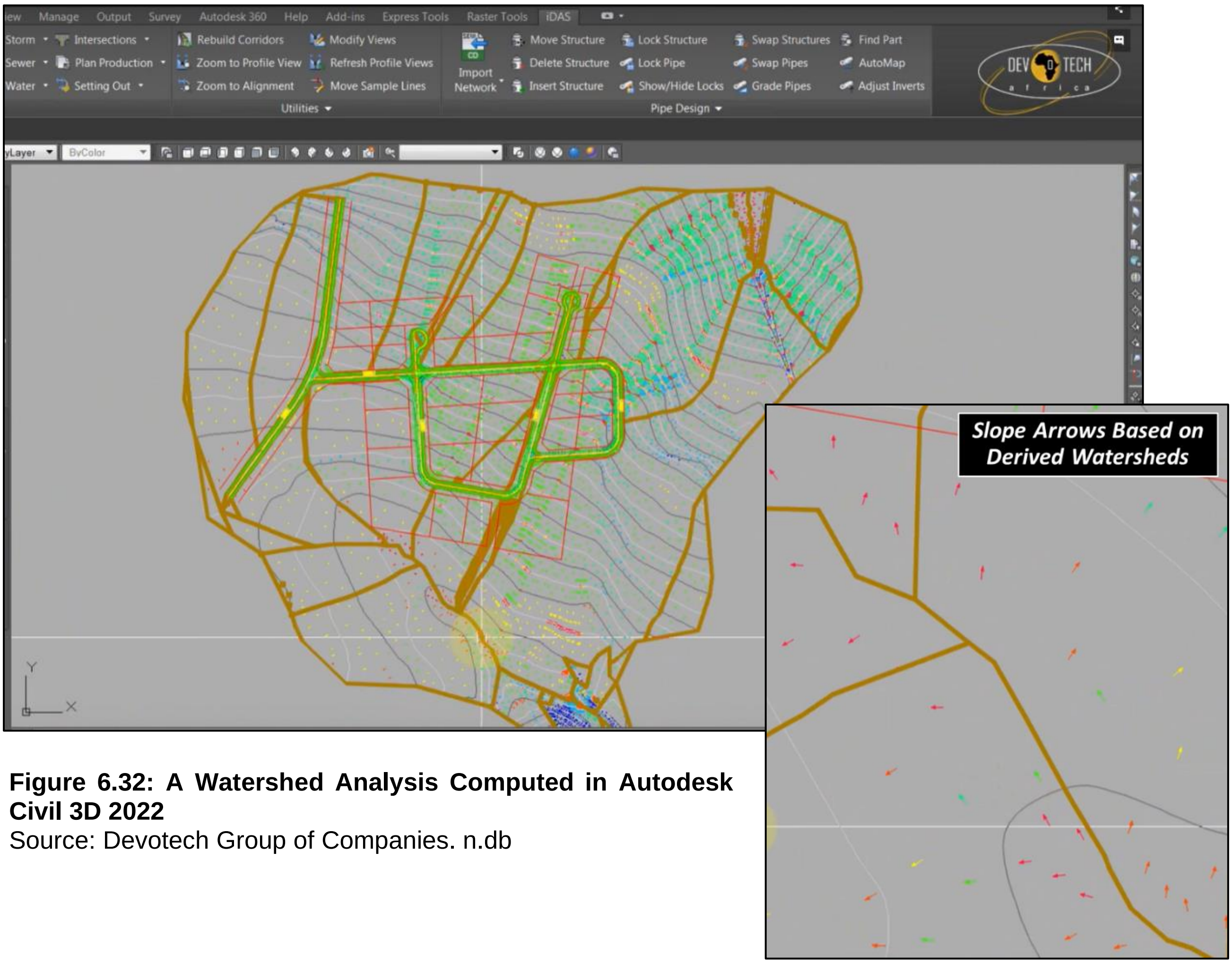


Figure 6.32: A Watershed Analysis Computed in Autodesk Civil 3D 2022
Source: Devotech Group of Companies. n.db

This functionality enables road and stormwater teams to check that their designs complement each other to arrive at the most suitable solution. The stormwater consultant/designer can then generate the stormwater network by either plotting the polylines of the network and converting them to a pipe network using the iDAS Stormwater Wizard, or by drawing the network directly by selecting the pipe type, diameter, and structure to be used, with either pipes and structures having the ability to be deleted or swapped with others. Whichever option is applied, the Devotech Civil 3D template comes with a range of already created catalogues widely used in South Africa as portrayed below:

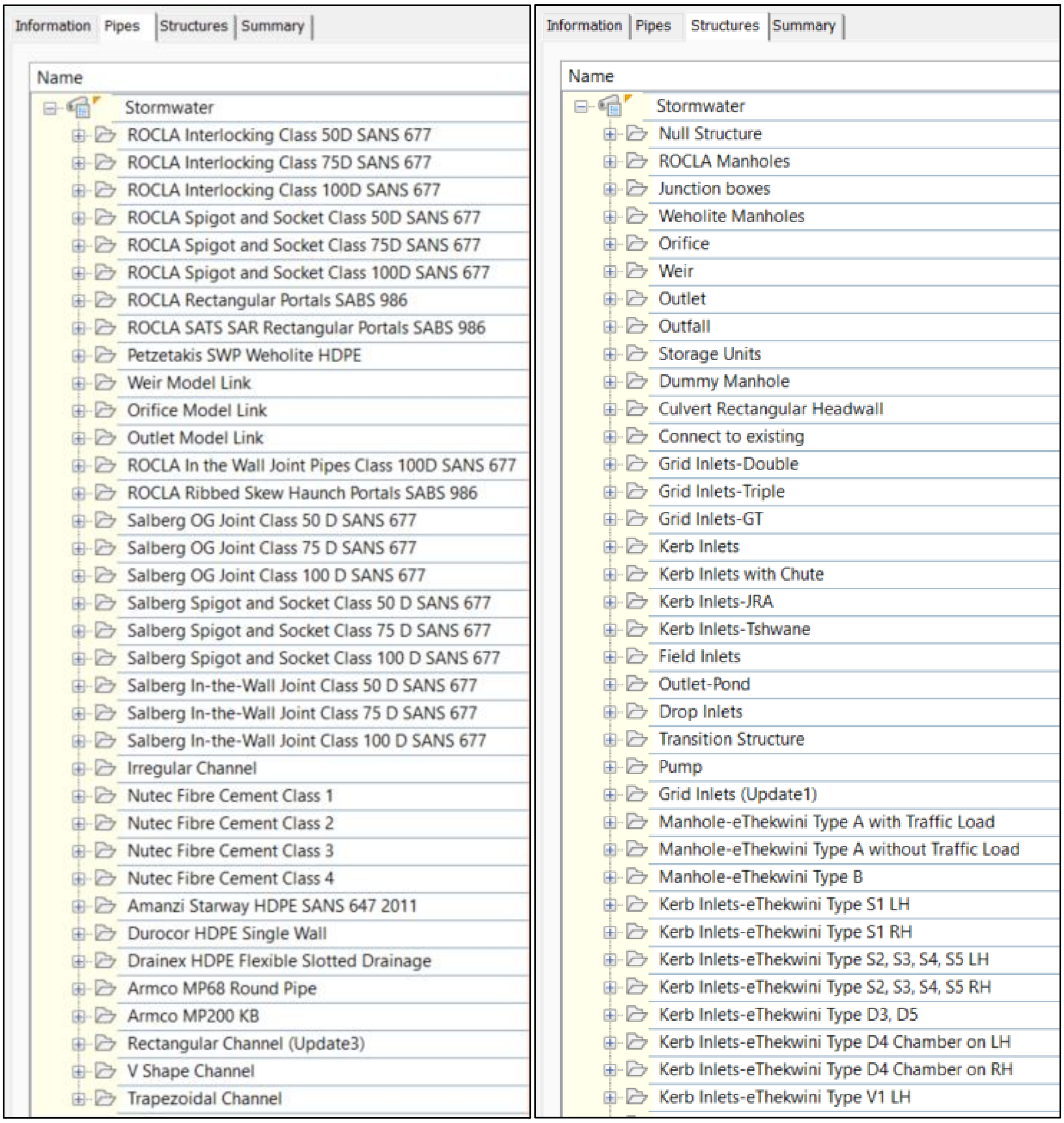


Figure 6.33: Pipes & Structure Stormwater Catalogues Created for SA Civil Consultants Available with the Devotech Civil 3D Template
Source: Devotech iDAS 2022 in Civil 3D 2022

Consultants/designers also have the option to create custom catalogues to suit their design needs. When it comes to analysis, it is of crucial importance that the network does not have missing or overlapping or duplicate vertices, gravitating in the correct direction, at the correct design slopes and covers. A map clean up can be applied using the GIS functionality found in Autodesk Civil 3D, ensuring that the vertices are correct or resolved. Devotech iDAS provides an automated BIM functionality to check the flow directions and regrade the network based on design criteria detailed in the SANRAL drainage manual, which can be edited based on different design requirements.

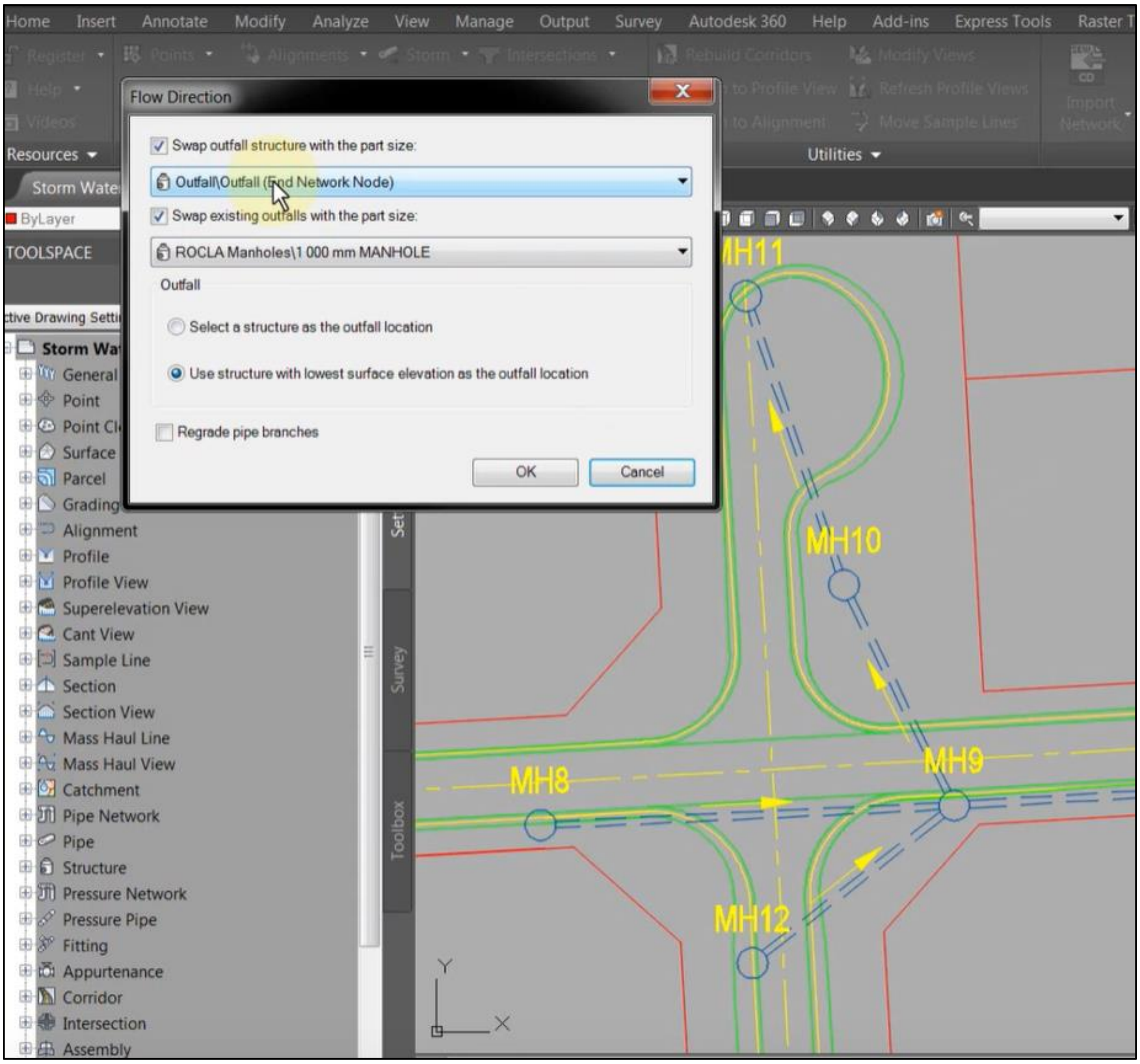


Figure 6.34: Checking of Flow Direction in a Stormwater Network, with the Option to Select Outfall or Gravitate to Lowest Elevation, as well as Regrade Network Based on Cover & Slope
Source: Devotech Group of Companies. n.db

Once the above have been computed, the catchments generated can be traced using the polyline function, and then converted to parcels, which are recognised as catchments in the Devotech iDAS Pipe Manager. Upon catchment derivation, flow paths are drawn to the corresponding inlets, required for analysis.

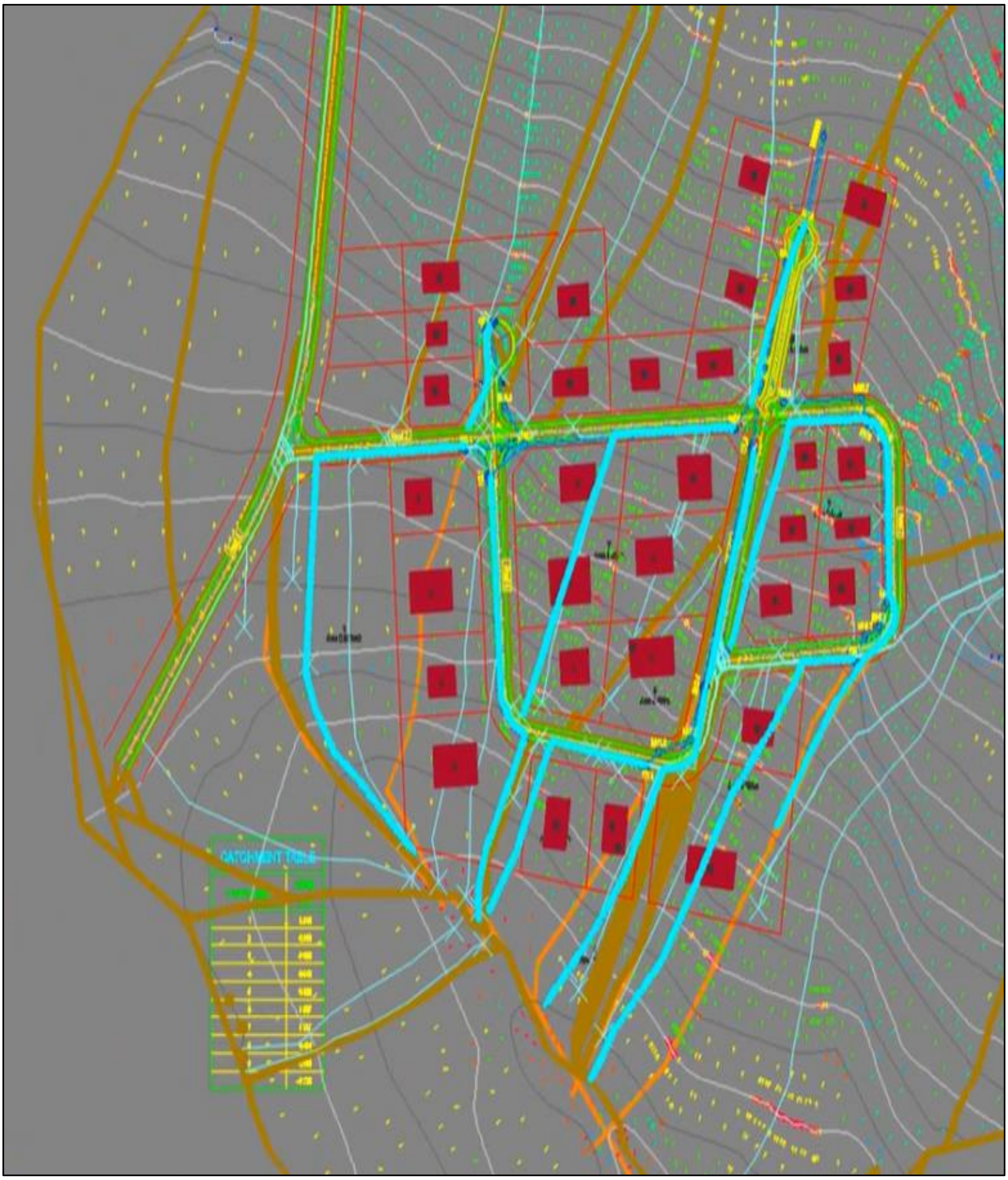


Figure 6.35: Drawing of Flow Paths (Cyan) to Corresponding Inlets Required for Analysis using Devotech iDAS in Autodesk Civil 3D 2022
Source: Devotech Group of Companies. n.d

With the CAD or modelling complete, the long sections/vertical profiles of the stormwater network can be generated automatically from the iDAS Pipe Manager, with the ability to regrade or edit the network in the long section/profile views. This functionality is dynamic, and updates related changes in the plan view as well, affording the consultant/designer efficiency and automation.

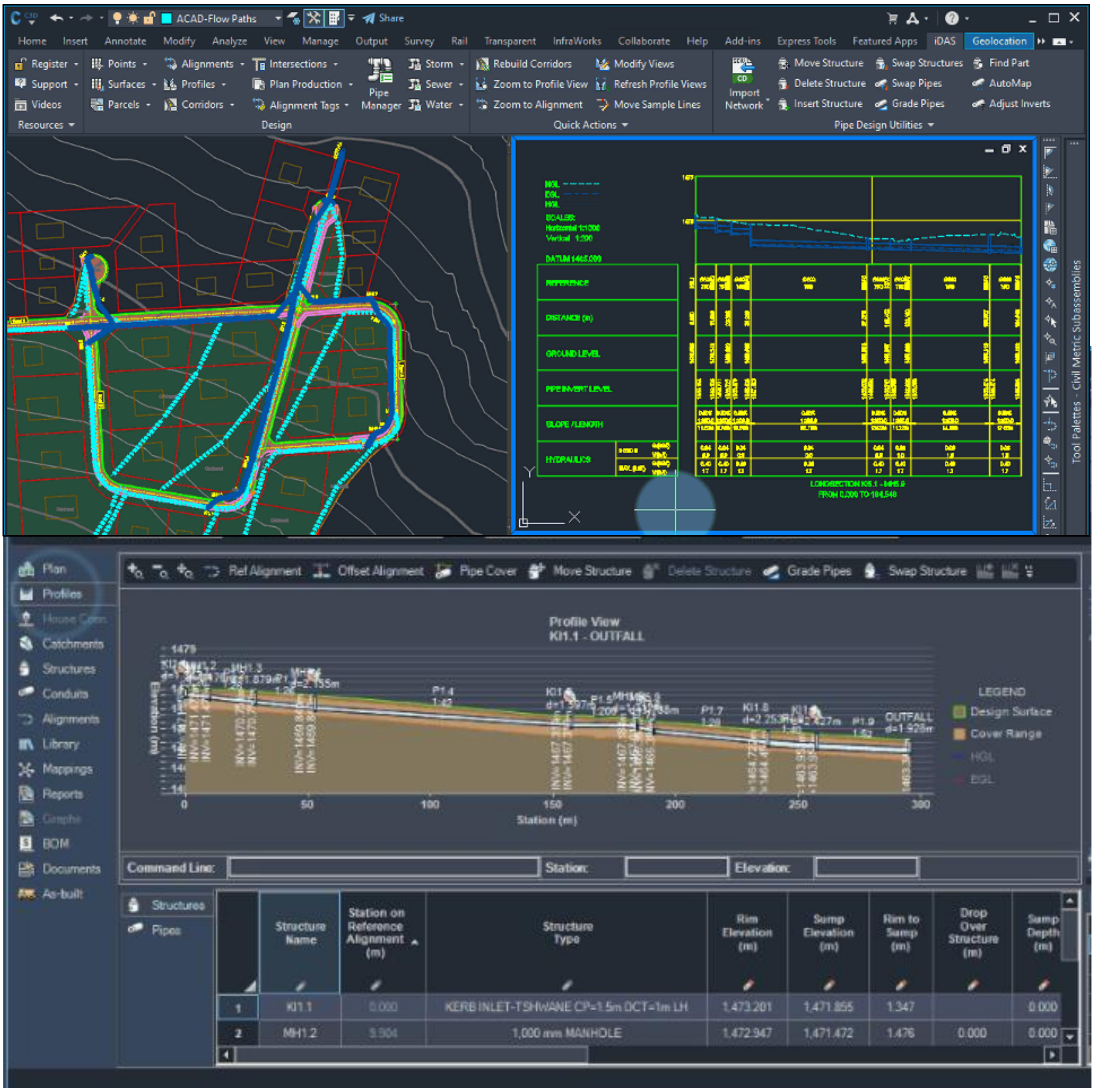


Figure 6.36: Pipe Long Section/Profile Depicted in Autodesk Civil 3D & Devotech iDAS Pipe Manager 2022
Source: Devotech Group of Companies. n.dc

With the stormwater network modelled, the consultant can now analyse the network using the iDAS Pipe Manager within Autodesk Civil 3D, with the outputs and modifications updated in Autodesk Civil 3D. In the Pipe Manager, the following design and analytic data capabilities for stormwater networks is available:

- Custom input of pipe and structure properties, for example, design flow and velocity, maximum flow and velocity, kerb inlet type, inflow and lateral inflow;
- Regrade entire network automatically;
- Grade multiple pipes at once (forward or backwards);
- Run-off calculation based on Rational and Epaswmm methods;
- Incorporation of IDF graphs;
- Specification of ascending and descending limb curve;
- Stormwater network analysis (steady flow, kinematic wave, dynamic wave);
- Pipe sizing/calculating of minimum conduit size required;
- Specification of proportional flow depth percentage;
- Analysis of attenuation ponds, channels, weirs, orifices, and culverts, and

The consultant can then review the analysis till a suitable result is derived to ensure optimal design performance and design compliance.

6.2.4 QUANTIFICATION

6.2.4.1.1 Roads

With the road corridors complete, consultant/designers can derive quantities for earthworks, as well as structural pavement layers volumes required for BOQs in Autodesk Civil 3D. They are also afforded the option to add and cut and/or fill factors to the quantities and output these quantities to a CAD table in the drawing and/or export these values to report which can be saved or copied and pasted into Microsoft Word, Excel, or other software with the sample outputs portrayed below.

Material Table-ROAD 01 ASPHALT

Chainage	Area	Volume	Cumulative Volume
0.00	0.18	0.00	0.00
20.00	0.18	3.60	3.60
40.00	0.18	3.60	7.20
60.00	0.18	3.60	10.80
80.00	0.18	3.60	14.40
100.00	0.18	3.60	18.00
120.00	0.18	3.60	21.60
140.00	0.18	3.60	25.20
160.00	0.18	3.60	28.80
180.00	0.18	3.60	32.40
200.00	0.18	3.60	36.00
220.00	0.18	3.60	39.60

Mass Haul Report

Project: Main Road
Designer: Shuaib Yunos
Alignment: Alignment 01
Sample Line Group: Alignment 01
Start Cha: 0+00.000
End Cha: 5+61.398

	Area Type	Area	Inc.Vol.	Cum.Vol.	MassHaul
		Sq.m.	Cu.m.	Cu.m.	Cu.m.
Chainage: 0+00.000					
	Adjusted Cut	8.01	0.00	0.00	
	Adjusted Usable	8.01	0.00	0.00	
	Adjusted Fill	0.69	0.00	0.00	
					0.00
Chainage: 0+20.000					
	Adjusted Cut	12.37	203.78	203.78	
	Adjusted Usable	12.37	203.78	203.78	
	Adjusted Fill	0.02	7.12	7.12	
					196.66
Chainage: 0+40.000					
	Adjusted Cut	17.35	297.16	500.94	
	Adjusted Usable	17.35	297.16	500.94	
	Adjusted Fill	0.15	1.73	8.85	
					492.09
Chainage: 0+60.000					
	Adjusted Cut	5.75	230.96	731.90	
	Adjusted Usable	5.75	230.96	731.90	
	Adjusted Fill	0.57	7.22	16.07	
					715.83
Chainage: 0+80.000					
	Adjusted Cut	6.97	127.25	859.15	
	Adjusted Usable	6.97	127.25	859.15	

Figure 6.37: Pavement & Earthworks Quantities for Roadway
Source: Derived by Shuaib Yunos using Autodesk Civil 3D 2022

Should there be any change to the road design, the quantity tables exported to CAD will update automatically due to the dynamic functionality, or if set to static, will need to be updated by the consultant/designer, and with the report being required to be exported again.

6.2.4.1.2 Bridges and Tunnels

The quantities for bridges and/or tunnels including rebar can be derived in Autodesk Revit. The quantities are placed in schedules which are customisable, detailing all pertinent quantities, with an example for rebar portrayed below.

Rebar Schedule P.3

Rebar Number	Bar Diameter	A	B	C	D	E	F	Shape	Shape Image	Hook At Start	Hook At End	Total Bar Length	Quantity	Reinforcement Volume	Weight
P.3a															
40	16 mm	3910 mm	1450 mm					91		None	None	58630 mm	11	11788.26 cm³	92.54 kg
41	16 mm	4025 mm	1450 mm					91		None	None	59840 mm	11	12031.55 cm³	94.45 kg
42	16 mm	1435 mm	2950 mm	0 mm	0 mm	0 mm	0 mm	94		None	None	178250 mm	31	35839.29 cm³	281.34 kg
43	16 mm	7950 mm	0 mm	0 mm	0 mm	0 mm	0 mm	00		None	None		35	55945.48 cm³	439.17 kg
44	16 mm	2950 mm	0 mm	0 mm	0 mm	0 mm	0 mm	00		None	None		89	52788.81 cm³	414.39 kg
45	28 mm	350 mm	2640 mm	0 mm	0 mm	0 mm	0 mm	12		None	None	2935 mm	1	1807.23 cm³	14.19 kg
46	28 mm	350 mm	2645 mm	0 mm	0 mm	0 mm	0 mm	12		None	None	2940 mm	56	101377.44 cm³	795.81 kg
47	20 mm	350 mm	2645 mm	0 mm	0 mm	0 mm	0 mm	12		None	None	2945 mm	10	9251.99 cm³	72.63 kg
48	20 mm	350 mm	2625 mm	0 mm	0 mm	0 mm	0 mm	12		None	None	2930 mm	2	1840.97 cm³	14.45 kg
49	16 mm	3910 mm	1450 mm					91		None	None	58630 mm	11	11788.26 cm³	92.54 kg

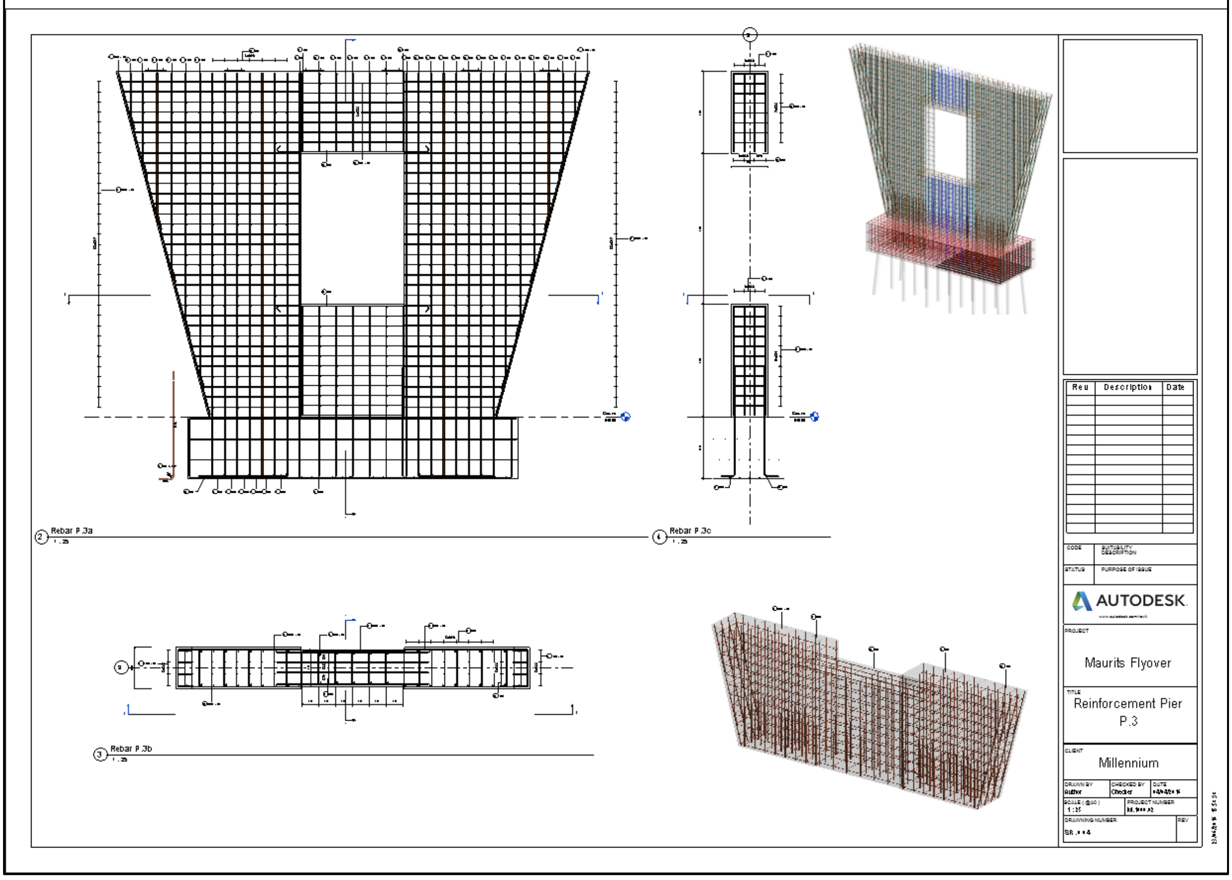


Figure 6.38: Rebar Drawings & Schedule Generated in Autodesk Revit
Source: Vermeulen, D. 2019

6.2.4.1.3 Stormwater Networks

The quantities of the stormwater network such as pipe type, diameter as well as structures such as manholes, kerb inlets, outfalls etc can be output to CAD tables or exported as a report using Autodesk Civil 3D and Devotech iDAS. The same applies for stormwater networks regarding edits and the dynamic nature explained for roads. With iDAS, consultants/designers can compute trench quantities as per SABS 1200, with sample outputs provided below:

Excavation Depth Increments (m): 1.0 Calculate Export BOM

Excavation Parameters
Excavation Volume (m³)
Excavation Volume Summary (m³)
Excavation Length (m)
Excavation Length Summary (m)
Pipes and Structures

	Pipe name	Part Size	Reference Surface	Bedding Class	Side Allowance (mm)	Message	Total Excavation
6	P1.1	600mm Class 75D	Final Surface	Class A	300.000	<None>	18.715
7	P1.2	600mm Class 75D	Final Surface	Class A	300.000	<None>	14.514
8	P1.3	600mm Class 75D	Final Surface	Class A	300.000	<None>	33.557
5	P1.4	600mm Class 75D	Final Surface	Class A	300.000	<None>	489.283
4	P1.5	600mm Class 75D	Final Surface	Class A	300.000	<None>	77.744
2	P1.6	600mm Class 75D	Final Surface	Class A	300.000	<None>	151.516
3	P1.7	600mm Class 75D	Final Surface	Class A	300.000	<None>	43.624
19	P1.8	600mm Class 75D	Final Surface	Class B	300.000	<None>	72.300

	Part Size	Total Excavation	Bedding Cradle	Compacted Selected Fill Blanket	Refill	0.00-1.00m	1.00-2.00m	2.00-3.00m	3.00-4.00m	4.00-5.00m
1	600mm Class 75D	2248.790	294.570	534.190	1420.029	930.281	846.041	371.703	71.938	5.987
Total		2248.790	294.570	534.190	1420.029	930.281	846.041	371.703	71.938	5.987

Minimum Diameter (mm)	Maximum Diameter (mm)	Side Clearance (mm)
0	125	300
125	700	300
700	1000	400
1000	2000	500
2000	10000	600

Structures

Structure Count Summary

Type	Quantity
Inlet	9
Manhole	14
Outfall	1

Pipes

Type	Length (m)
600mm Class 75D	727.231m
Total:	727.231m

PIPE LIST-STORMWATER

PIPE NAME	START INVERT LEVEL	END INVERT LEVEL	3D LENGTH TO INSIDE EDGES	SLOPE	DIAMETER AND C
P1.1	1471.870	1471.700	10.026	1.579%	600m
P1.2	1471.650	1471.499	6.597	1.986%	600m
P1.3	1471.449	1468.377	8.417	35.301%	600m
P1.4	1468.327	1467.580	125.222	0.593%	600m
P1.5	1467.530	1465.985	27.285	5.547%	600m
P1.6	1465.935	1465.342	51.796	1.122%	600m
P1.7	1465.292	1464.477	17.495	4.478%	600m
P1.8	1464.427	1464.264	32.164	0.500%	600m

STRUCTURE LIST-STORMWATER

STRUCTURE NAME	Y	X	RIM ELEVATION	SUMP ELEVATION SUMP DEPTH	INVERT ELEVATION	MATERIAL
KI1.1	26 088.156	2 842 358.084	1473.019	1471.870 1.148	P1.1-INV OUT 1471.870	Concrete
KI1.2	26 032.753	2 842 221.829	1468.522	1467.530 0.992	P1.4-INV IN 1467.580 P1.5-INV OUT 1467.530	Concrete Concrete
MH1.1	26 080.501	2 842 350.463	1472.877	1471.650 1.227	P1.1-INV IN 1471.700 P1.2-INV OUT 1471.650	Concrete Concrete
MH1.2	26 073.129	2 842 348.695	1472.754	1471.449 1.305	P1.2-INV IN 1471.499 P1.3-INV OUT 1471.449	Concrete Concrete
MH1.3	26 066.464	2 842 343.096	1472.548	1468.327 4.221	P1.3-INV IN 1468.377 P1.4-INV OUT 1468.327	Concrete Concrete
MH1.4	26 024.576	2 842 195.202	1468.533	1465.935 2.598	P1.5-INV IN 1465.985 P66-INV IN 1465.985 P72-INV IN 1465.985 P1.6-INV OUT 1465.935	Concrete Concrete Concrete Concrete

Figure 6.39: Pipe Network Quantities Derived in Autodesk Civil 3D using Devotech iDAS
Source: Derived by Shuaib Yunos using Autodesk Civil 3D and Devotech iDAS 2022

6.2.5 CAD OUTPUTS

6.2.5.1.1 Roads

Plan and longsection/profile drawings with north arrows, as well as cross section sheets can be generated easily using automation features as per paper size, with the option to customise the layouts being very flexible using Autodesk Civil 3D and/or Devotech iDAS. Other outputs such as setting out tables and reports can be generated as well, including a mass haul diagram, with a sample of the above-mentioned outputs portrayed below.

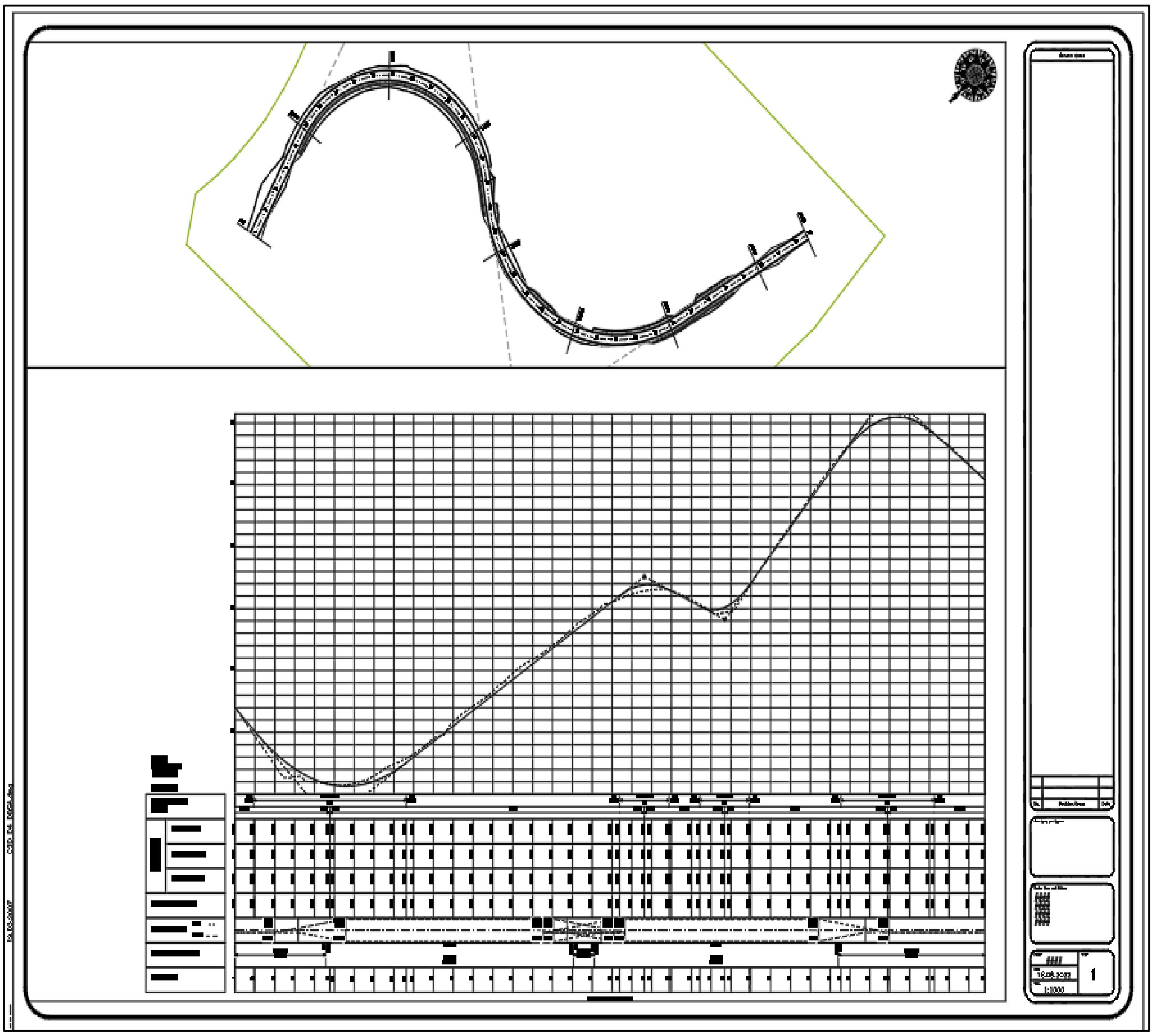


Figure 6.40: Construction Road Plan & Profile Drawing Production in Autodesk Civil 3D using the Devotech Civil 3D Template 2022
Source: Produced by Shuaib Yunos using Autodesk Civil 3D 2022

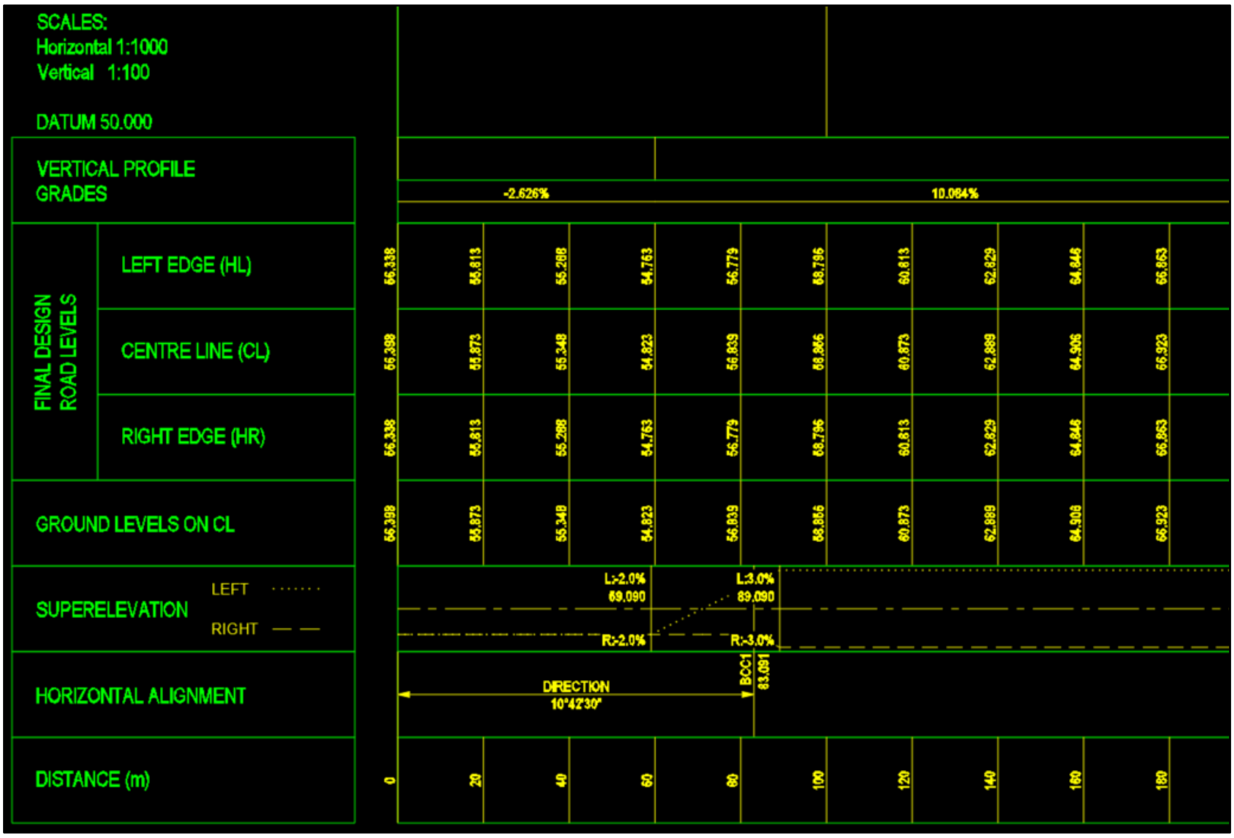


Figure 6.41: Data Bands in Long Section in Autodesk Civil 3D using the Devotech Civil 3D Template 2022
Source: Derived by Shuaib Yunos using Autodesk Civil 3D 2022

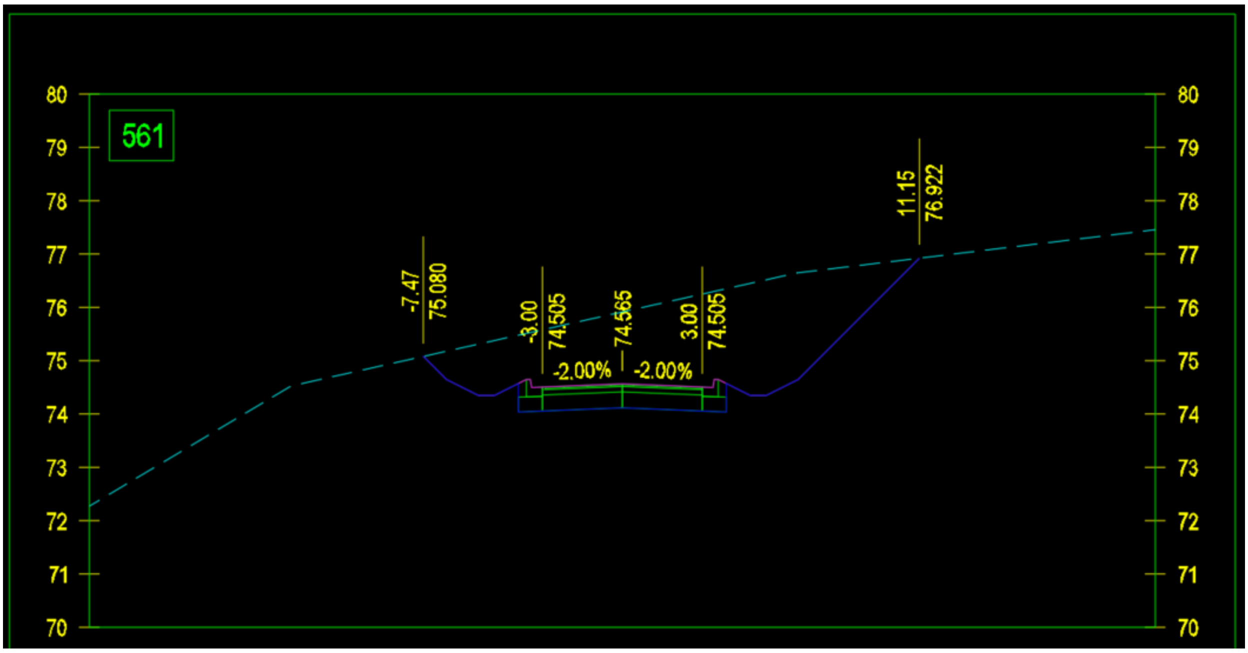


Figure 6.42: Road Cross Section in Autodesk Civil 3D using the Devotech Civil 3D Template 2022
Source: Created by Shuaib Yunos using Autodesk Civil 3D 2022

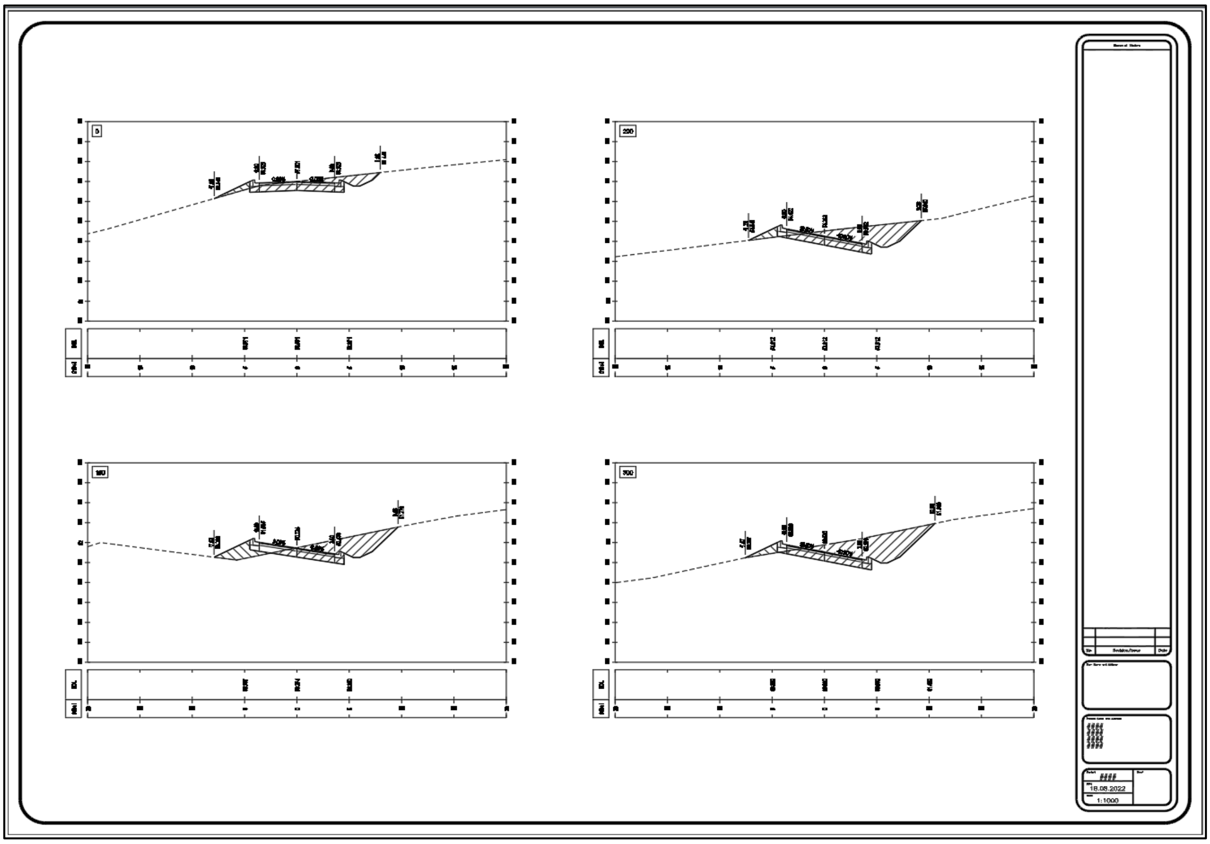
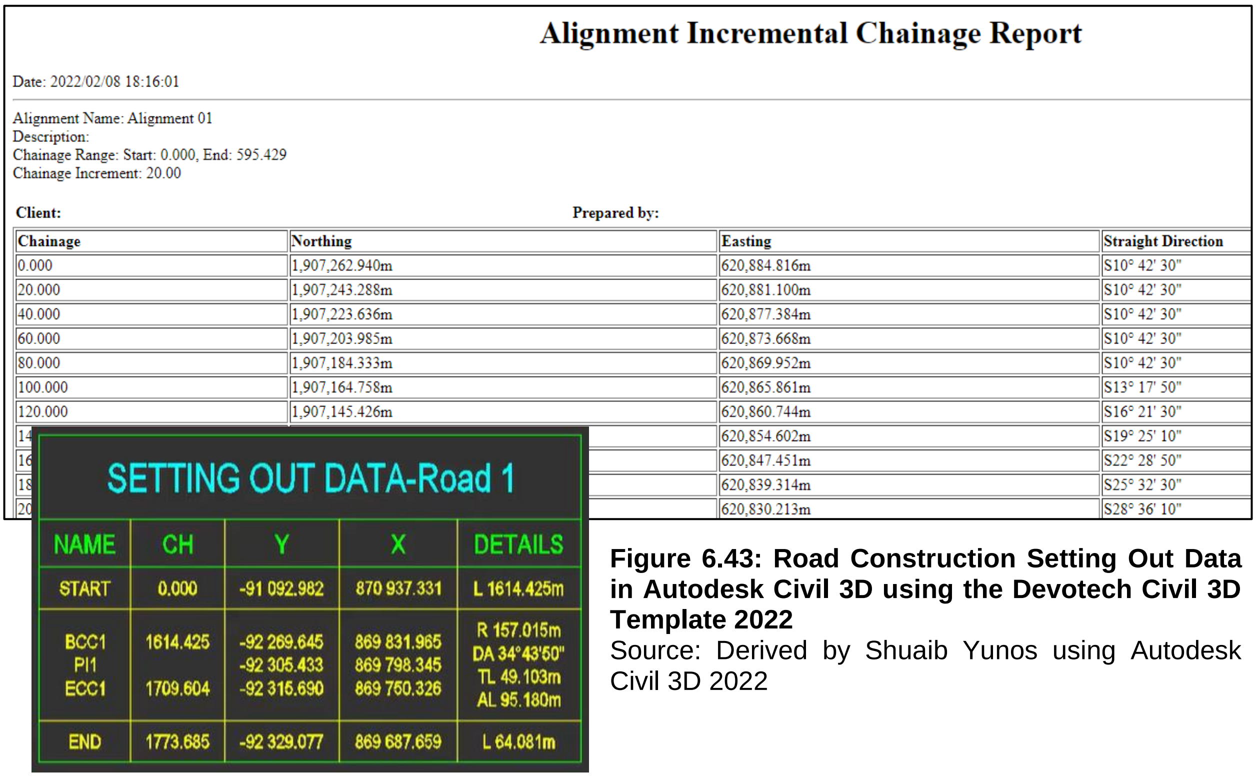


Figure 6.44: Construction Road Cross Section Drawing Production in Autodesk Civil 3D using the Devotech Civil 3D Template 2022
Source: Produced by Shuaib Yunos using Autodesk Civil 3D 2022



Alignment Incremental Chainage Report

Date: 2022/02/08 18:16:01

Alignment Name: Alignment 01
Description:
Chainage Range: Start: 0.000, End: 595.429
Chainage Increment: 20.00

Client: **Prepared by:**

Chainage	Northing	Easting	Straight Direction
0.000	1,907,262.940m	620,884.816m	S10° 42' 30"
20.000	1,907,243.288m	620,881.100m	S10° 42' 30"
40.000	1,907,223.636m	620,877.384m	S10° 42' 30"
60.000	1,907,203.985m	620,873.668m	S10° 42' 30"
80.000	1,907,184.333m	620,869.952m	S10° 42' 30"
100.000	1,907,164.758m	620,865.861m	S13° 17' 50"
120.000	1,907,145.426m	620,860.744m	S16° 21' 30"
14		620,854.602m	S19° 25' 10"
16		620,847.451m	S22° 28' 50"
18		620,839.314m	S25° 32' 30"
20		620,830.213m	S28° 36' 10"

SETTING OUT DATA-Road 1

NAME	CH	Y	X	DETAILS
START	0.000	-91 092.982	870 937.331	L 1614.425m
BCC1 PI1 ECC1	1614.425 1709.604	-92 269.645 -92 305.433 -92 316.690	869 831.965 869 798.345 869 750.326	R 157.015m DA 34°43'50" TL 49.103m AL 95.180m
END	1773.685	-92 329.077	869 687.659	L 64.081m

Figure 6.43: Road Construction Setting Out Data in Autodesk Civil 3D using the Devotech Civil 3D Template 2022
Source: Derived by Shuaib Yunos using Autodesk Civil 3D 2022

6.2.5.1.2 Bridges and Tunnels

With the intelligent BIM workflow for roads, bridges and tunnels, the structures are included in the long sections/profiles generated in Autodesk Civil 3D. When it comes to the structures themselves, the drawings and construction documentation can be created very easily in Autodesk Revit by simply dragging and dropping views at the required scale on the specified paper size, with sample of the above-mentioned outputs portrayed below.

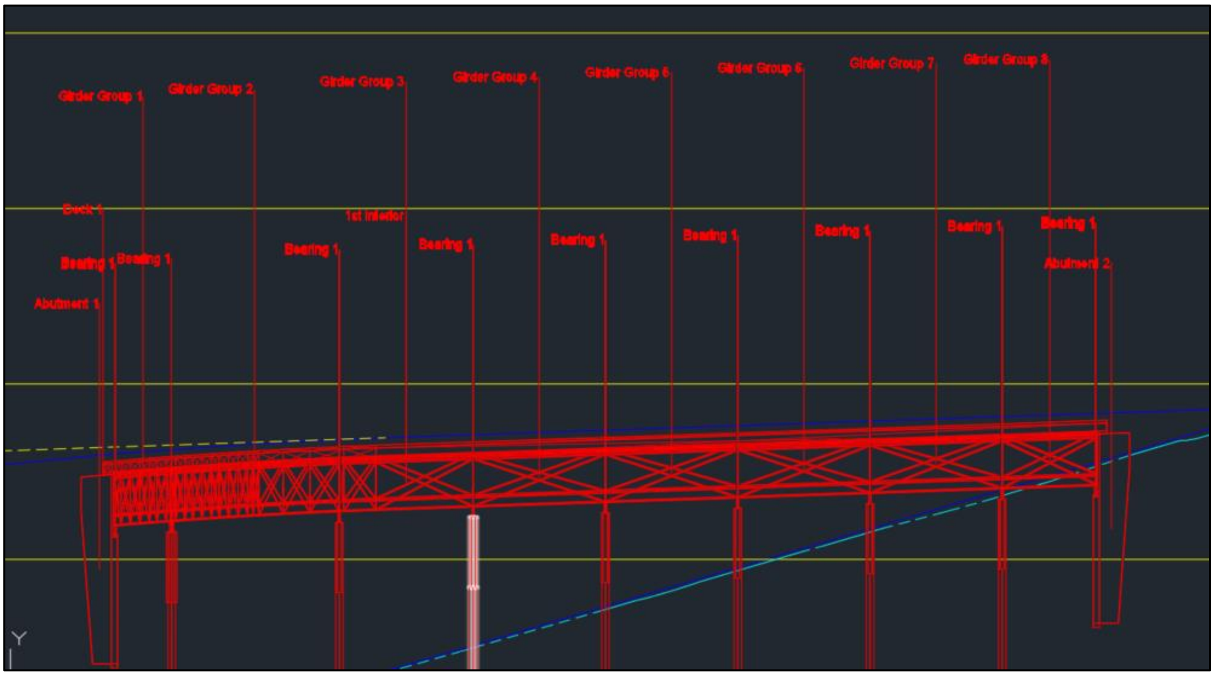


Figure 6.46: Bridge in Road Long Section/Vertical Profile
Source: Created by Shuaib Yunos using Autodesk Civil 3D 2022

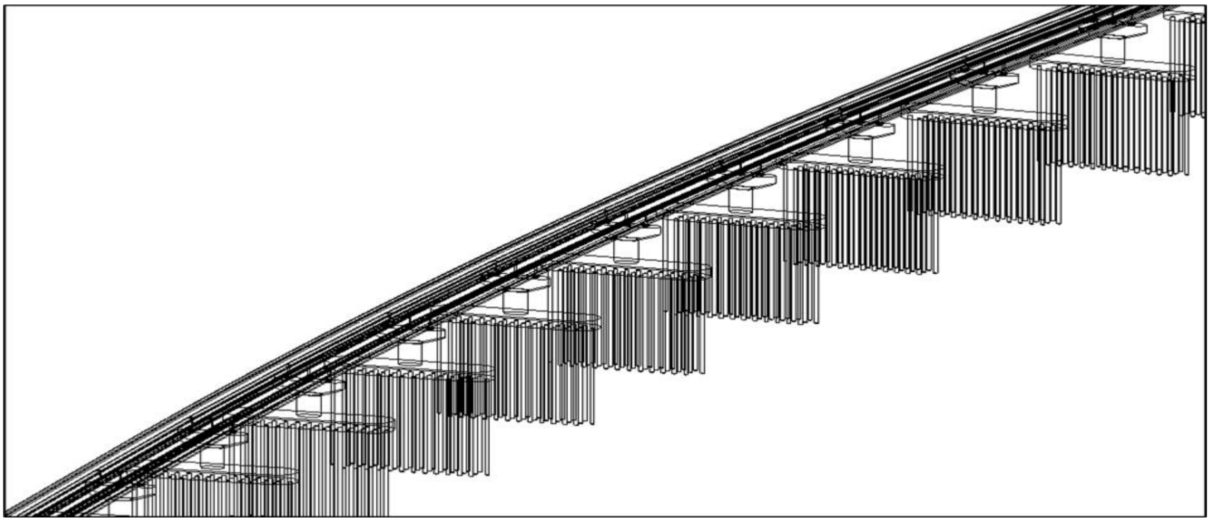


Figure 6.45: Bridge Layout in Autodesk Revit
Source: Created by Shuaib Yunos using Autodesk Revit 2022

6.2.5.1.3 Stormwater Network

The method to generate construction drawings for stormwater networks is very similar to that of roads in Autodesk Civil 3D, with the only difference being that of selecting the upstream structure and the output being that of plan and profile drawings per network branch as portrayed below.

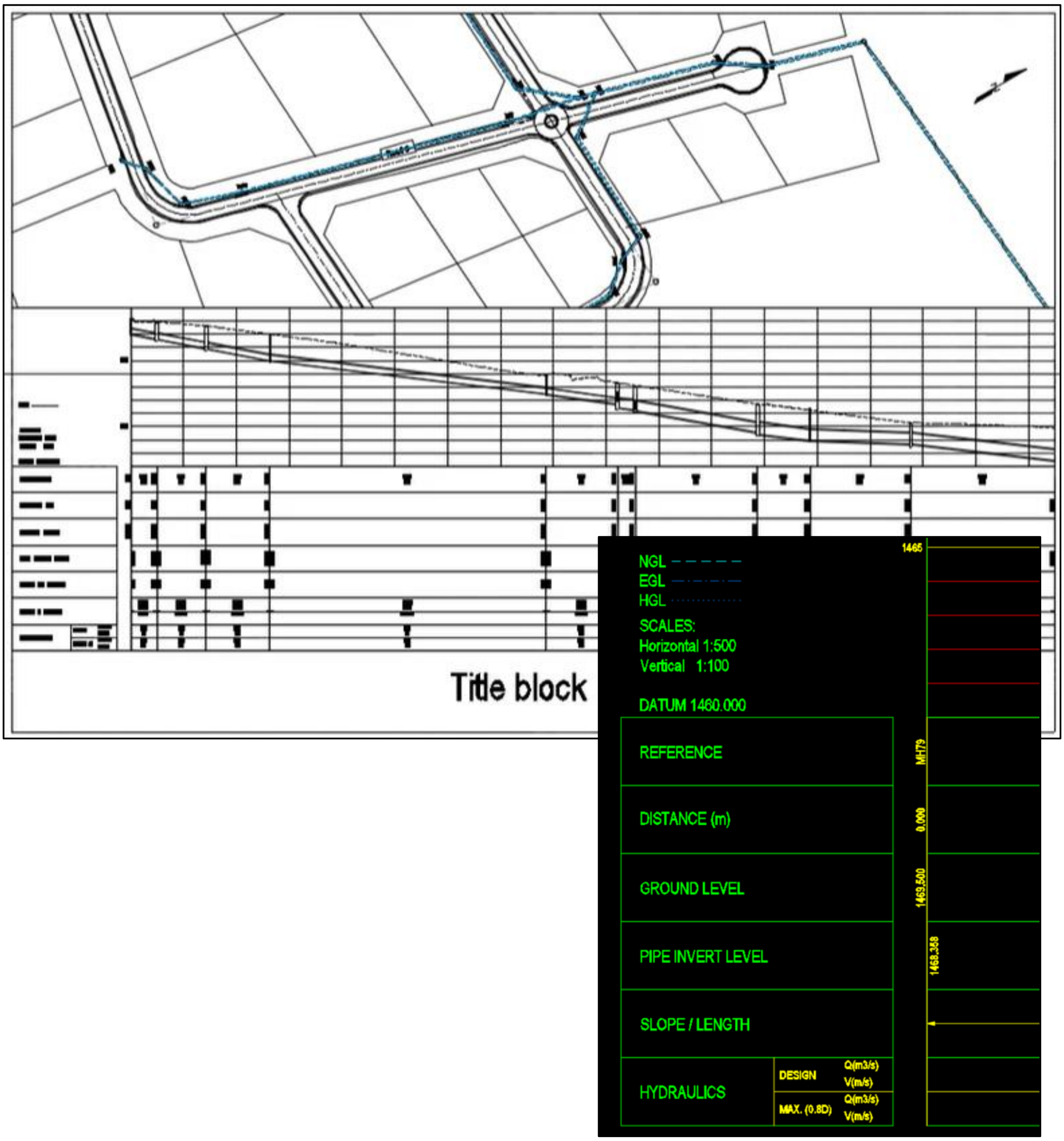


Figure 6.47: Pipe Plan & Profile Construction Drawing Production in Autodesk Civil 3D using Devotech iDAS and the Devotech Civil 3D Template 2022
Source: Devotech Group of Companies, n.db

6.2.6 VISUALISATION AND GAMIFICATION

An added advantage and by-product of BIM technologies and workflows is that of visualisation and gamification, which are very powerful tools when it comes to design review and realism. Visualisation can be applied during the proposal stage to derive compelling and highly visual and realistic model imagery and animation to help sway the bid in the consultants' or designers' favour due to the realism afforded to the client. The consultant/designer is afforded many options in this regard, depending on requirements. The most basic of visualisation and review can be conducted in Autodesk Civil 3D, which provides the opportunity to drive through a road corridor in 3D as preconfigured or custom visual styles, with a preview provided below.

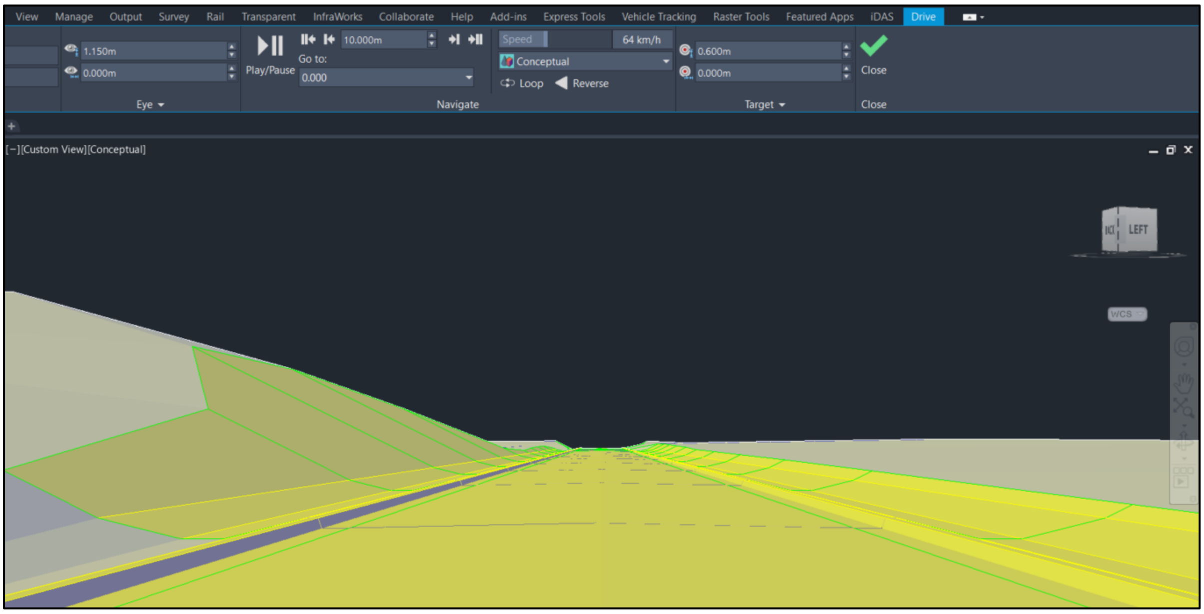


Figure 6.48: Conceptual View of Drive Along Road Function
Source: Created by Shuaib Yunos using Autodesk Civil 3D 2022

This provides a basic but great review tool when it comes to checking the final road BIM model. Another option which is becoming very popular is that of importing the finished Autodesk Civil 3D model into Infraworks. This option affords the consultant/designer a visually richer contextual experience, with the option of exporting CAD line markings generated in Autodesk Civil 3D to Infraworks and assigning the correct colours/textures. The consultant/designer can also make use of the pavement marking option in Autodesk Infraworks for roadways, as well as map the corridor components to another colour/texture/material (if required based on corridor mapping in Autodesk Civil 3D) such as lanes, kerbs, sidewalks and medians, including the option to place objects such as cars, people and associated 3D elements, as

Figure 6.49: Adding of Additional Model Elements in Autodesk Infraworks 2021
Source: Autodesk Customer Success Stories, Africa. 2021

portrayed below:

With this visual advantage, consultants/designers can incorporate visually rich and contextual model snapshots into their reports and drawing layouts. Consultants/designers can also create videos for export of their model to portray design intent or as a showcase of their portfolio, with the easiest one being a flythrough along a road alignment at a set horizontal and vertical offset, with a preview provided below.

Figure 6.50: Drive Along Road Function in Autodesk Infraworks using Keyframes to generate a Video Animation
Source: Created by Shuaib Yunos using Autodesk Infraworks 2022

The above-mentioned visualisation outputs are by far the easiest but can be taken to a much higher level of detail, such as 4K quality and advanced animation effects using Autodesk 3D Studio Max (3DS Max). 3DS Max is used to create highly realistic and compelling visualisations and animations, and is also used in the film industry, which speaks volumes with regards to the quality of output derived.

There are a variety of renderers that can be used with 3DS Max, the two most popular being VRay and Arnold. These two renderers provide outstanding realism based on the computing power used, meaning the higher the specifications of the computer, the more realistic the output, with many visualisation experts/specialists setting up render farms, which are a series of computers purely dedicated to rendering and visualisation.

Due to the above, most consultants/designers prefer Autodesk Infraworks as their go to visual solution; however, decent renders can be computed on computers with a decent graphics card and with 32GB of RAM minimum. Below is a render output using an HP Z Book Studio G3 with 16GB of RAM:

Figure 6.51: Basic Render in 3DS Max on an Entry Level Laptop using the Arnold Renderer
Source: Created by Shuaib Yunos using Autodesk 3DS Max 2022

The model from Autodesk Civil 3D or Infraworks can be imported to 3DS Max for rendering visualisations, with the option to create VR and gamification. These options of VR and Gamification are more impactful at the early stages, to see how the model is contextually in an immersive environment but can be applied once the base model is generated at any stage of the project lifecycle.

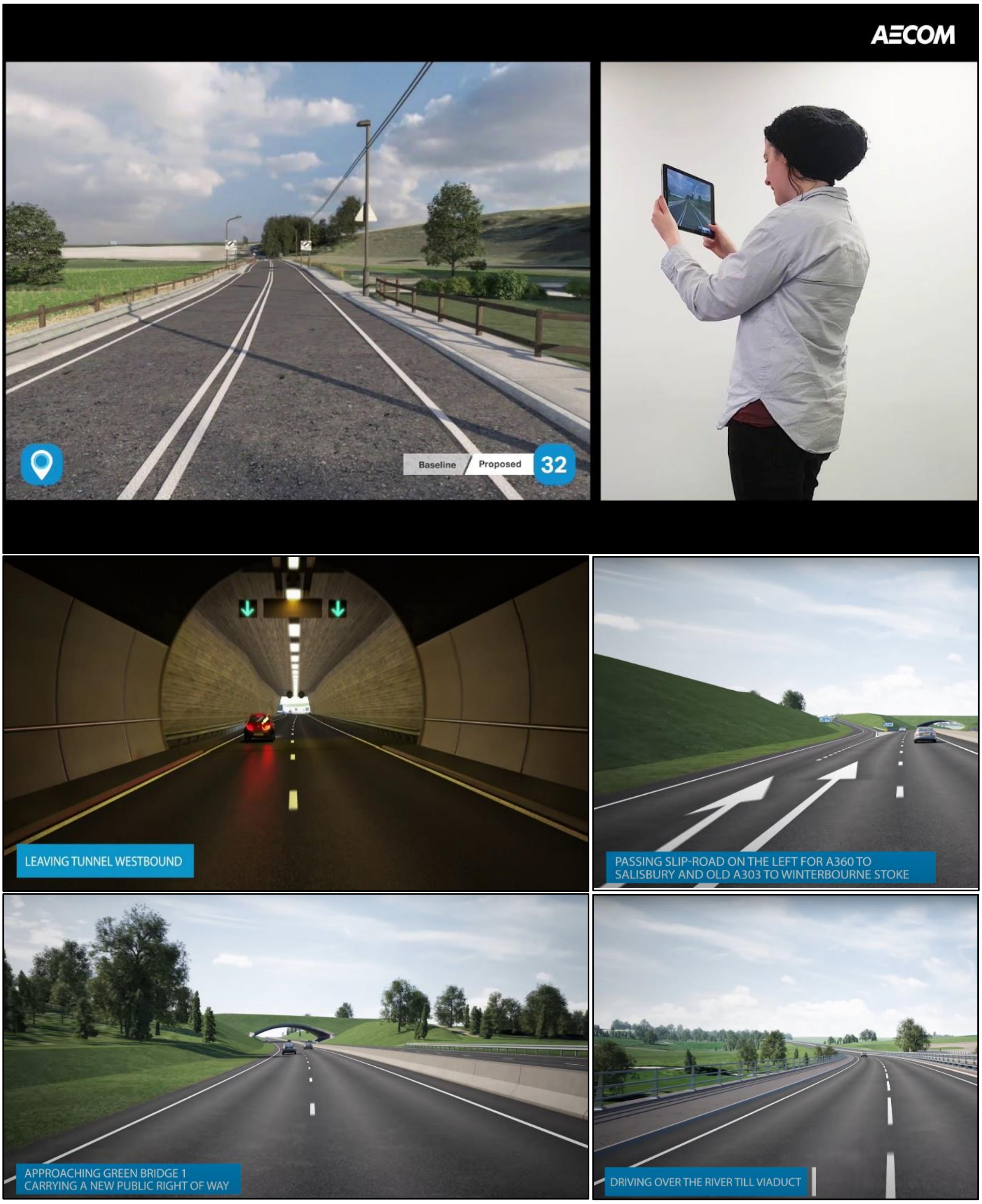


Figure 6.52: Snapshots from the A303 Stonehenge Road Model
Source: Winchester, H. 2020

6.2.7 DESIGN MANAGEMENT AND COLLABORATION

With all the above-mentioned advantages and impressive functionality provided by BIM technologies and workflows, the question of design collaboration and file management comes into play. During the COVID19 pandemic, the need to be connected from anywhere had become more apparent than ever, with technology being the only solution in effectively achieving this. This has seen a rise in development and the adoption of various cloud technologies, with one of them being the Autodesk Construction Cloud (ACC).

ACC has been popularly adopted by professionals in the AEC industry, as it provides functionality for both document and design files that can be viewed and managed in a web browser without the need to have the design software installed on your computer or mobile device. The cloud also negated the need for a VPN to link to a server, consisting of permission controls, uncapped storage, and direct integration with Autodesk BIM technologies, such as Civil 3D, Revit, and Plant 3D.

For road projects, design files can be shared on ACC via an offering called Autodesk BIM Collaborate Pro, allowing consultants/designers to share files and link them directly into their Civil 3D from the cloud, a functionality called Data Shortcuts. Data Shortcuts allow consultants/designers to link in files from other disciplines as a reference, without the ability to edit them. This is very powerful for a team working on a development site with different members responsible for different design deliverables, such as roads, stormwater, civils and structures.

From a project/team management and access perspective, administrations can set up permissions and access for users, ensuring they have access to only what is pertinent to them as required, promoting security and data access. From a document management perspective, the platform has an auto-versioning control, so that the latest version/revision is documented and highlighted, with previous versions saved should there be a requirement to revert to a previous design option.

Drawing mark ups and issues (on the road BIM model in this case) can be raised and assigned to users with a due date/deadline directly on the platform, with the assigned user receiving a push notification via email. This provides a digital paper trail of all activities, enhancing project delivery and control. With teams added and linked to projects on ACC, all data is channelled to one central location, serving as a single source of truth. Upon project creation and progression, a dashboard that can be configured or customised by asset cards or APIs can provide a bird's eye view of the progression of the project, with a preview provided below.

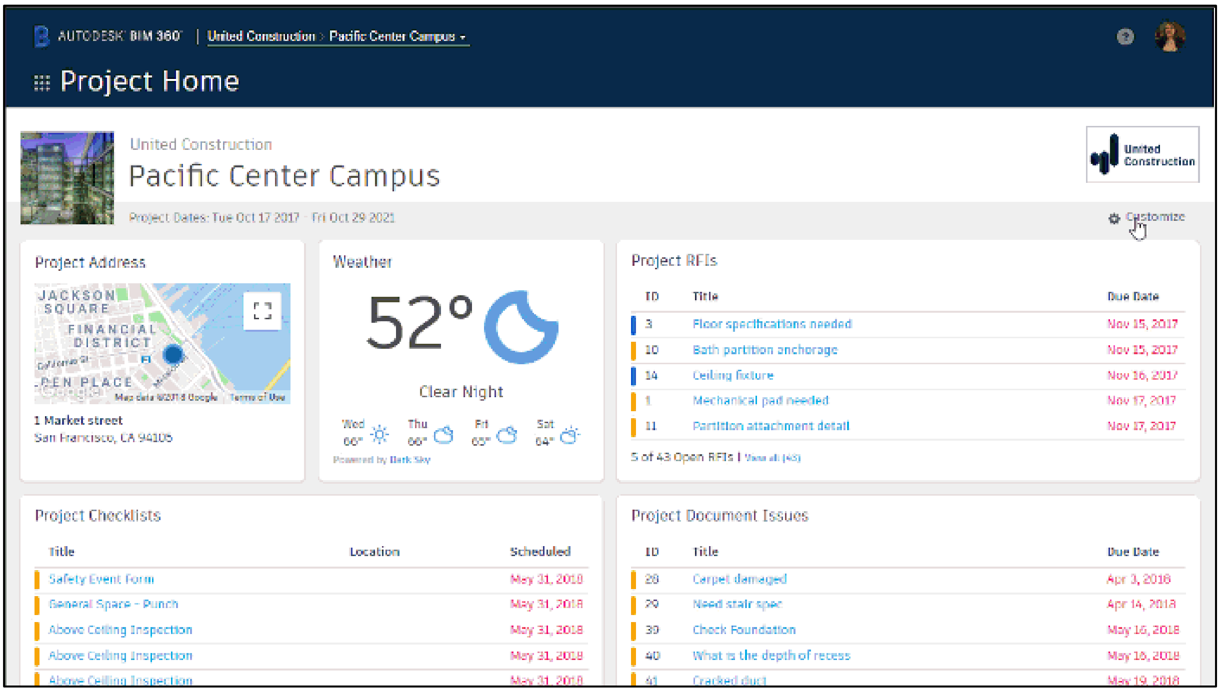


Figure 6.53: Snapshot of a Project Dashboard in the Autodesk Construction Cloud – Autodesk Document Management
Source: Autodesk Document Management

With the ACC having a range of offerings and functionality for design coordination and collaboration, AEC professionals can stay connected and in sync from anywhere in the world. The functionalities touched on above are just a few that can be reaped from the ACC solution of BIM Collaborate Pro (which comes inclusive of Autodesk Document Management from which the document capabilities are harnessed, and is included in the AEC Collection), with more functionality highlighted later in this thesis.

6.2.8 SUMMARY

With the amount of flexibility and intelligence afforded at this stage, consultants/designers can create their designs to a detailed or final construction level. This is because of the time saving, automation, intelligence and efficiencies provided by BIM and cloud technologies and the possibilities they afford the consultant/designer as early as the preliminary design stage, including the negation of data loss from the proposal stage.

It is worth mentioning that despite the focus of this thesis being on road projects, the application and methodology is very similar to other civil projects, such as railways, sewers, water, and bulk water pipelines, all of which can be achieved using the technologies highlighted thus far.

6.3 TENDER COMPILATION BY CIVIL CONSULTANT(S)

At this stage, the civil consultants are tasked with compiling the tender document required by the municipality/client. This will include the tender drawings and BOQ from the consultant with the necessary information required for contractors to bid for the project. With the BIM workflow, consultants can now put together an intelligent, confident, visual, detailed and thoroughly thought-out tender, which can give the contractor(s) a greater understanding of the project at hand.

Once the tender documentation is complete, the municipality/client will review the document and approve it should it be satisfactory. Thereafter, the project will be advertised to contractors to bid for the project.

6.4 TENDER BID SUBMISSION BY CONTRACTOR(S)

At this stage, a compulsory tender briefing will be held, with all interested contractors in attendance. Questions and concerns are raised during this meeting based on the items listed in the tender document and highlighted during the meeting. Upon completion of the tender briefing, contractors are now tasked with compiling their construction programme, BOQ, and bidding their price to construct the road.

With the incorporation of 2D and 3D drawings, the contractor has a better, practical understanding of what is to be constructed, allowing for a competitive, reasonable rate. Depending on legislature or documentation, the consultant/designer could share their outputs with the contractor for greater insight if specified, Currently, this is typically not done or deemed a requirement.

Once the bid is completed, it is submitted to the municipality, which typically has a public bid opening, and after review, appoints a suitable contractor.

6.5 CONSTRUCTION DRAWINGS ISSUED TO CONTRACTOR

As mentioned previously, depending on legislature or project documentation, the consultant/designer could share their BIM outputs with the contractor for greater insight if specified, but this is typically not done or currently, deemed a requirement in the majority of projects.

If this is the case, the consultant has provided 3D visuals to the contractor which would be immensely beneficial especially with complex roadways, something that is typically not afforded to contractors or is not an option using a non-BIM approach.

Should there be a specification for the consultant/designer to share the relevant data, not all data, as it could comprise a company's intellectual property (IP) with the contractor or should the consultant/designer and contractor come to an understanding where the data will be shared, then the contractor is afforded a plethora of benefits.

The contractor can now also immerse themselves in the BIM approach, by which the adoption of BIM and cloud technology will promote intelligent construction and project management.

From this point forward, this thesis will apply the assumption that the contractor has access to the relevant BIM data/model from the consultant/designer to illustrate how both parties can benefit from the BIM approach, creating the perfect symbiosis between design and construction teams for effective, resilient, and sustainable civil infrastructure delivery.

6.6 PROJECT and CONSTRUCTION MANAGEMENT

With the BIM approach, the contractor has both the construction drawings and BIM model supplied by the consultant/designer. In projects where this is the case, there are two scenarios:

- The first scenario is where the consultant/designer allocates seats to the contractor's team to access their ACC (the offering typically being Autodesk Build) either at a fee or no charge (depending on whether the consultant included the cost in their proposal or by understanding). This ensures that all the data is housed by the consultant/designer, with the consultant revoking their seat/access upon project completion. The consultant can do the same when it comes to other BIM software required by the contractor

- The second scenario is where the contractor has or purchases their own ACC and BIM software and depending on the type of ACC cloud offering purchased, will be invited to the consultant's ACC hub or vice versa. Should either not be invited or decide to work on their own, ACC does have a capability to share files via a public link, however, the prior option will be the best in terms of functionality, interactivity, and connectivity between both the parties.

For the purpose of this dissertation, we will apply the first scenario. With the contractor's team having access to BIM technologies and being added to the consultant's ACC for the road project, the construction phase can now be infused with BIM and cloud processes. After analysing and reviewing the data/elements within the site extents of the roadway, the contractor has the option of 5D construction scheduling and simulation using Autodesk Navisworks Manage. This BIM solution is popularly adopted for clash detection and construction scheduling by incorporating the 3D model of the road exported as CAD solids from the BIM model using Autodesk Civil 3D with the contractor's construction programme or schedule. In most cases, the consultant/designer shares only the 3D solids from the BIM model with the contractor which they can download via ACC, with only view access assigned to the contractor for the BIM model itself to protect the company's IP. The model solids are then mapped according to the construction schedule based on time (4D), with the option to include cost (5D), and the preview is provided below.

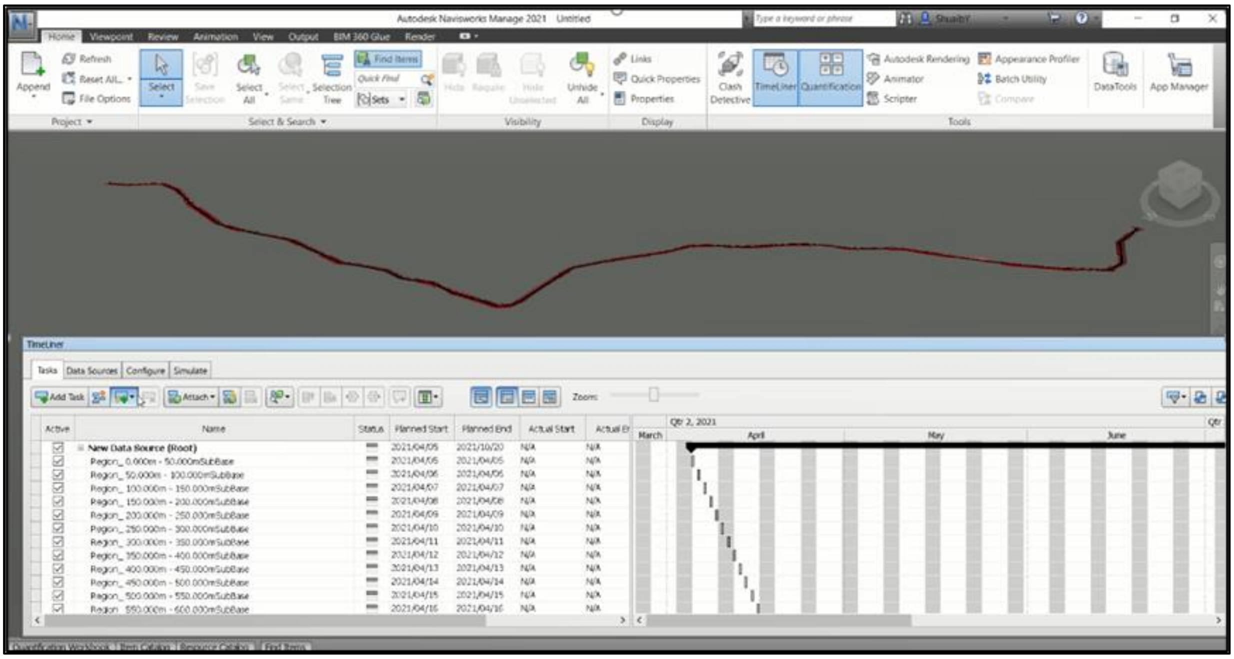


Figure 6.54: 4D Construction Scheduling of a Roadway by Linking 3D Model to Construction Schedule
Source: Created by Shuaib Yunos using Autodesk Navisworks 2022

This game-changing BIM functionality affords the contractor the opportunity to simulate and review their construction process/methodology before construction can commence, allowing for further tweaking or scheduling of tasks for faster and more efficient delivery, with the goal of completing the construction comfortably within the specified duration. The contractor can also use this simulation to adjust tasks based on delays or other factors experienced during the construction phase to be on top of delivery, with the added option to compare planned versus actual progress on site, to further optimise delivery and construction management.

When it comes to site logs and daily occurrences, activities and communication on site, the contractor can communicate with their construction/site teams using Autodesk Build. Autodesk Build affords the contractor the same document capabilities experienced by the consultant/designer, with specific functionality required by the construction teams, such daily site logs, meeting minutes, a construction focused dashboard, as well as the capability to create lists such as quality, safety, snags and punch lists, all paperless and easily accessible from a mobile device, with a few examples illustrated below.

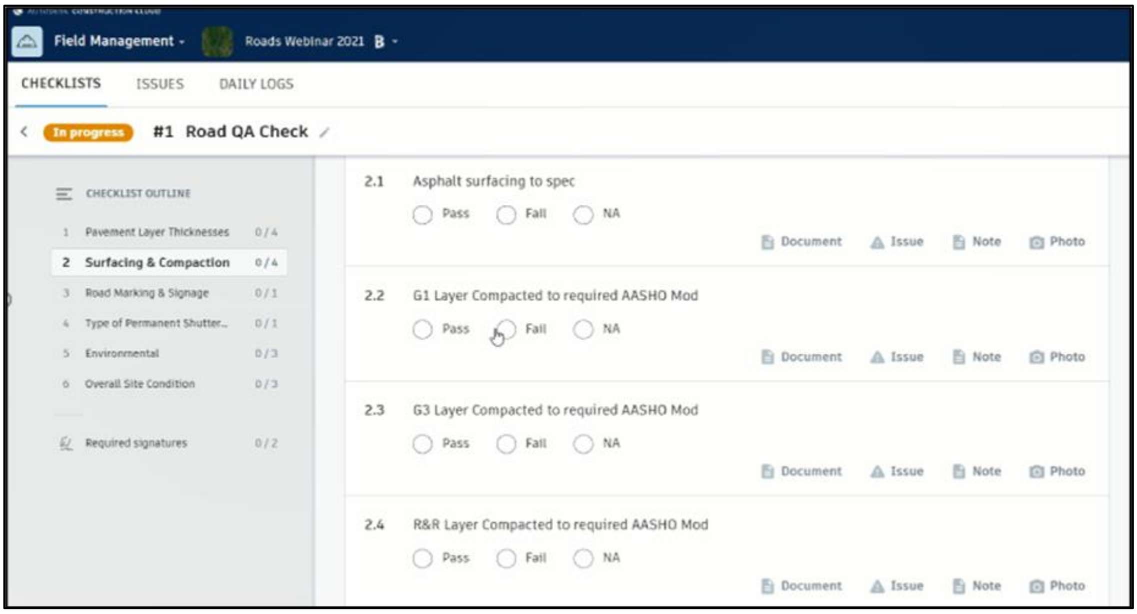


Figure 6.55: Road Quality Assurance Checklist
Source: Created by Shuaib Yunos using Autodesk Build

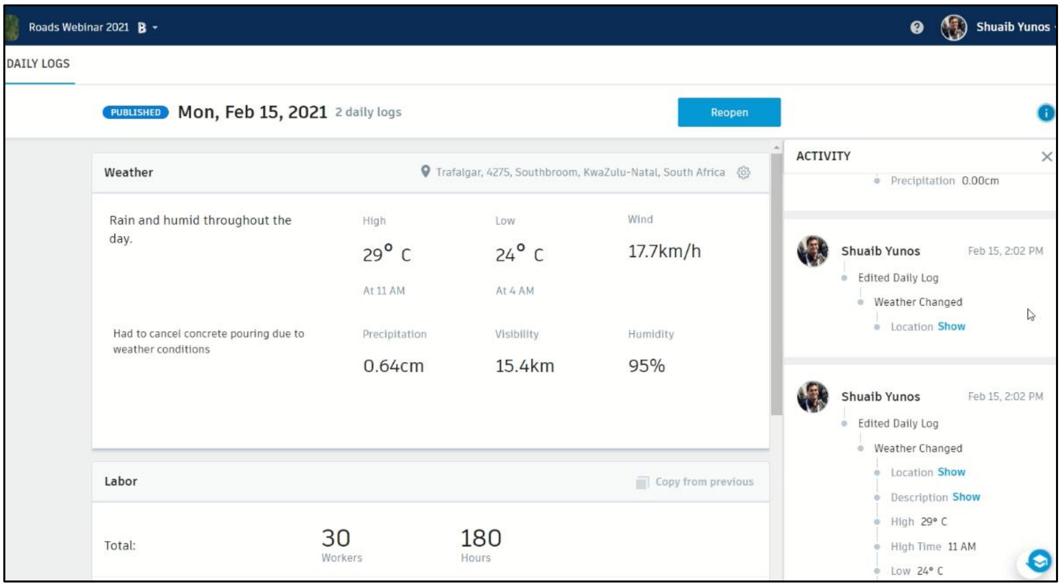


Figure 6.56: Site Conditions & Labour Logging
Source: Created by Shuaib Yunos using Autodesk Build

When it comes to communicating with the consultant, the contractor can reach out to the consultant's team on the same ACC platform, especially when it comes to requests for information (RFIs) and submission of claim certificates for approval. This ensures that the RFI reaches the pertinent personnel as soon as it is logged, with the contractor having the option of attaching images from the site as well as pinning the location on the design model, which when selected, zooms to that location on the model, ensuring there is no ambiguity.

Items that require approval from the consultant, such as claim certificates, can be approved by the relevant personnel by creating an approval workflow. This process is typically created by the consultant, incorporating the required approvers and the contractor. Upon submission by the contractor, push notifications are sent to the required approvers for review and comment, with the option to reject or approve the submission, and the contractor is notified immediately the process is complete.

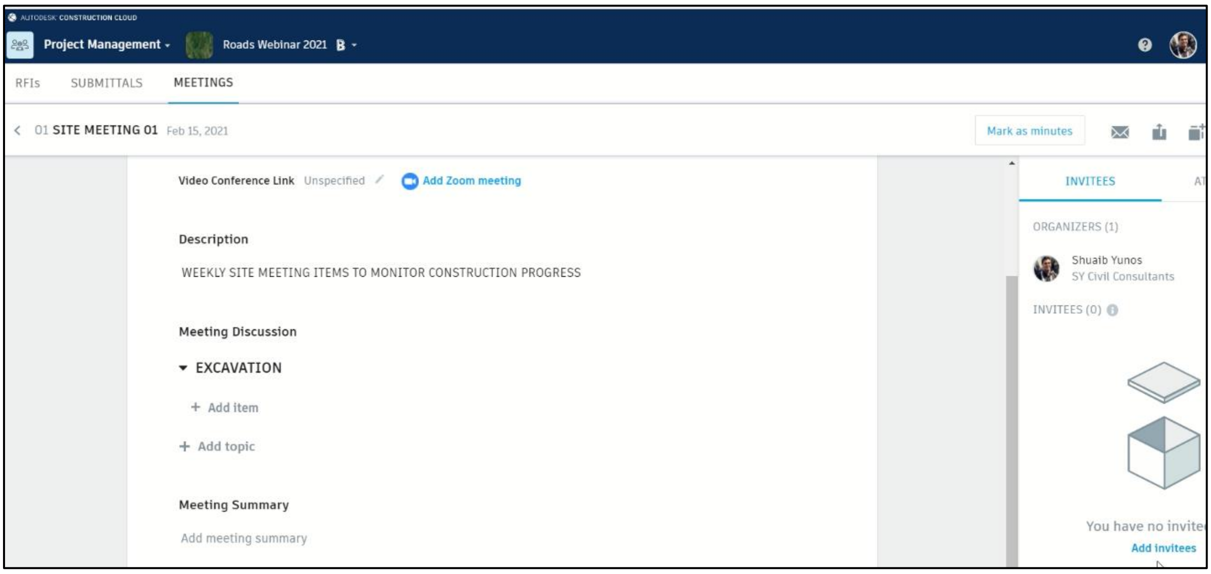


Figure 6.57: Site Meeting Scheduled including Agenda
Source: Created by Shuaib Yunos using Autodesk Build

With all of these construction and project management functionalities afforded to the contractor by BIM and cloud technologies, construction disputes, errors, clashes, and bottlenecks can be reduced or avoided completely, resulting in effective project execution and service delivery within the allocated duration of the construction.

6.7 PROJECT CLOSE-OUT AND HANDOVER

At this stage, the construction of the road or project is now complete. The consultant is required to inspect the completed construction site and prepare a project close-out report detailing the construction aspects and relevant information. With the use of BIM and a CDE, the pertinent data required to be included in the report is easily found and accessible. In conjunction with this report, the consultant is required to produce as-built drawings for the road, which serve as a means to provide the accurate information about the constructed asset.

Thanks to the BIM workflow, consultants have a few options they could explore and apply with regards to generating the as-built BIM model of the roadway:

- The road centerline and associated road profiles such as edge of lane profiles can be captured by the surveyor, then imported to Autodesk Civil 3D design drawing, thereafter, replacing the design profiles with the as-built data, updating the corridor and saving the file as a separate copy. The drawing layouts will update, and the consultant will be required to edit the relevant title block data and print the as-built drawings.

- Reality capture could be applied, thereafter using the linear extraction feature in Autodesk Infraworks to extract lane elevation profiles. Once this is done, the model can then be taken to Autodesk Civil 3D, and the steps highlighted previously for road corridor modelling.

- Start a new drawing from scratch, import the site data and then the as-built data captured by the surveyor, followed by the steps previously highlighted for road corridor modelling.

Whichever method is applied, the consultant/designer will derive an as-built BIM model of the roadway. The as-built drawings are then supplied to the client/municipality, with the BIM model being supplied either by contract stipulation, free value add or an additional charge.

6.8 ROAD OPERATIONS AND MAINTENANCE

At this stage, the municipality/client is responsible for ensuring the efficient operation and maintenance of the road is upheld. Any form of damage, deformation, deterioration, hazards, or potholes is typically reported by the community which the road serves.

This process or methodology can be described as reactive rather than proactive; waiting for the road to deteriorate beyond the point at which it could be an endangerment to life or unusable and then only taking the correct reactive actions to remedy the situation, which is not ideal. Depending on the effectiveness of this methodology or the capacity of the municipality/client, this process could prove to be manageable. However, in most cases, it is seen as an area that is lacking in terms of the effective upkeep of civil infrastructure.

This results in the neglect of roads over their design life, which results in the road not achieving its full design life and level of service, which in turn translates into the ineffective use of the taxpayer's money and non-resilient infrastructure. Over time, the road may serve out its designed life or not. Depending on the operations and maintenance plan implemented, the roadway might be required to be upgraded or rehabilitated. This then results in the municipality/ client in advertising for proposal from suitable consultants and the process starts over again.

BIM plays a pivotal role in the operations and maintenance phase of a roadway. As mentioned in the previous section, the BIM model may be a required deliverable or not. For the purpose of this thesis, we will apply the assumption that the as-built BIM model is supplied to the client/municipality to illustrate its effectiveness in the operations and maintenance phase of a roadway. Should the roadway require remedial action, the as-built BIM model can be utilised in Autodesk Civil 3D in conjunction with the elevation data captured by the surveyor of the deteriorated road, a functionality called Road Rehab. This function compares the as-built levels to the as-is levels of the deteriorated roadway, providing an accurate rehabilitation approach as portrayed below.

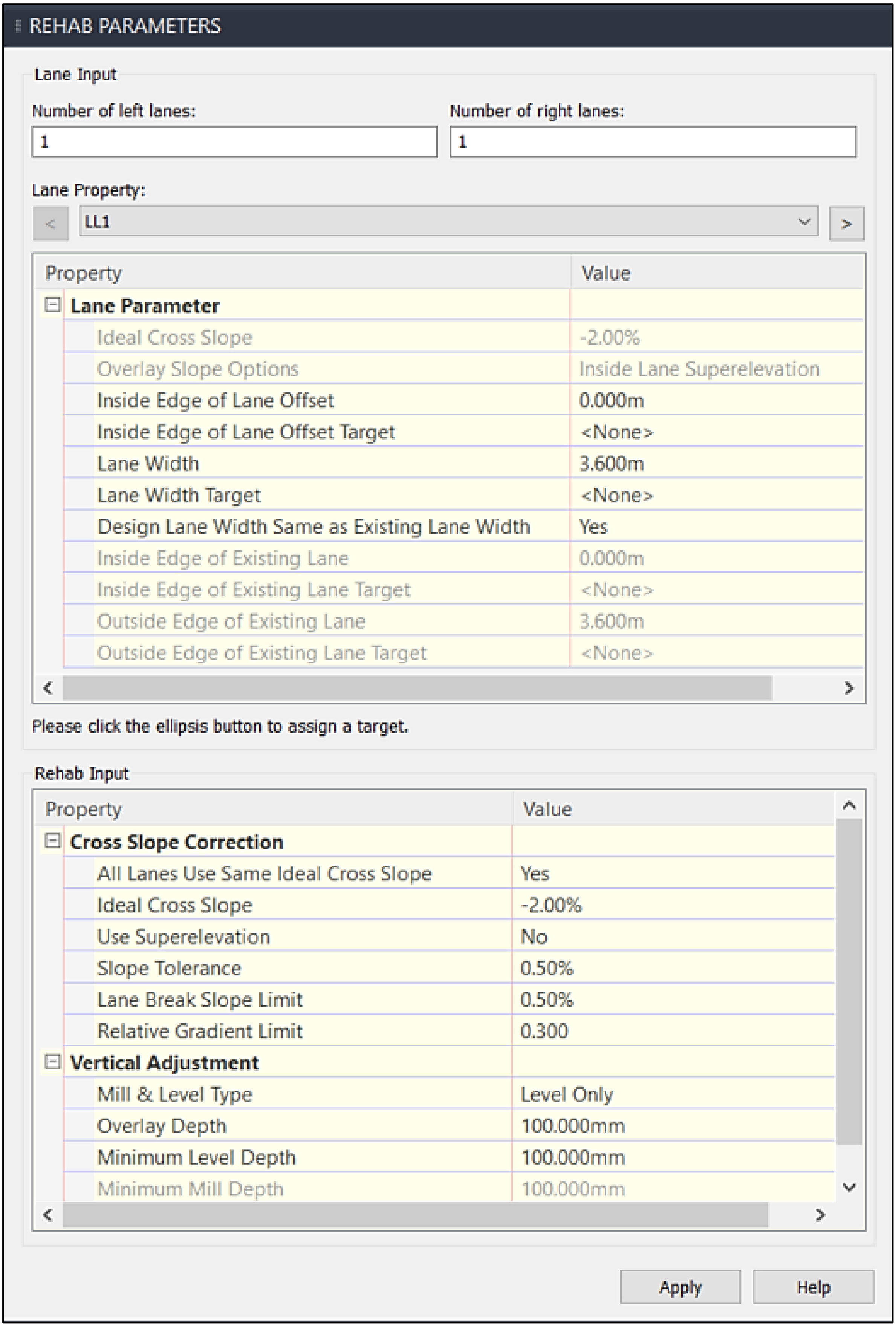


Figure 6.58: Road Rehabilitation Design Menu with options to Level Only, Mill Only or Mill & Level
Source: Autodesk Civil 3D 2022

This methodology provides accurate quantification and contextual remedial action that is efficient. The best method of maintaining a road effectively is by means of digital twinning via the internet of things (IoT). This futuristic, intelligent, and insightful method involves the BIM model being the digital replica of the roadway, forming the foundation for sensory and mass data collection to create a living virtual representation of the roadway (a digital twin), which will be explored in the next chapter of this dissertation.

7. DATA ANALYSIS AND FINDINGS

7.1 SUMMARY OF FINDINGS

On comparison of both traditional and BIM approaches across the road project lifecycle, it is apparent that BIM is the more intelligent, efficient, and economical approach, aligning closely if not perfectly to the MacLeamy Curve, with the following main benefits.

- Proposal preparation and submission by civil consultants are more intelligent, efficient, and economical, affording the consultant with versatility to provide design options, 3D visuals and terrain/elevation data that is reusable and dynamic.

- 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.

- BIM enables consultants to be more creative and competitive, increasing their chances of winning a bid, whilst providing greater insight and tools for contractors to schedule and manage their construction programs.

- 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 integrated into the design easily, with enhanced coordination and analysis capabilities.
- Quantification is automated and dynamic, resulting in an accurate BOQ.

- 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 ecosystem available, provide an unprecedented advantage, in which teams can be connected and collaborative from any part of the globe.

- Clash detection can be executed before hitting 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 adequate and accommodating.

- VR, 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-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.

- BIM provides the basis for futuristic and innovative asset management, fulfilling the foundational requirement to digital twinning by providing a digital replica of the future virtual asset.

7.2 BIM, DIGITAL TWINNING AND SMART CITIES

7.2.1 BIM vs DIGITAL TWINNING AND SMART CITIES – WHAT IS THE DIFFERENCE?

In 1991, David Gelernter, an American computer scientist, published a book titled "Mirror Worlds", which proposed the concept of digital twins (DTs). Just over a decade later, Dr Michael Grieves was credited with the first use of digital twins in manufacturing and his formal announcement of the digital twin software concept in 2002 at a Society of Manufacturing Engineers conference in Troy, Michigan, proposing the digital twin as the conceptual model underlying product lifecycle management (PLM). Thereafter, in 2010, the first practical definition of "digital twin" originated from the National Aeronautics and Space Administration (NASA) endeavouring to improve the physical model simulation of their spacecraft, with NASA's John Vickers coining the phrase "digital twin” in a 2010 Roadmap Report, which is commonly used today (IBM, n.d).

The DT market is expected to be valued at USD48.2-billion by 2026 (MarketsandMarkets, 2020), with the topic increasing in interest across industries, especially the AEC industry, as portrayed below.

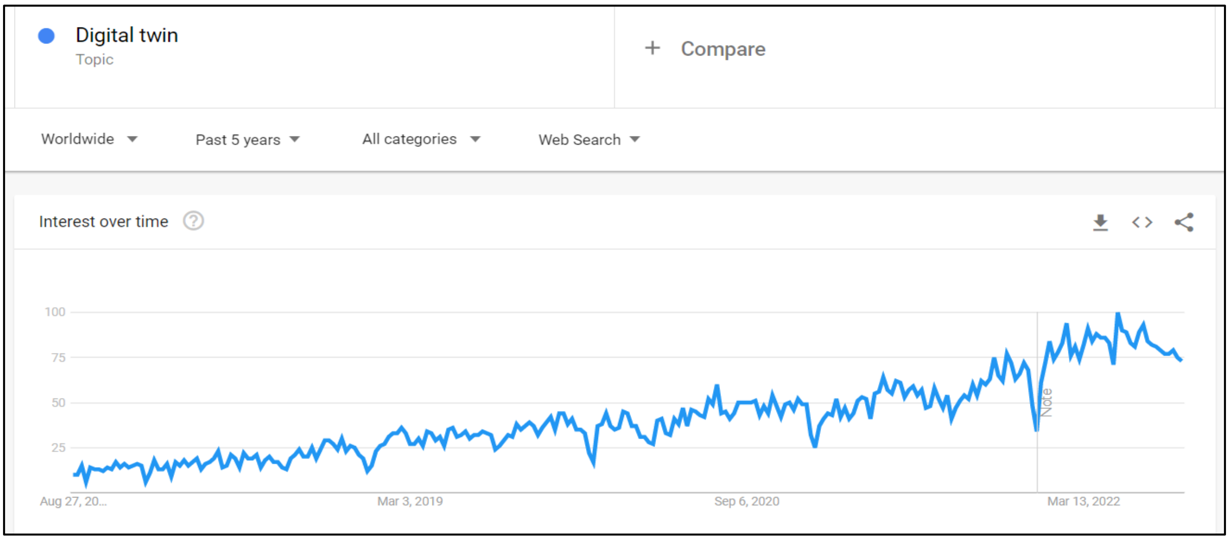


Figure 7.1: Interest in Digital Twins over the Past 5 Years
Source: Google Trends, 2022

With the acceleration in BIM workflows, processes and technologies and the presence of digital twins in the AEC and PDM industries, a common misconception has surfaced expressing that BIM equals Digital Twinning. BIM does not equal a digital twin, but rather is the most effective and efficient path to achieving a digital twin, with the BIM model serving as the starting block or foundation for the journey ahead.

With BIM providing the digital replica, the internet of things (IoT) forms the critical component required in converting the digital replica to a virtual, living asset, namely, a digital twin, which serves as the real-time digital counterpart of a physical object or process. An IoT ecosystem can consist of artificial intelligence (AI), machine learning (ML), software analytics with special network graphs, as well as web-enabled smart devices that use embedded systems, such as processors, sensors, and communication hardware, to collect, send and act on data they acquire from their environments (Industry 4.0).

Therefore, a DT equates to smart cities, which BIM alone cannot. The BIM process incorporates data created during the planning and design phases, with a digital twin extending data capture to the construction and operational phases of the asset, which can also inform planning and design for future projects.

DTs inform the intelligent expansion, operations and maintenance of a smart city. A holistic definition of a smart city, as defined by Carshif Talip (Leader for Urban Planning Land Infrastructure, Zutari), is a city where opportunity, amenities, safety, resilience, inclusivity, and prosperity are imperatives, and innovation across financing, design, construction, operations, and governance is embraced by all stakeholders to achieve these imperatives. The emphasis on digital platforms also enables data collection, and the availability of large data sets is one of the first steps towards optimisation.

From a technical standpoint, a smart city is a city that uses technology to provide services and solve city problems. The main goal of a smart city is to optimise city functions and promote economic growth while also improving the quality of life for citizens by using smart technologies and data analysis. By digitising and creating a living virtual representation of major infrastructure and contributing factors in a city, IoT, mass data and data analytics provide enhanced insights and decision-making to

ensure the best or optimal options are implemented relative to citizens, resources, environment among other factors with a brief description of the near
and long-term impacts portrayed below.

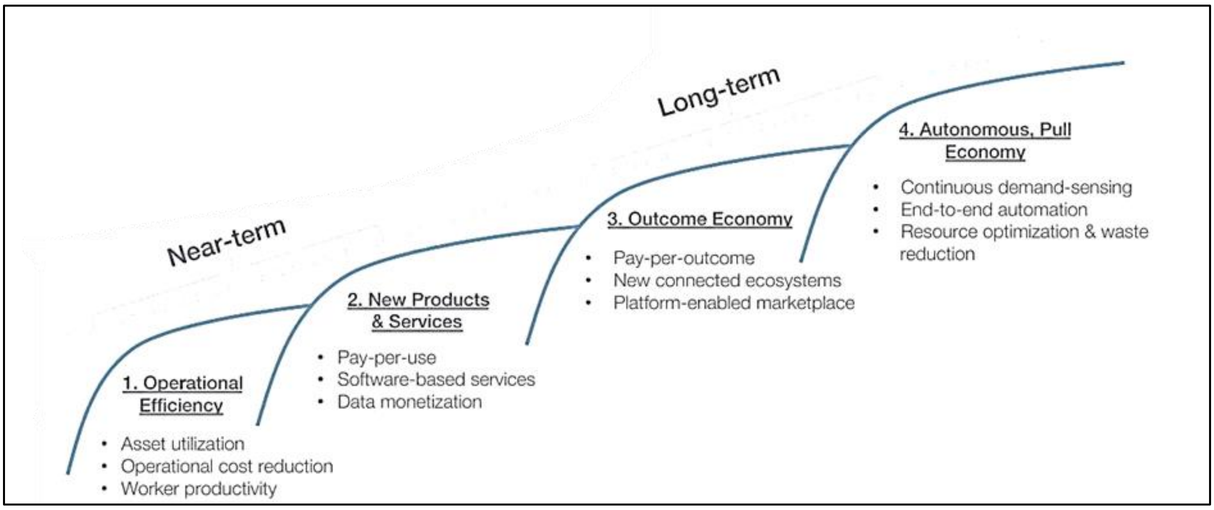


Figure 7.2: The Adoption & Impact of the Industrial Internet
Source: Arenas M, 2016

Across many works of literatures, the number of indicators/criteria suggested to gauge the true smartness of a smart city varies, with the six key smart city indicators portrayed below:

Figure 7.3: Six Key Smart City Indicators
Source: Bee Smart City, n.d.

Despite the variation in terms of indicators across the different pieces of literature, the component of smarter roads and public transportation (commonly referred to and falling under the term "Smart Mobility") is always included in them all, seen as a critical infrastructural component in the pursuit of a true smart city. With roads playing a critical role in the way cities interact and operate on a day-to-day basis, DTs for road networks can transform the way we tackle current and future challenges, with the next section focusing on the major benefits of DTs on a holistic level, as well as for road networks.

7.2.2 DIGITAL TWINNING – WHAT ARE THE BENEFITS?

7.2.2.1.1 Major Holistic Benefits

As established in the previous section, BIM is the foundation for the effective creation of an accurate, high-value DT. With BIM providing the industry with a variety of benefits, smart cities informed by DTs further compound these benefits, with the major benefits being as follows:

- Smarter product and/or process design, efficiency, testing and simulation, and manufacturing.
- Smarter research and development (R&D) for improved insights, processes, outcomes, optimisation, and deliverables.
- Smarter computational troubleshooting for risk and disaster management.
- Smarter Predictive/preventative maintenance contributing to smarter longevity.
- Smarter team collaboration and decision-making due to live, dynamic loops of data.
- Smarter energy and environmentally friendly optimisations and alternatives, including the effective management of natural resources.
- Smarter financial and economically impacting decisions and problem-solving for leaner, sustainable solutions.
- Smarter insight and transparency due to all interconnected factors feeding into a live dashboard for intelligent mass data management, computation, optimisation, and analysis.
- Smarter security and surveillance, promoting and enhancing safety/crime and/or risk management.
- Smarter, greener outcomes and deliverables that are leaner, cost-effective, and sustainable, as well as contribute to a healthier, reduced, or non-polluted clean environment.
- Smarter, faster, and streamlined infrastructure/service delivery and management contribute to a greater quality of life for citizens.

As can be seen above, DTs play a pivotal role in promoting the overall benefits above across various industries, with the specific benefits to roads listed in the next section.

7.2.2.1.2 Major Benefits Specifically For Road Networks

When it comes specifically to roads, road infrastructure due to their linear nature traversing across long lengths/distances can be difficult to manage, operate and maintain. DTs for roads boast the following possible benefits:

- Smarter, effective traffic/mobility modelling, analysis and management promoting efficient road commuting and a reduction in emissions for a greener environment.
- Smarter predictive/preventative road maintenance from live loops of data or repairs/incidents logged by citizens, being proactive and calculated rather than reactive and delayed.
- Smarter simulation and analysis for pavement deformation, stresses and behaviour promoting longevity, sustainability, as well as contributing to further R&D for enhanced design and construction for future projects/pavements.
- Smarter expansion and planning (road master planning) for future development, road corridor identification and routing based on mass data analysis.
- Smarter safety and response to accidents by identifying possible danger zones, reducing danger zones/conflict points, as well as monitoring road surface conditions and stormwater systems.
- Smarter security and surveillance, promoting and enhancing safety/crime and/or risk management.
- Smarter financial and economically impacting decisions and problem-solving for leaner, sustainable solutions, and socio-economic growth.
- Smarter and innovative optioneering using computational analysis (including AI and ML) such as regarding energy generation in the storing of kinetic energy from traffic for suitable use, piloting and generating entire road lanes or road lane segments using solar panel/energy technology to harness and harvest energy, reuse of stormwater runoff, and other methods.

As time and technology progress, much more will be achievable by DTs, which is a critical transition required for effective management, operations, and maintenance of civil infrastructure for present and future population demand, contributing to a smarter, enhanced quality of life.

7.2.3 DIGITAL TWINNING and IoT FOR ROADS – WHAT IS POSSIBLE

With DTs most popularly applied/created in the mechanical, plant and built environments, some inroads have been made for road networks, with four possible applications and case studies showcased below.

7.2.3.1.1 Road Conditions Monitoring – Chapman's Peak Drive, South Africa

One of the most critical factors in road infrastructure is that of safety and road operational efficiency, especially for roads that traverse mountainous areas or pass-through areas posing a potential threat due to environmental and weather conditions. With IoT and digital twinning, these situations could be identified and addressed earlier rather than later using predictive and/or preventative monitoring and maintenance. This concept is being delved into by the department of Civil Engineering at the University of Pretoria (UP) in South Africa.

The university is experimenting with IoT technology that could serve as an early warning system for dangerous road conditions (de Vries, 2022). Professor Wynand Steyn, head of the UP Department of Civil Engineering, says South African authorities could use IoT network systems to detect dangerous road conditions in advance, using Chapman’s Peak Drive in Cape Town as a reference.

Professor Wynand highlighted how a grid of accelerometers and moisture sensors could be used in an area such as Chapman's Peak Drive, where heavy rainfall typically results in loose debris on the road. With this advantage of IoT network systems, detection/prediction of when slope failure is likely to occur can be established beforehand (proactively rather than reactively), enabling SA authorities to close identified risk areas earlier and promoting proactive risk management. Sensors can also be used in pavement monitoring; Steyn’s team uses sensors embedded in the road to study the thermal characteristics of paving materials and investigate road cracking.

7.2.3.1.2 A Transportation Digital Twin Approach For Adaptive Traffic Control Systems

With the rise in ownership of private vehicles, traffic congestion has become a common, persistent challenge to urban/city planning and transportation systems. With this in mind, a proof of concept looking at a DT approach for adaptive traffic signal control (ATSC) had been explored (Dasgupta et al. 2021) to improve a traveller's driving experience by reducing and redistributing waiting time at an intersection.

With the traditional ATSC combined with a connected vehicle concept being ineffective in reducing traffic delay for congested traffic conditions, a DT-based ATSC was generated, which considered the waiting time of approaching vehicles towards a subject intersection along with the waiting time of those vehicles at the immediate upstream intersection, with Dasgupta et al.'s (2021) concept illustrated below.

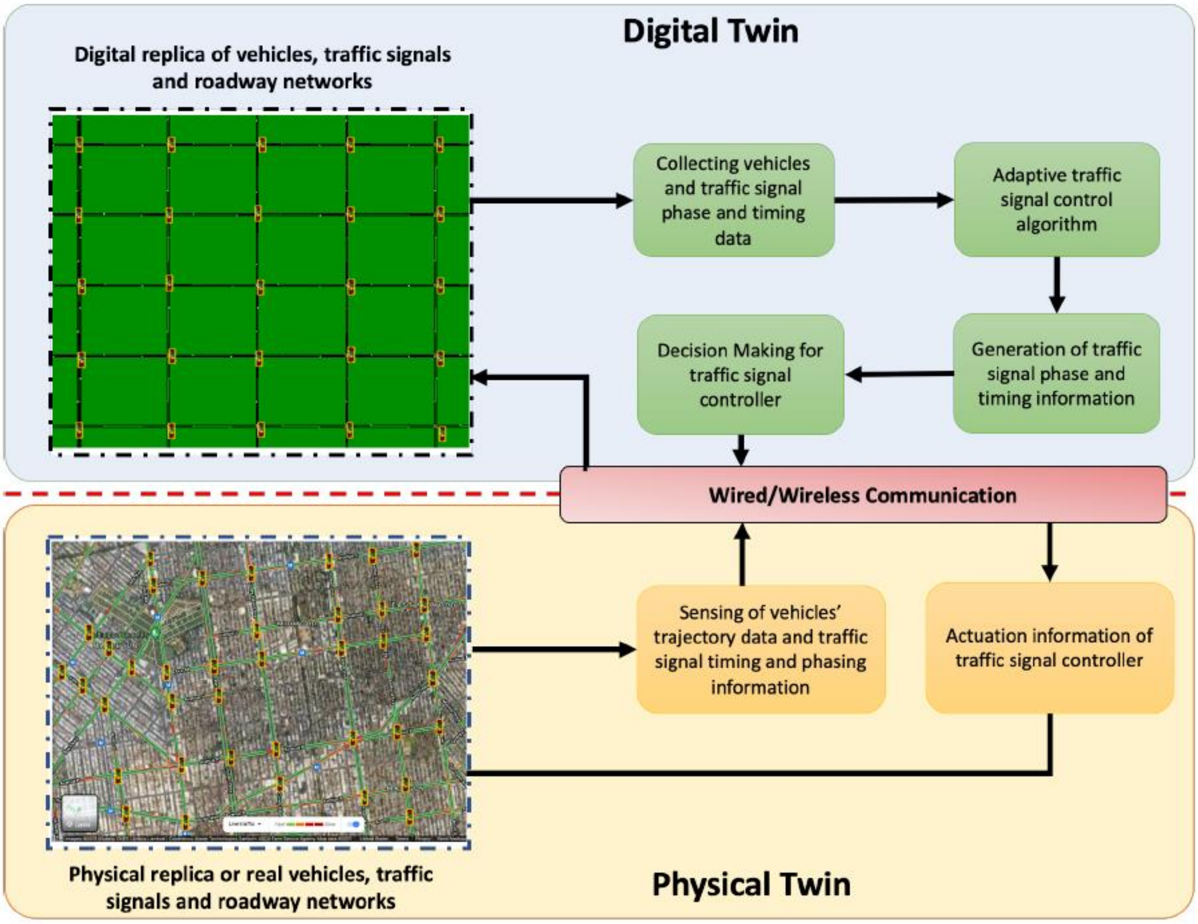


Figure 7.4: Twining of Digital and Physical Space of Adaptive Traffic Signal Control Systems
Source: Dasgupta et al. 2021

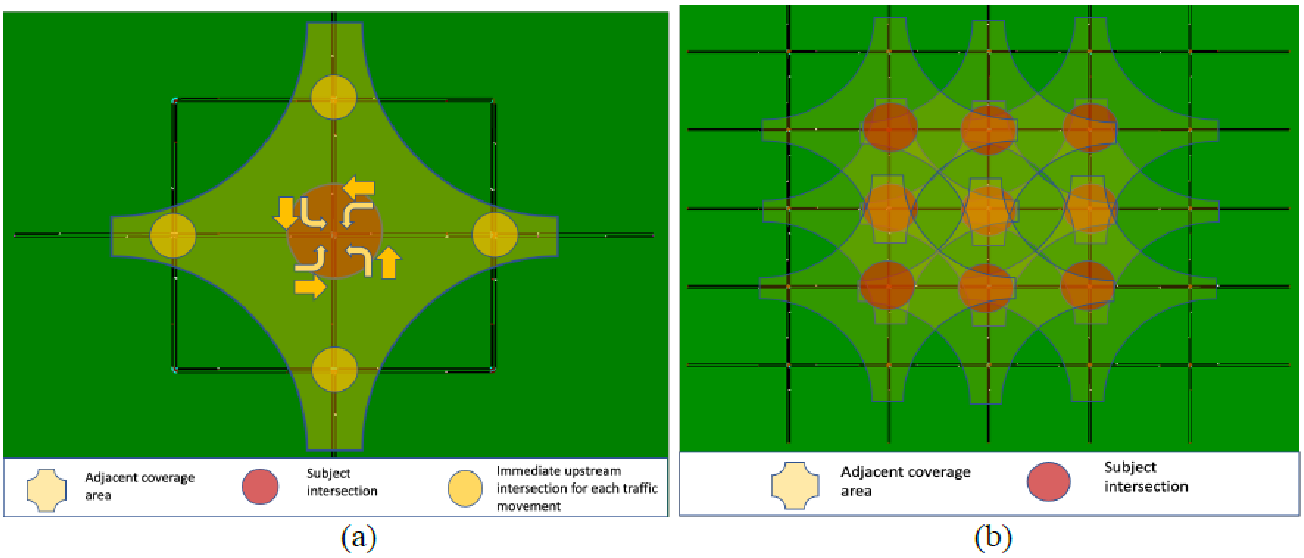


Figure 7.5: Digital twin conceptual architecture for improving user (driving) experience in a High-density urban roadway network: (a) for a signalised intersection; (b) city-wide signalised intersections
Source: Dasgupta et al. 2021

The case study was conducted using a microscopic traffic simulation, simulation of urban mobility (SUMO), by developing a digital replica of a roadway network with signalised intersections in an urban setting where vehicle and traffic signal data were collected in real-time. An overview of the DT-based ATSC logic applied is illustrated below (Dasgupta et al. 2021).

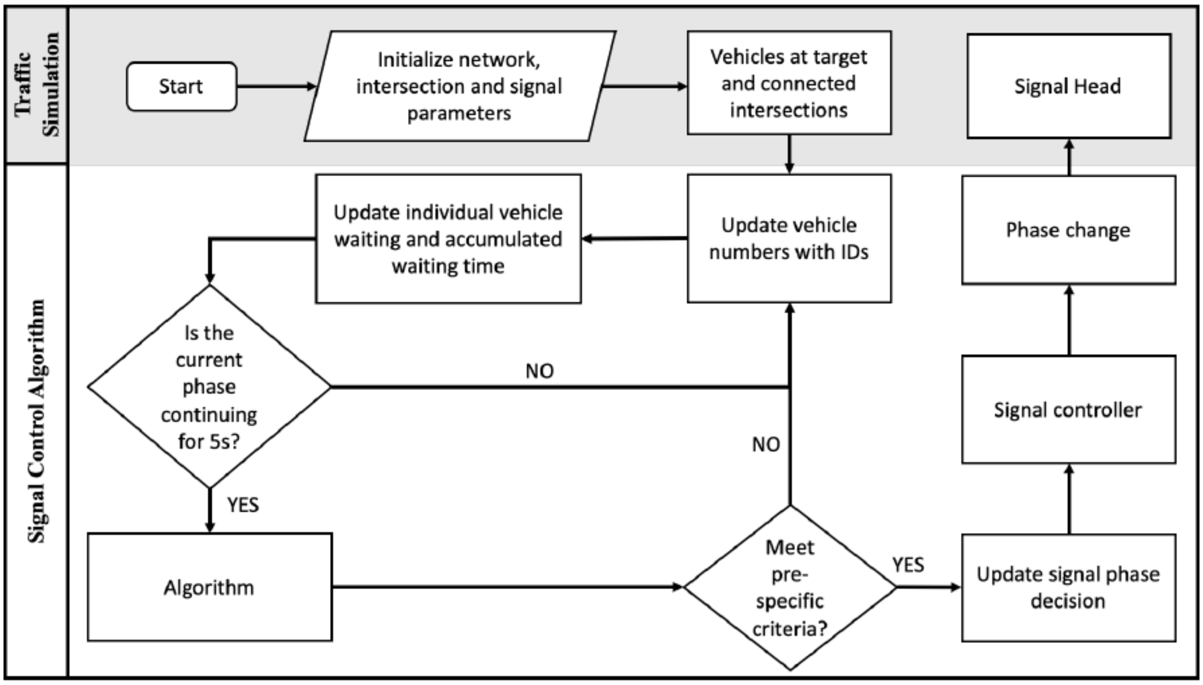


Figure 7.6: Overview of the DT-based ATSC Logic
Source: Dasgupta et al, 2021

The analysis concluded that the DT-based ATSC outperformed the traditional connected vehicle-based baseline ATSC in terms of average cumulative waiting time, distribution of drivers' waiting time, and levels of service for each approach for different traffic demands, demonstrating the effectiveness and better capabilities using the DT-based ATSC.

7.2.3.1.3 Digital Twins And Road Construction Using Secondary Raw Materials

In this case study (Meza et al. 2021), the objective was to establish a fully functioning DT for a road construction project. This involved the integration of sensor data with BIM on an approximately 300m-long access road project in Maribor, Slovenia. The road was designed using secondary raw material (SRM)- based products, such as recycled aggregate for the subgrade and base course and ground recycled asphalt with supplements for the surface course.

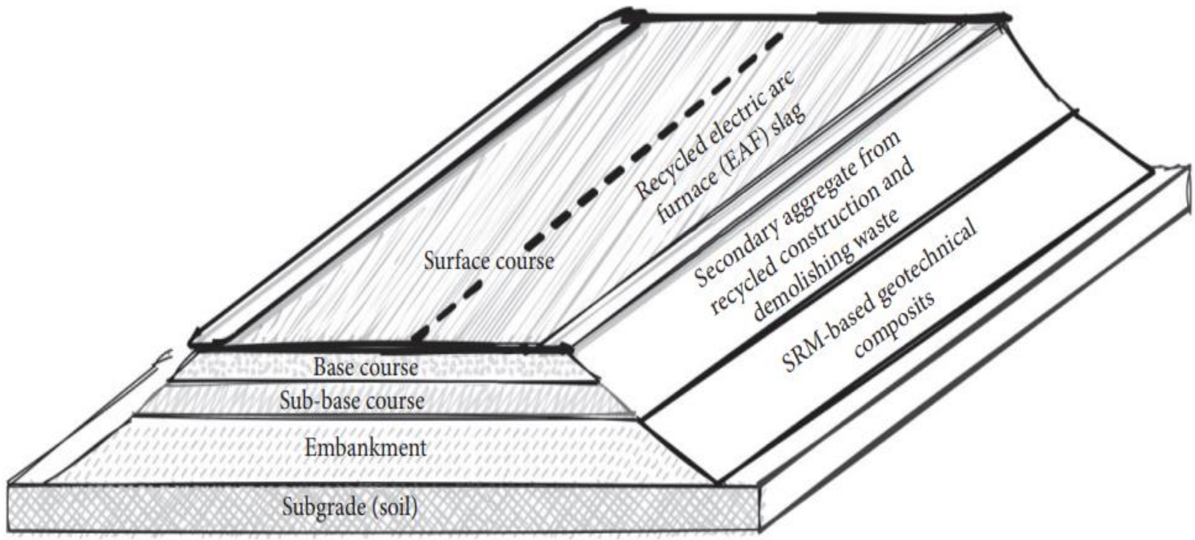


Figure 7.7: Typical Road Layers and Type of SRM Used.
Source: Meza et al, 2021

To best simulate cross-functional integration on this small-scale project, various BIM modelling and BIM coordination tools were used such as custom BIM elements that embody BIM sensors (object libraries), various embedded sensor data structures. Based on pertinent literature and international norms and standards such as EN ISO 19650-1:2018, minimal functional requirements for the platform suitable for digital twinning of the road construction were identified, such as:

- Capability to import and federate multiple IFC model files (preferably to support both IFC2x3 and IFC4 schema);
- Support for handling and analysing BIM metadata;
- Capability for data augmentation (adding new attributes) directly within the system;
- An interface for reading, analysing and automating the exchange of the model metadata (such as scripts, extensions and add-ins)—this is crucial since importing additional information from external data sources, such as structured XML or CSV files, is the envisioned concept of sensor data integration, and
- Capability to export integrated BIM with sensor data and links to external documentation, in the open IFC file format (preferably to both IFC2x3 and IFC4) to ensure compatibility with other supported BIM software.

The overall workflow consisted of four interconnected tasks as illustrated below:

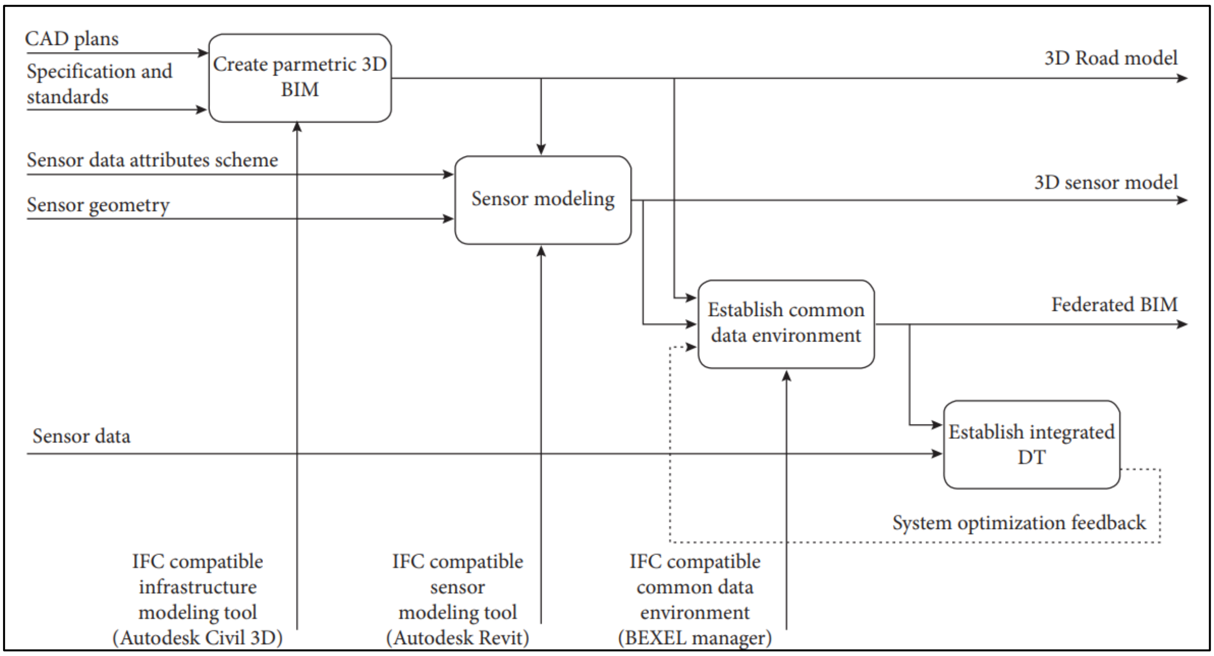


Figure 7.8: IDEF0 Case Study Execution Workflow Diagram Portraying the 4 Interconnected Tasks
Source: Meza et al, 2021

Using Autodesk Civil 3D and Revit, the BIM model was created from the 2D CAD data available initially, with only Revit being certified as an IFC file format compatible software by buildingSMART at the time. Upon completion of the BIM model, the CDE was established, resulting in the Bexel Manager BIM analysis and management tool being selected due to it being fully compliant with requirements, with the federated BIM model is portrayed below.

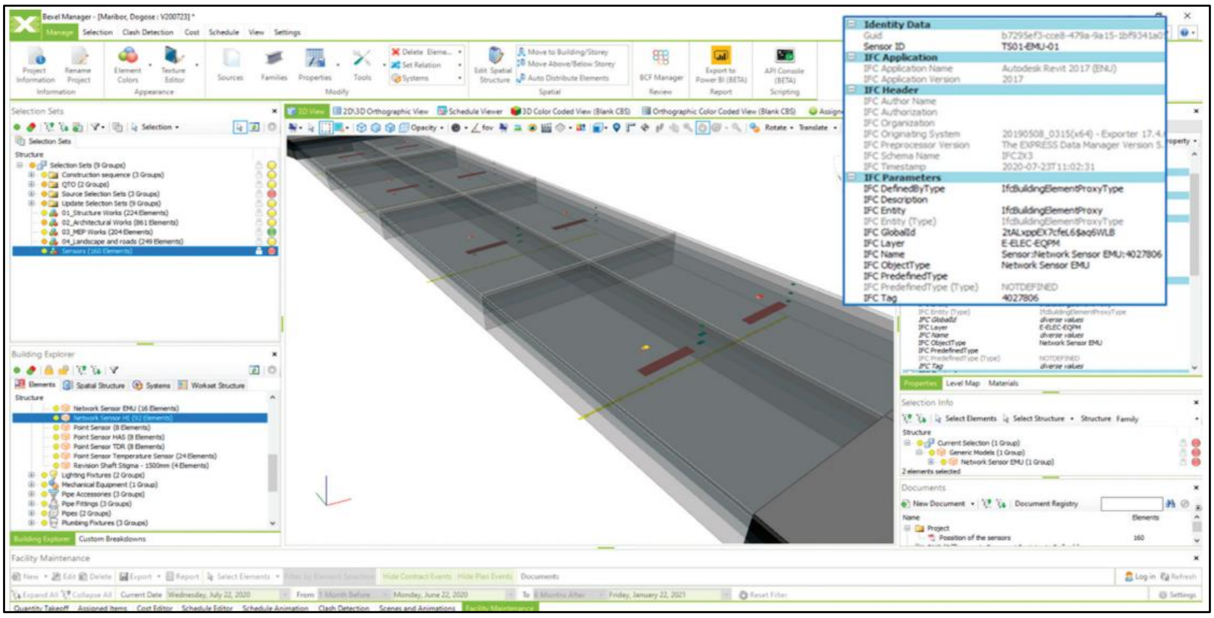


Figure 7.9: Federated BIM Model Serving the Basis of a DT
Source: Meza et al, 2021

Sensors were modelled as separate sources in Autodesk Revit, with the adopted BIM Model LOD representing each material and layer of the road structure as a separated BIM element. Additionally, to relate sensor readings with specific test sections of the monitored road, the BIM Model was longitudinally separated into elements 10m in length. All elements (layers) of the single road test section include the attribute test section ID, containing the specific tag (test section ordinal identifier) that is also included as part of the Sensor ID attribute of corresponding sensors, as depicted below.

Sensor	Mark	Type	Count	Position
Temperature sensor	T	Point sensor	36	Between the layers, in road axis and boundary
Inductive displacement sensor (vertical deformation)	EMU	Network sensor	16	On top and the bottom of subbase courses, below assumed wheels position
Soil moisture sensor	TDR	Point sensor	8	Between the base and subbase course layers, in road axis
Asphalt strain sensor	HAS	Point sensor	8	Below surface course, below assumed wheels position
Horizontal inclinometer (vertical deformation)	HI	Network sensor	4	Below subbase course in the entire profile, measuring points distance: 25 cm
Pressure pads (vertical pressure)	PP	Surface sensor	8	Between two base courses layers, below assumed wheels position

Figure 7.10: Implemented Sensors, Types, & Position in the Road Cross Section
Source: Meza et al, 2021

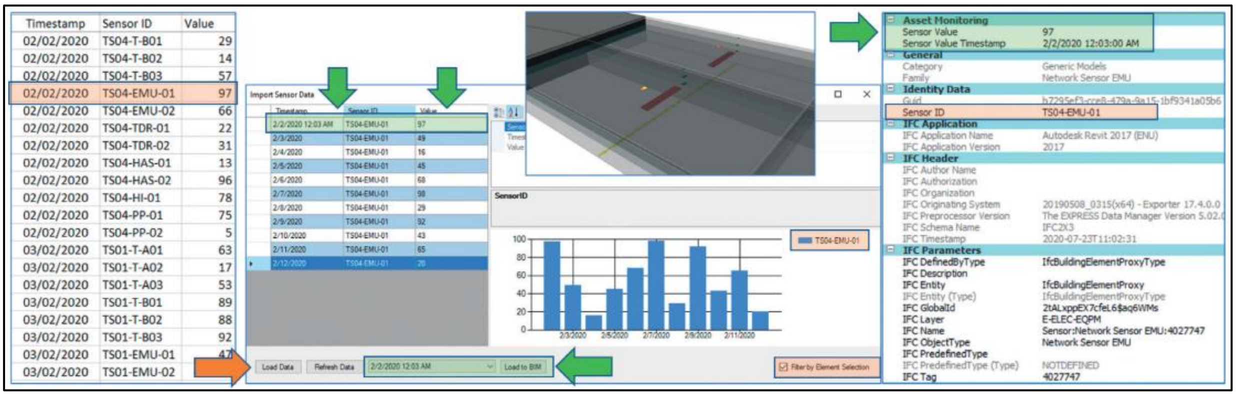


Figure 7.11: Sensor Data Integration Data Flow Scheme, Import of Test Sensor Data By Metadata Enrichment
Source: Meza et al, 2021

The relationship between sensors and road model elements was defined during the modelling process using the standardised tagging of road model elements within the Test section ID attribute and the well-structured naming of the Sensor ID property, which contains the Test section ID. Therefore, it was possible to create smart selection sets containing sensor elements and the corresponding road elements by creating simple attribute queries. The main advantages of the attribute-based queries are the automated update of element sets if the BIM model is updated, as well as the ability to filter sensor data based on a specified time range.

It was concluded that sensing road components and their environmental impact is crucial to ensure safety and operability through their life cycle, all the way to decommissioning, recycling, and potential reuse, further proving the hypothesis that DTs could be a valuable technology to address the challenges posed by using SRM-based materials in civil engineering projects. With the successful integration of sensor data readings and BIM, the first step toward a fully functioning DT was achieved.

Despite the road construction ongoing and the fact that construction has not been completed in the CINDERELA project region, two theoretical evaluations have indicated the possibility of two advantages: centralised data collection and graphical presentation. Both can contribute to better-informed decision-making, which is one of the essential goals of digital twinning.

7.2.3.1.4 Road Monitoring System Based On IoT Technology For Smart City

When it comes to road networks, one of the most common challenges faced is that of potholes. This study showcased the creation of a device which finds potholes in a road surface, as a part of an IoT road monitoring system, being an economical, highly accurate and purely automatic road quality control system, which can be built into any car (Klymenko et al. 2020).

The car houses the device, which is a microcontroller with an accelerometer attached to it. The microcontroller exchanges information with the server using Ethernet technology. The microcontroller reads data from the accelerometer and performs the primary processing of the received data. During processing, extra data is removed and a data packet is prepared for transmission to the server. The data received by the server undergoes a formatting process. The values obtained from the accelerometer are reduced to units of measurement, $g = 9.8m / s^2$.

After processing, the results go through a pit search algorithm that identifies possible problem areas of the road surface. The general architecture of our system consists of hardware and server parts, as shown below.

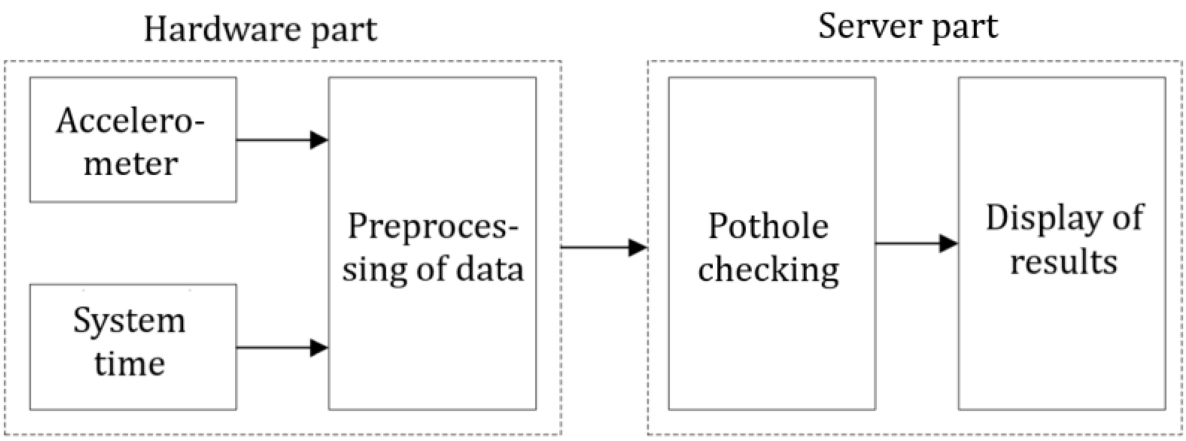


Figure 7.12: System Architecture
Source: Klymenko et al, 2020

A custom algorithm had been created to identify potholes, with the objective being to define pits on the Z-axes. Based on this acceleration, the device is placed parallel to the road to ensure accurate results. The custom algorithm performs a two-level test.

Initially, when the car hits a pothole, the car significantly changes its acceleration along the vertical axis. With this change in acceleration, the first method in testing titled the Threshold method compares the acceleration value against the threshold value. Since entering the pit of acceleration takes the form of a sinusoid - sharply accelerating, and then just as sharply slowing down as it is shown on the right, it is necessary to set both the upper and lower thresholds of acceleration.

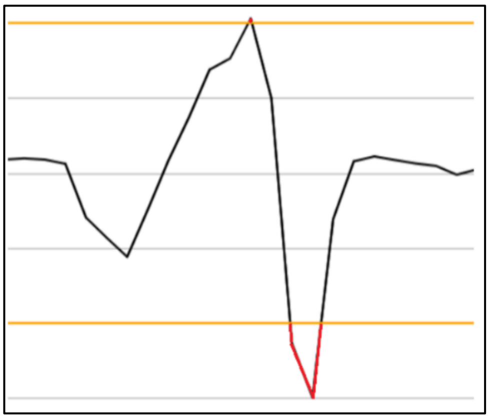


Figure 7.13: Threshold Method
Source: Klymenko et al, 2020

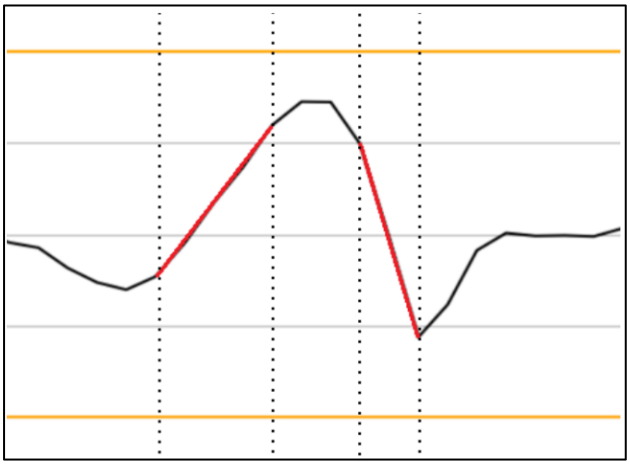


Figure 7.14: Difference Method
Source: Klymenko et al, 2020

The acceleration when entering the pit increases very sharply, so it is possible to detect cracks that may not lead to high performance, but the change between successive measurements will be significant to assume the presence of a defect on the road's surface. Therefore, the second method to check the indicators titled the Difference Method compares neighbouring values in the indicator buffer.

With the above methods established, the test was conducted at a speed of 60 km/h. The Threshold Method showed the best results using 0.4g as an indicator with 76% found bumps. The difference method finds 92% of potholes when the indicator is equal to the 0.2g algorithm, but it has more false results because it finds pavements and rail crossings as holes in the road. With further testing, re-runs, different speeds and the incorporation of possible AI and ML, this system could contribute to safer road networks, feeding back to the DT of a smart city.

8. CLOSING

8.1. BIM FOR ROADS

Based on the findings presented in this dissertation, it is without a doubt that BIM is an ideal methodology for intelligent road engineering design, construction, and digital twinning. The intelligence of parametric, computational and dynamic BIM technologies, workflows, cloud computing, document management, reality capture and other technology workflow integrations revolutionise the traditional road project lifecycle, with an advantage right from the onset of the process to the very end being as-built. This ensures road infrastructure/networks are designed and constructed intelligently, contextually, efficiently, economically, time-consciously, and sustainably.

With a plethora of benefits provided by BIM on its own, those benefits can be catalysed and compounded further when serving as the foundational component in the DT process, contributing to the pursuit of smart cities that fulfil the six smart indicators, with BIM and IoT playing a pivotal role.

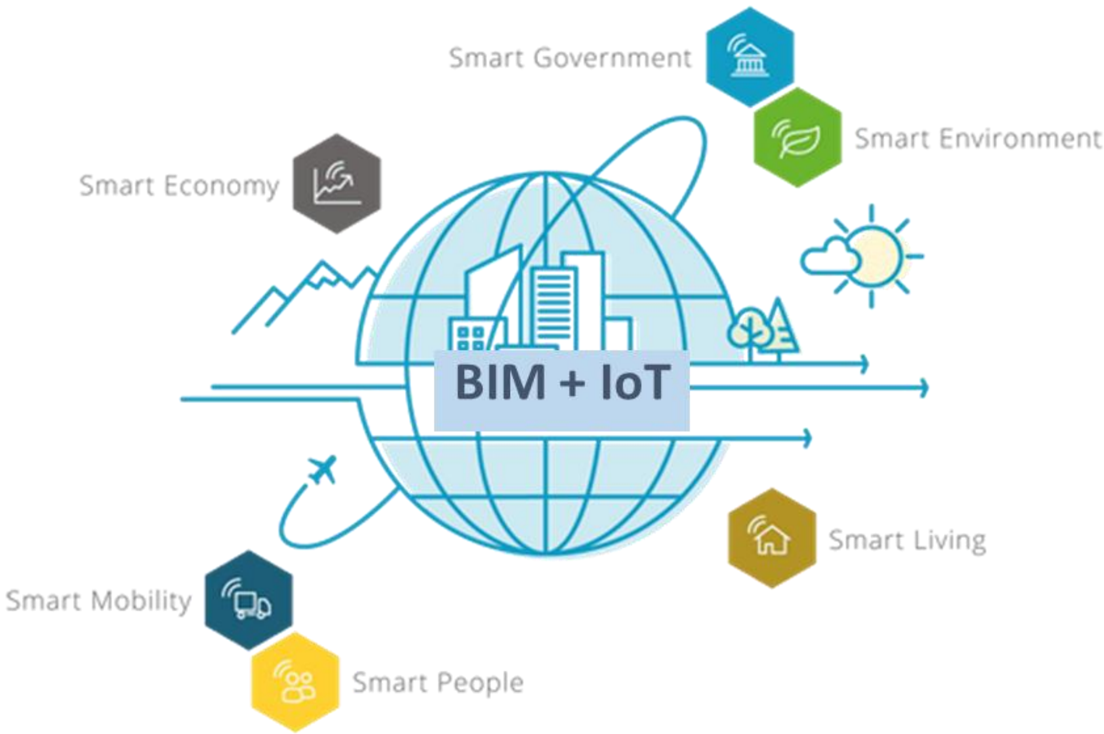


Figure 8.1: Six Key Smart City Indicators Achieved using BIM & IoT
Source: Bee Smart City, n.d.

8.2. BIM TODAY and THE FUTURE

With BIM being so advantageous in its application and implementation in the AEC industry, it has led many countries and regions across the world to mandating its use on projects. The map below showcases the countries/regions that have planned or already mandated its use:

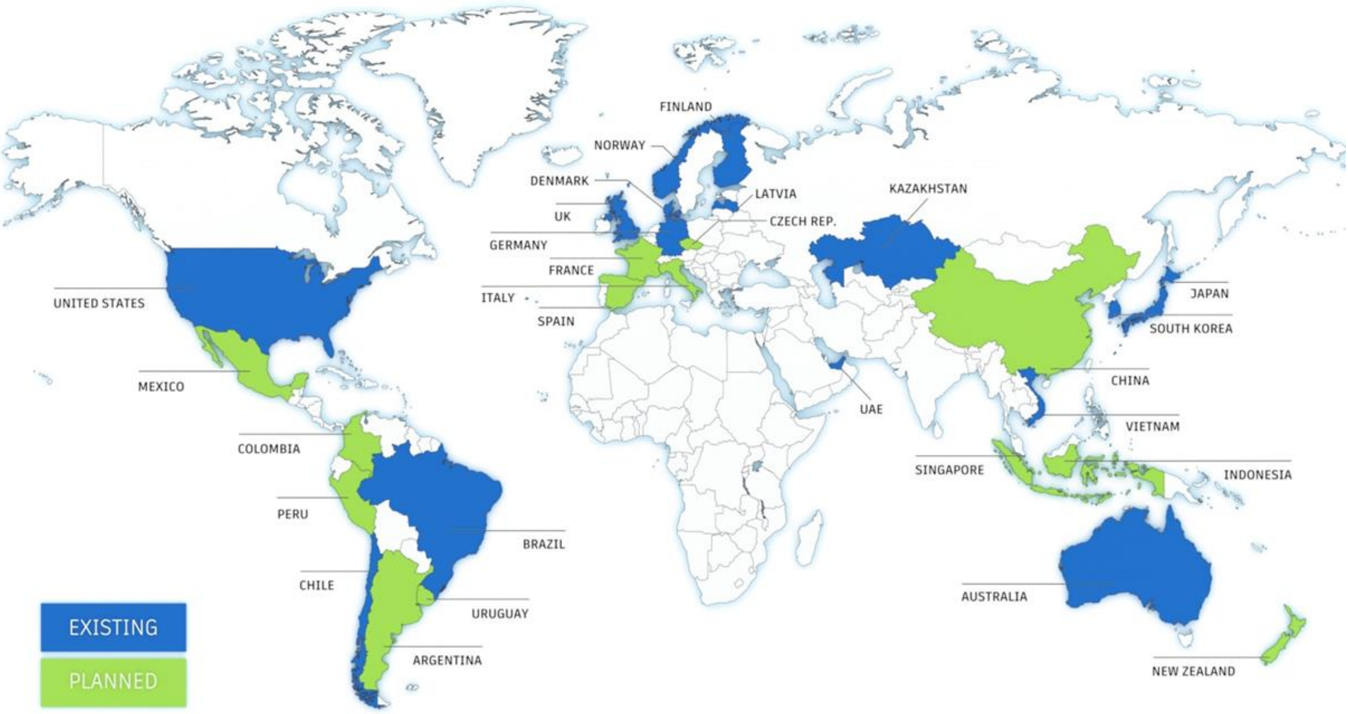


Figure 8.2: BIM Mandates Around the World illustrated by Autodesk
Source: Ryder, Z. 2022

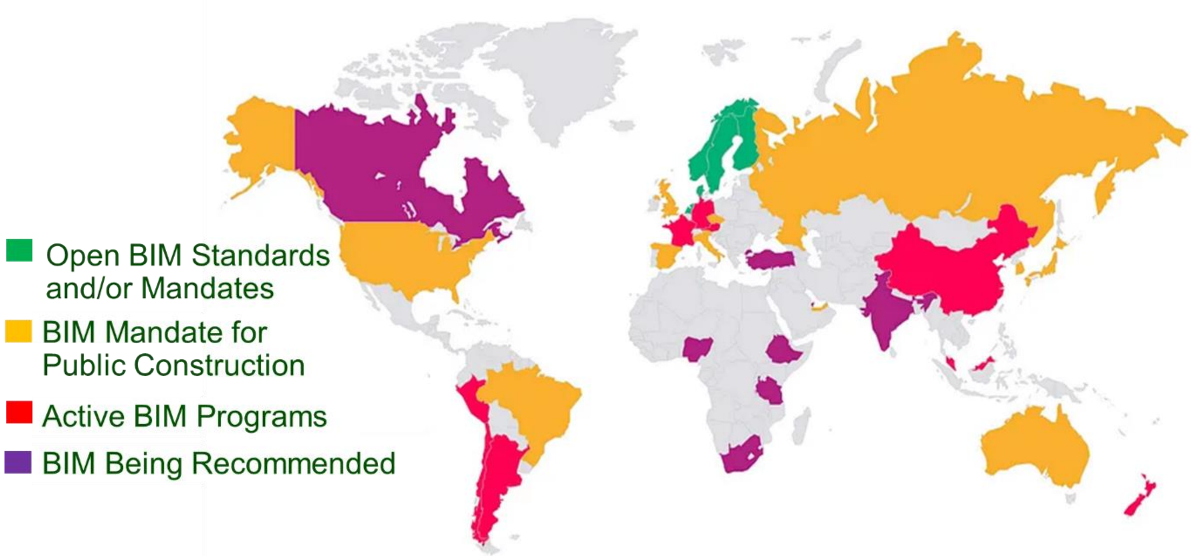


Figure 8.3: BIM Adoption Across The World: A Global Outlook
Source: Eischet, O. 2022

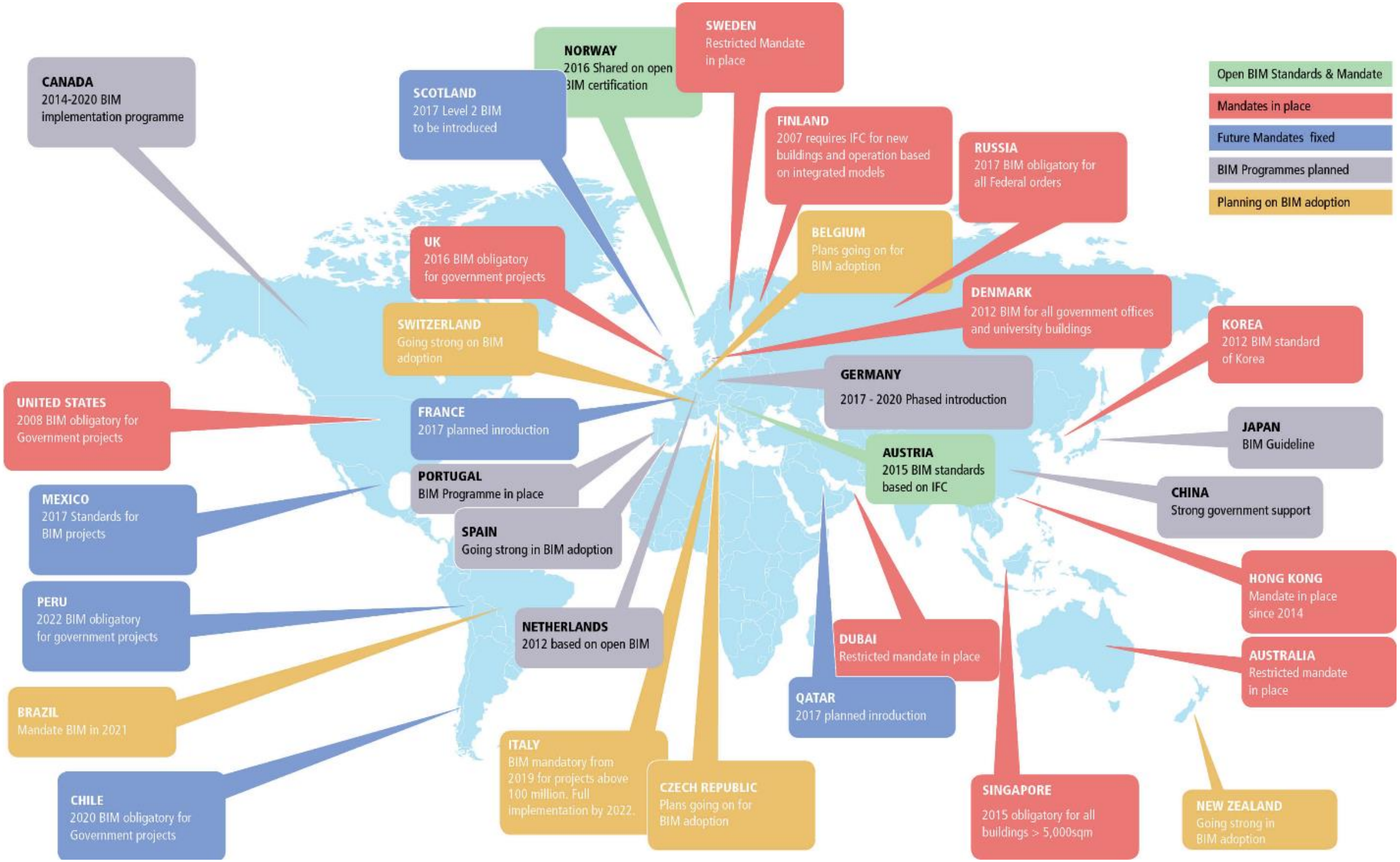


Figure 8.4: Overview of Global BIM Adoption
Source: Stroma Group Ltd, 2018

From these countries/regions, there are certain countries leading with BIM adoption as depicted below, with the global leader in BIM adoption being the UK.

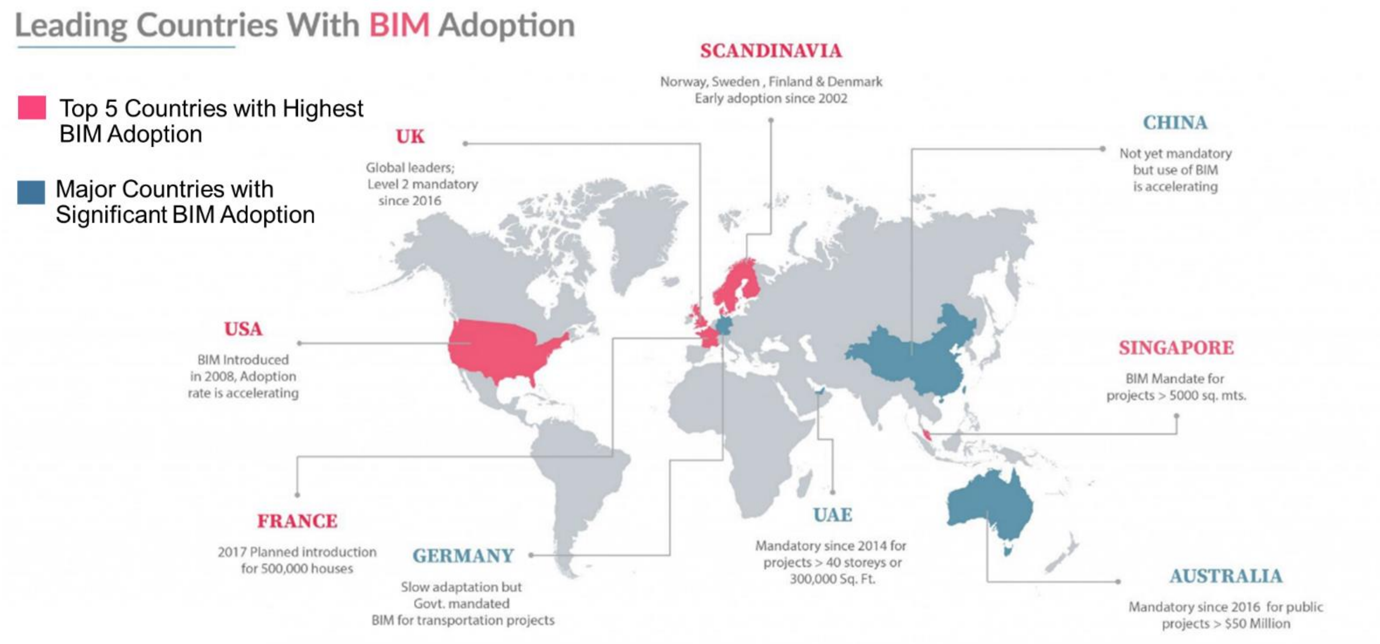


Figure 8.5: Leading Countries with BIM Adoption
Source: United BIM, n.db.

Based on the widespread adoption of BIM on a global scale, it is clear that BIM is here to stay. BIM today has cemented its place in the AEC industry and will serve as a foundational requirement for the future of civil infrastructure. It is only a matter of time before it is embraced and mandated by every country. Besides serving as a form of standardisation and catalyst for the digital transformation of the AEC industry, the use of BIM or the BIM model of an infrastructure asset will serve as the starting block for the digital twinning process, which is elaborated on later in this dissertation.

Another arena that BIM is currently playing in and will further immerse its usefulness is that of gamification. The concept of gamification in the AEC industry refers to the creation of an immersive environment to provide enhanced realism for reviewing AEC designs and construction, motivated and influenced by the gaming industry, and reliant on a BIM intelligent model. The concept of gamification in the AEC industry is already a hot topic in the industry, with projects having already incorporated its application for enhanced and immersive decision-making and project review. Despite being a hot topic in the industry, the adoption of this concept is currently seen as a novelty to the majority of the AEC industry This has led to many companies or professionals being hesitant in its use because they are unsure how to execute it successfully on their projects. With the gaming industry being ever so popular, this concept is only expected to grow in adoption in the near future and beyond, especially on large-scale civil infrastructure and city planning projects as it affords stakeholders and decision-makers an avenue to analyse and approve future projects and developments in a manner that boasts transparency, realism and futurism. With the process of digital twinning extending the use of BIM to its next naturally progressive, evolutionary step, as well as the inclusion of the concept of gamification in the AEC industry, BIM further cements its place in the future of the AEC industry, as well as still serving as the link between manufacturing and prefab construction, thus connecting the AEC and PDM industries.

With technological advancement occurring daily, processes and methodologies are seen to have a shelf life, with processes being superseded by progressive and innovative developments in the technology field. Based on this statement, a question commonly raised is that of the future developments of BIM.

Whilst the future might be quite unpredictable in the realm of technology, the biggest sentiment shared is that of BIM playing an end-to-end role in the project lifecycle. This means that its application will be fully understood and applied to its maximum across project phases. The use of connected BIM and cloud computing could also be expanded. which will enhance the BIM model and open its capabilities to added possibilities, including enhanced visual scripting and programming.

With BIM being more fully realised in mature and developing countries, the focus will shift from the actual building of the model to the information attributed or attached to the asset. More information ensures better communication, resulting in better decisions and outcomes. From a smart cities' perspective, BIM is seen to have become the norm as the foundational digital replica interacting with other BIM models to enhance city operations, as well as urban planning, design, and expansion. Prototypes can be examined against previous designs and analytical input, and dashboard data can be tweaked to test different outcomes and improve performance. With BIM shifting to a mandatory role in the future, technologies of visualisation, simulation and augmented and virtual reality will become the new way of reviewing and approving civil infrastructure design, finding itself in the same position as BIM currently in developing countries.

Therefore, the expanded use of BIM is governed by strides made in the current and future cloud and other technology/workflow integrations, with realistic, immersive visualisation leading the way in the future, being the first step in this approach. The information model will serve further expanded uses across construction phases, including operations and maintenance.

8.3. HURDLES CURRENTLY OBSERVED IN BIM ADOPTION

Although BIM is clearly acknowledged as a beneficial tool in the civil infrastructure industry, its adoption is very low in Africa and developing countries. The following have been observed as hurdles currently influencing its poor adoption:

8.3.1. ABSENCE OF A BIM MANDATE

The topic of BIM mandates is increasing in South Africa and developing countries, but nothing has come to fruition yet. With the absence of a mandate, professionals see no hurry in the adoption of BIM, putting it off until it is mandatory.

8.3.2. BIM AS A DELIVERABLE

Consultants share that a BIM model or connected BIM is not a requested deliverable/requirement on their projects, with just hardcopies being the deliverable. In the absence of a mandatory requirement for BIM, existing processes can be continued.

8.3.3. COST OF BIM ADOPTION

A common sentiment shared across the African continent is that of the upfront cost/capital required to purchase, adopt, and implement BIM technologies and processes. Developing countries consist of the majority of small and medium-sized enterprises (SMEs), which makes affordability a challenge.

8.3.4. BIM AWARENESS AND RESISTANCE TO CHANGE

BIM awareness and knowledge/exposure are low across the civil industry when compared to the architectural industry, with the misconception that it is only associated with the architectural environment. This has discouraged civil professionals from pursuing and investigating the application of BIM in their civil environment. On the other hand, there are civil professionals who are aware of BIM and how it can be applied in their fields of specialisation, but are too complacent and comfortable to change, seeing change as a burden or not worth the effort.

8.3.5. EDUCATION, TRAINING AND UPSKILLING

Civil professionals who are on board with BIM and acknowledge its benefits often bring up the issue of education, training, and upskilling. With the exposure in the civil industry low, there is a feeling of abandonment regarding who to turn to for guidance academically, managerially, technically, and practically.

8.3.6. ABSENCE OF BIM CHAMPIONS IN THE CIVIL INDUSTRY

Closely linked to the point above, there are very few known/established BIM champions in the civil industry, making it difficult for other professionals to start their BIM journey and become BIM-ready. Without industry influencers and thought leaders for BIM for civil infrastructure, professionals feel that BIM is just a hype which will not materialise in the broad scheme of industry developments.

8.3.7. BIM SEEN AS A NICE-TO-HAVE FOR DIGITAL TWINNING

For concepts involving older infrastructure that have no as-builts, BIM is seen as a nice-to-have depending on function/requirement, with those in the field saying that sensors, IoT and dashboards are sufficient for their concepts and operations.

8.3.8. NO CIVIL PROJECTS REQUIRING IoT AND DIGITAL TWINS

With DTs currently being explored in mature BIM countries, the demand/request for projects involving IoT and DTs in the civil industry is non-existent or minimal, with most conducted in the research and development (R&D) space.

8.3.9. BIM, GIS, and ACCESS TO DATA

The majority of civil professionals using BIM agree that using BIM and GIS is a gamechanger, but do not know where to leverage such data that is reliable, updated and readily available.

8.4. RECOMMENDATIONS TO OVERCOME THESE CURRENT HURDLES

With the current challenges identified, the following recommendations are proposed to overcome these hurdles:

8.4.1. NATIONAL MANDATING OF BIM BY THE GOVERNMENT ON TENDERS

Government support is seen as the most impactful solution in ensuring the mandating of BIM. By mandating BIM in tenders on a national level, consultants will have to conform to the adoption and incorporation of BIM in their processes and outputs. This will result in the following main benefits:

- Digital transformation in the civil infrastructure/AEC industry
- Increase in innovation and creativity
- More resilient, sustainable, and economically designed infrastructure
- Create a strong foundation to pursue DTs using BIM models as a base in the near future
- Faster turnaround times for infrastructure delivery
- Enhanced, systematic operations and maintenance of critical public infrastructure.

- Clear contractual frameworks, allocations and definitions of roles and responsibilities in line with the law, legal and other related legislation.

Without the support and drive from government legislature, BIM adoption will remain slow across the civil infrastructure industry.

8.4.2. CONTRACTUALLY MANDATING A BIM DELIVERABLE BY THE PUBLIC AND PRIVATE SECTOR

With the government needing to play a huge role in driving digital transformation by mandating BIM, consultants should be proactive and not wait till that day arrives to start their journey. It has been seen across a few projects where companies have taken the initiative of specifying a BIM model as a deliverable on their projects, particularly in the private sector. With leaders in consortiums specifying this deliverable in their contracts/bids, a culture of BIM will be fostered. This will ensure that companies are already putting processes and procedures in place so that when BIM eventually gets mandated, they are BIM-ready rather than on the reactive backfoot.

8.4.3. GOVERNMENT FUNDING and BUSINESS ANALYSIS

The cost/capital required for BIM is a hurdle that SMEs will evidently face. One proposal will be for the government to provide funding to SMEs that apply for tenders mandating BIM at the initial inception adoption stage of a BIM-mandated country. This will influence and encourage SMEs to adopt BIM in the civil industry. Another step that can be taken is at a company or organisational level, where companies quantify unnecessary expenditure constantly experienced across projects due to traditional processes to build a business case. This can then be used to justify their expenditure on investing in BIM and the returns expected. The banking sector can also play a role in investing in SMEs and making loans/funding an easier process.

8.4.4. COMBINING INDUSTRY EXPERIENCE AND INNOVATION

To increase awareness and reduce/eradicate resistance to change, industry perception needs to be unbiased and logical. With Africa having the youngest median average population, and with technology embraced more by the younger population, seasoned professionals and fresh graduates need to combine their strengths. This will result in an industry that uses innovation backed by the experience to engineer a better tomorrow, forming the perfect symbiosis for resilient infrastructure and digital transformation. Professional bodies and institutions need to include BIM and digital transformation as part of their development plan, thus increasing knowledge share through a variety of mediums. By constantly engaging in this conversation, vocalisation, exposure, and the presence of BIM will become more prevalent amongst industry peers and professionals.

8.4.5. PARTNERING WITH BIM CONSULTANTS AND SERVICE PROVIDERS

Civil consultants need to partner with BIM consultants and service providers that service their fields of specialisation. These organisations are the best to advise and guide professionals on their BIM journey, having authorised training centres and certified professionals. With COVID-19 playing a catalyst to remote work, these service providers can facilitate companies online or virtually, should there not be any accredited service providers in proximity to the region. These BIM consultants and service providers will provide a scalable approach, ensuring companies transition smoothly to BIM.

8.4.6. LEADERSHIP BY BIM PROFESSIONALS AND PROFESSIONAL BODIES

Another pivotal role is that of BIM technical specialists (BTS) and professional bodies. BTS need to be as vocal as possible in the civil industry, stepping up and ushering their peers in the right direction, but more importantly, stirring up a conversation and buzz about BIM in the industry by showcasing their work, talents, and achievements across a variety of platforms, conferences, events, and social media. BTS need to be the thought leaders and guiders in their field of specialisation, which in the near future will give rise to others who have been inspired and acknowledge what is possible with BIM, knowing it is possible and achievable, creating the mindset of “If they can do it, I can too”. Professional bodies, industry and educational organisations need to include BIM and technological advancements in curriculums, as well as a requirement for professional development when applying for professional registration. They also need to provide a platform to BTS and other related persons or organisations that possess the skillset and knowledge, ensuring a larger reach in the industry.

8.4.7. PARTNERING WITH IoT CONSULTANTS AND SERVICE PROVIDERS

Whilst BIM may be seen as a nice-to-have in certain instances relative to IoT and DTs, the bigger picture needs to be acknowledged. Should the goal be a DT of a city, BIM will be a preferred option as it will serve an interactive function with other surrounding infrastructure. If a BIM model is not required or deemed unnecessary, then it may be bypassed. Based on various literature, it is gathered that a BIM model is the ideal recommendation in conjunction with IoT to achieve a DT that is digitally referenced, serving as a digital replica of a virtual output that can be built on as the area/city expands and develops. This needs to be identified and agreed upon by professionals in this field, who will advise accordingly.

As with BIM, companies and organisations involved in the DT process or projects need to partner with IoT consultants and service providers. RandD teams need to form a collaboration with IoT professionals, resulting in more quality data, development, progression, and innovation, including fields such as machine learning, AI, robotics and 4IR. Forming partnerships with credible, qualified, and knowledgeable providers will create greater understanding, awareness and a more systematic, structured approach and progression.

8.4.8. SYNERGY BETWEEN GOVERNMENT, CONSULTANTS and DATA

In cases where access to data and not the technology is an issue such as GIS data, government and consultants in the civil and geospatial industries need to form a synergy. In mature countries, GIS data is freely accessible or can be obtained for a fee with clear directions as to which organisation it can be obtained from. In developing countries, this is not the case, where consultants whilst acknowledging the power of GIS in their designs, will not pursue it as they have no idea who to turn to. Synergy is needed to make this data available to consultants on a per-project basis either freely or as a service fee which can be included in the consultant's cost. This will be the most systematic manner to overcome this hurdle.

8.4.9. PRIVATE SECTOR INFLUENCE

It is a well-known fact that civil infrastructure projects in the private sector are completed quickly and boast innovation and edge. This can be seen by developments that come up in a shorter period compared to the past, with more facilities and innovative offerings. The private sector needs to become more vocal and intentional in influencing the government to embrace digital transformation through collaboration and forming partnerships.

8.5. THE BIM SITUATION ON THE AFRICAN CONTINENT

In context to the African continent, digital transformation has been gaining traction, however, the overall transformation has been slow. This impedes the impact on technological and innovative methodologies such as BIM. In addition to the challenges previously mentioned, below are specific challenges faced by Africa and other developing regions which have hindered the adoption of BIM and other methodologies:

- Infrastructure Gaps: Limited access to reliable and affordable internet connectivity, especially in rural areas, hampers digital transformation efforts. Insufficient infrastructure, including inadequate broadband coverage and power supply, poses significant challenges for expanding digital technologies across the continent.

- Digital Divide: There is a significant digital divide in Africa, both within and between countries. Disparities in access to digital technologies, including smartphones, computers, and internet services, create inequalities in digital literacy and hinder the widespread adoption of digital solutions.

- Skills and Capacity Gaps: The shortage of skilled professionals with expertise in emerging digital technologies, such as artificial intelligence (AI), data analytics, and cybersecurity, hinders the implementation and maintenance of digital systems. Limited training opportunities and inadequate educational programs in digital skills further contribute to this challenge.

- Affordability and Accessibility: The high cost of digital devices, internet services, and data plans often makes them unaffordable for a significant portion of the population. Limited availability of localized content and language barriers can also limit the accessibility of digital services and hinder digital inclusion.

- Regulatory and Policy Frameworks: Inadequate or outdated regulatory frameworks and policies related to digital technologies can create uncertainty and hamper innovation and investment. Establishing clear and conducive regulations, data protection laws, and promoting cross-border collaboration are critical for enabling digital transformation.

- Cybersecurity and Data Privacy: The increasing digitization also brings concerns about cybersecurity and data privacy. The lack of robust cybersecurity measures, data protection regulations, and awareness among individuals and organizations make Africa vulnerable to cyber threats and hinder trust in digital systems.

- Financial Constraints: Limited access to capital and funding options can impede the development and deployment of digital solutions. Insufficient investment in digital infrastructure and innovation ecosystems can slow down digital transformation efforts.

- Local Content and Language Diversity: Africa's linguistic and cultural diversity presents challenges in creating and delivering digital content and services that cater to local needs and preferences. Localizing digital solutions and supporting content creation in various languages can enhance adoption and user engagement.

Addressing these challenges requires a multi-faceted approach involving public and private sector collaboration, investment in infrastructure and skills development, supportive policy frameworks, and initiatives to promote digital inclusion and affordability. Organisations across Africa have initiatives placed at the developmental forefront in efforts to accelerate this transformation to the desired progression and overcome bottlenecks.

Organisations such as BIMcommUNITY Africa and BIM Africa are spreading knowledge and awareness of BIM across Africa, consisting of professionals from various industries and disciplines across the African continent. An increasing inclusion of BIM in university curriculums across Africa has also accelerated BIM awareness and benefits in academic circles, with many papers, dissertations and theses being produced, further examining and substantiating the positive impact of BIM on projects in countries across Africa.

With BIM acknowledged as one of the World Economic Forum’s top 10 disruptive technologies in construction, as well as playing a part in the digital transformation of various industries and disciplines, particularly the AEC industry, many notable organisations have already begun their BIM journey in Africa. The African BIM Report 2022 illustrates this where it showcases BIM applied on projects in the banking, education, healthcare, industrial and mix development sectors.

As the construction industry in Africa continues to develop and mature, the state of BIM adoption is likely to evolve. The push for sustainable development, urbanization, and infrastructure growth in many African countries creates a compelling case for the further integration of BIM into construction practices, with many firms taking the initiative to incorporate BIM into their processes.

It is evident, as slow as it may be perceived, BIM is transforming the construction landscape in Africa, bringing new efficiencies and innovations to an industry critical to the continent's development. Through enhanced collaboration, streamlined planning, and sustainable practices, BIM empowers African countries to embark on ambitious infrastructure projects with confidence. However, challenges remain, including infrastructure limitations, the digital divide, and policy frameworks. Addressing these challenges requires concerted efforts from governments, private sector stakeholders, and the construction community.

As Africa's construction industry continues to embrace BIM, the continent stands poised to realize its vision of sustainable, resilient, and inclusive urban development, ultimately paving the way to a brighter future for its people and communities.

8.6. CONCLUSION

With the rapid growth in world population and urbanisation, BIM methodologies, workflows, technological integrations, and processes are effective in providing infrastructure that is built to last, in a manner that is smart to cater for and support the populations of today and the future. This dissertation proves that the application of BIM is relevant to the civil infrastructure industry, providing the transportation sector with an innovative methodology to reimagine the way we plan, design, construct, manage, and maintain roads. With growing acceptance globally and across the continent, BIM mandates are soon to become a reality in Africa, as the continent looks towards futuristic methods to solve complex infrastructure challenges, empowering Africans to engineer a better Africa, positively impacting socio-economic development and steer the continent as a whole towards the pursuit of smart living in the form of smart cities.

Whilst the adoption of BIM in Africa holds immense promise, several hurdles and challenges remain. Limited access to technology, inadequate infrastructure, financial constraints, localisation, mandates, skill gaps, and a lack of awareness about BIM's benefits are some of the primary obstacles hindering its widespread implementation across the African continent. Additionally, integrating BIM into existing construction practices requires substantial investment and commitment from stakeholders.

However, despite these challenges, the future prospects for BIM in Africa are optimistic. There have already been a spread of BIM projects and initiatives across the continent and as technology becomes more accessible and awareness spreads, the construction industry will increasingly realize the potential advantages of BIM. Governments, private companies, national and international organizations must collaborate to invest in BIM implementation, support research and development, and promote training initiatives to foster a vibrant BIM ecosystem on the continent.

With BIM showing so much promise now and in the future of infrastructure, we should be proactive as industry professionals in Africa and other developing regions today, to ensure a digitally transformed tomorrow.

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