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Engineering a better future for our planet and its people

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Foreword

Welcome to the latest edition of our AtkinsRéalis Technical Journal. In this issue we are proud to feature papers which highlight the innovative ways we're revolutionizing the world's infrastructure and energy systems.

This edition features some of the work we have been doing in transport planning, water and environment, geotechnical engineering, nuclear engineering and data governance. It highlights our strong focus on improving the safety performance of new and existing infrastructure and improving the sustainability and resilience of the new assets we create. It also spotlights our capability in data governance, citing its use in Asset Management.

To improve the safety of existing infrastructure, we have carried out a cost-benefit analysis of Ireland's Advanced Driver Assistance Systems retrofit program, highlighting substantial road safety and economic benefits across all vehicle categories and identifying critical implementation strategies like incentives, regulation, and awareness campaigns. We have also used our AtkinsRéalis-developed SafeMove system to enable safe, efficient, autonomous transport of radioactive materials in nuclear facilities, reducing human exposure and operational bottlenecks to improve reliability, safety, and cost efficiency. And we have used computational fluid dynamics (CFD) simulations for phased reservoir rehabilitation to reveal risks like stagnation and uneven disinfectant distribution, demonstrating CFD's value in validating designs, protecting water quality, and reducing costly trial-and-error. To improve the safety of new infrastructure, we have employed an innovative layered hazard assessment approach for Small Modular Reactors, improving safety by screening hazard combinations at generic, area, and layout levels.

To help safeguard the environment, drive sustainability and improve the resilience of our assets, we have used computational and agile methods to accelerate flood defence design for the Middle Level System River Management Scheme, enabling automated analysis, early cost forecasting and stakeholder engagement. This data-driven approach improved design assurance, reduced risk, and supported strategic flood resilience. We have also developed a qualitative carbon framework to identify and reduce carbon across projects, integrating benchmarks and interventions which drive meaningful reductions, support net zero goals and foster a culture of sustainability. And we have conducted an innovative geotechnical and hydrogeological investigation and modelling for the Mottram Underpass, part of the A57 upgrade, leading to the use of contiguous piles as a cost-effective, environmentally preferable solution.

Lastly in this edition, we showcase development of a scalable data governance framework for infrastructure organizations, integrating systems, improving data quality and supporting compliance. The program enables automation, organizational change, and adoption of emerging technologies, positioning data governance as a strategic enabler of innovation.

The above examples provide only a small insight into the wealth of innovation that AtkinsRéalis creates day to day and we hope you find this collection of papers enjoyable, helpful and thought-provoking.

CHRIS HENDY

Rédacteur en chef de la Revue technique d'AtkinsRéalis
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Avant-propos

Bienvenue dans la toute dernière édition de la Revue technique d'AtkinsRéalis. Dans ce numéro, nous publions avec fierté des articles qui mettent en lumière les façons novatrices dont nous révolutionnons les infrastructures et les systèmes énergétiques dans le monde entier.

Nous y présentons certains travaux effectués dans les domaines de la planification des transports, de l'eau et de l'environnement, de la géotechnique, de l'ingénierie nucléaire et de la gouvernance des données. Les différents articles soulignent notre détermination à améliorer le rendement en matière de sécurité des infrastructures nouvelles et existantes, et à bonifier la durabilité et la résilience des nouveaux actifs que nous réalisons. Ils mettent également en lumière nos capacités en ce qui a trait à la gouvernance des données, en citant des exemples de son utilisation dans la gestion des actifs.

Afin d'améliorer la sécurité d'infrastructures existantes, nous avons effectué une analyse coûts-avantages du programme irlandais de modernisation des systèmes avancés d'aide à la conduite, en soulignant les avantages substantiels sur le plan de la sécurité routière et de l'économie pour toutes les catégories de véhicules, et en définissant les stratégies critiques d'implantation – notamment les incitatifs, la réglementation et les campagnes de sensibilisation. Nous avons également fait appel au système SafeMove développé par AtkinsRéalis pour assurer le transport sécuritaire, efficace et autonome des matières radioactives dans les installations nucléaires, en réduisant l'exposition humaine et les entraves opérationnelles de façon à améliorer la fiabilité, la sûreté et la rentabilité. Et nous avons utilisé la dynamique numérique des fluides (DNF) pour effectuer des simulations en vue de la remise en état progressive de réservoirs d'eau potable, afin de révéler les risques comme la stagnation et la distribution inégale de désinfectant. Nous avons ainsi pu démontrer la valeur ajoutée de la DNF lorsqu'il s'agit de valider les conceptions, protéger la qualité de l'eau et réduire les essais et erreurs coûteux. Pour améliorer la sécurité des nouvelles infrastructures, nous avons opté pour une approche novatrice d'évaluation par étapes des dangers pour les petits réacteurs modulaires, en examinant les combinaisons de risques de manière générale, à des niveaux spécifiques et selon la configuration des équipements.

Pour aider à protéger l'environnement, à favoriser la durabilité et à améliorer la résilience de nos actifs, nous avons mis en place des méthodes de calcul agiles pour accélérer la conception de technologies de défense contre les inondations dans le cadre du projet Middle Level System River Management Scheme, de façon à automatiser les analyses, à prévoir les coûts en amont et à mobiliser les parties prenantes. Cette approche fondée sur des données a amélioré l'assurance de la conception, réduit les risques et soutenu la résilience stratégique face aux inondations. Nous avons également élaboré, pour l'ensemble des projets, un cadre qualitatif par rapport aux émissions carbone, dans le but de mieux les définir et les réduire. Ce cadre intègre des points de référence et des interventions qui entraînent des réductions significatives, soutiennent les objectifs net zéro et favorisent une culture de durabilité. Nous avons mené une étude et une modélisation géotechnique et hydrogéologique innovante dans le cadre du projet de passage souterrain Mottram de l'autoroute A57, ce qui a mené à l'utilisation de pieux contigus comme solution rentable et préférable sur le plan environnemental.

Enfin, toujours dans ce numéro, nous présentons l'élaboration d'un cadre évolutif de gouvernance des données pour les organisations responsables d'infrastructures, en intégrant les systèmes, en améliorant la qualité des données et en soutenant la conformité. Le programme permet l'automatisation, le changement organisationnel et l'adoption de technologies émergentes, établissant par là même le rôle de la gouvernance des données comme catalyseur stratégique de l'innovation.

Les exemples ci-dessus ne donnent qu'une petite idée de la richesse de l'innovation que crée quotidiennement AtkinsRéalis et nous espérons que vous trouverez cette série d'articles intéressante, utile et inspirante.

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01: Cost-Benefit Analysis of Retrofitting Advanced Driver Assistance Systems in Ireland

Significance Statement

Adding Advanced Driver Assistance Systems (ADAS) to Ireland's older vehicles could make roads much safer. With most cars on Irish roads over nine years old, this research shows that retrofitting smart technologies—like collision warnings and lane departure alerts—could prevent hundreds of crashes and save lives, under the right conditions. When these systems perform at their best, especially in heavy goods vehicles, the safety benefits outweigh the costs. By encouraging upgrades through incentives, regulation, and education, Ireland can move closer to its goal of halving road deaths and injuries by 2030, making travel safer for everyone.

Énoncé d'importance

L'ajout de systèmes avancés d'aide à la conduite (ADAS) aux véhicules anciens en Irlande pourrait rendre la circulation routière beaucoup plus sécuritaire. La plupart des voitures circulant sur les routes irlandaises ayant plus de neuf ans, cette étude montre que l'installation a posteriori de technologies intelligentes, telles que les avertisseurs de collision et les alertes de sortie de voie, pourrait prévenir des centaines d'accidents et sauver des vies dans des conditions adéquates. Lorsque ces systèmes fonctionnent de manière optimale, particulièrement lorsqu'ils sont installés sur des véhicules lourds, les avantages pour la sécurité l'emportent sur les coûts. En encourageant ces mises à niveau au moyen d'incitatifs, de la réglementation et de campagnes de sensibilisation, l'Irlande peut se rapprocher de son objectif de réduire de moitié les décès et les blessures sur les routes d'ici 2030, rendant ainsi les déplacements plus sécuritaires pour tous.

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Abstract

This paper presents a comprehensive analysis of Ireland's Road Safety Authority initiative to retrofit Advanced Driver Assistance Systems (ADAS) as part of its strategy to halve road fatalities and injury collisions by 2030. With Ireland's average vehicle age exceeding nine years, the study examines two ADAS bundles tailored to different vehicle categories: Bundle 1 (Forward Collision Warning, Speed Limit Information, Lane Departure Warning) for passenger (Category M1) and light goods vehicles (Category N1), and Bundle 2 (with additional Turn Assist) for heavy vehicles (Category N2 and N3). In 2030, full implementation could prevent 7.2 to 15.1 fatalities and 177 to 494 injury collisions for passenger vehicles, while light goods vehicles with complete Bundle 1 implementation could prevent 1.1 to 2.2 fatalities and 19 to 52 injury collisions. Heavy goods vehicles with Bundle 2 implementation could reduce fatalities by 2.2 to 4.3 and prevent 11 to 33 injury collisions by 2030. The economic analysis demonstrates varying investment requirements and returns across vehicle categories: passenger vehicles require an investment ranging from €100 million to €1 billion, with benefits ranging from €64.1 million to €1.5 billion under different effectiveness scenarios; light goods vehicles show implementation costs ranging from €12.7 million to €128 million, with benefits spanning €7.1 million to €166 million; and heavy goods vehicles require investments from €12 million to €120.9 million, while generating benefits between €11.2 million and €231.2 million. The paper explores potential methods to realise these safety and economic benefits through investigating various implementation strategies, including financial incentives, regulatory measures, and awareness campaigns.

KEYWORDS

Road safety technologies; Advanced driver assistance systems; Connected and automated vehicles; Regulatory frameworks

1. Introduction

Ireland's fifth Government Road Safety Strategy outlines ambitious targets for the period between 2021-2030, aiming to reduce annual road deaths from 144 to 72 and injury collisions from 1,259 to 630. This comprehensive strategy encompasses 50 high-impact actions and 136 support actions across seven safety intervention areas, implemented in three phases. The safe vehicles intervention area, which addresses user safety through legislative standards, consumer information, and industry initiatives, forms a crucial component of this strategy.

The integration of Advanced Driver Assistance Systems (ADAS) represents a significant opportunity to enhance road safety through both collision avoidance and severity mitigation. In November 2019, the EU General Safety Regulations (GSR2) (EU) 2019/2144 established new requirements for ADAS implementation in both new and existing vehicle types. These regulations mandate several safety features for new vehicle types from July 2022 and existing types from July 2024. However, with Ireland's average vehicle age exceeding nine years, achieving meaningful safety improvements requires addressing the existing fleet through retrofit solutions.

The technical feasibility of ADAS retrofitting depends significantly on the ability to interface with vehicle systems. According to the (European Automobile Manufacturers' Association, 2016), integrating external devices with vehicle electronic systems presents notable cybersecurity challenges. To address these concerns, while maximising safety benefits, this study focuses on warning-only systems rather than those that intervene in vehicle control. This approach allows for enhanced safety features while minimising risks associated with unauthorised system access or potential cyber-attacks.

Research indicates that ADAS technologies working in combination deliver greater safety benefits than individual systems operating independently. This synergistic effect, combined with commercial availability and proven retrofit capability, guided the selection of two ADAS packages for this study: Bundle 1 (Forward Collision Warning, Speed Limit Information and Lane Departure Warning) for passenger vehicles (Category M1) and Light Goods Vehicles (LGVs) (Category N1), and Bundle 2 (including additional Turn Assist) for Heavy Goods Vehicles (HGVs) (Category N2 and N3).

This study addresses two primary objectives:

- To quantify the potential safety benefits and economic impacts of ADAS retrofitting across four adoption scenarios (10%, 40%, 60%, and 100% by 2030), examining fatality and injury collision prevention rates alongside comprehensive cost-benefit analysis.
- To develop evidence-based implementation strategies incorporating financial incentives, regulatory measures and awareness campaigns, drawing upon international best practices while addressing Ireland's specific context for building resilient mobility systems.

The significance of this research extends beyond immediate safety benefits, contributing to the broader framework of sustainable and resilient transport systems. By examining both economic viability and implementation strategies for ADAS retrofitting, this study provides valuable insights for policymakers, industry stakeholders and safety practitioners working towards enhanced road safety through technological adaptation of existing vehicle fleets.

2. Methodology

This study employs a comprehensive methodology to quantify the potential costs and benefits of ADAS retrofitting in Ireland.

2.1. SCENARIO DEVELOPMENT

The approach focuses on analysing multiple scenarios of technology adoption, assessing safety benefits and conducting a detailed economic evaluation. The baseline scenario represents the natural, market-driven adoption of ADAS systems as factory-fitted options. The study developed four additional scenarios that progressively increase the technological intervention across the vehicle fleet. These scenarios are designed to demonstrate the potential safety and economic benefits associated with more proactive ADAS implementation strategies.

The four comparative scenarios are structured as follows:

- **Slow Uptake Scenario:** 10% retrofit rate by 2030
- **Medium Uptake Scenario:** 40% retrofit rate by 2030
- **Medium-High Uptake Scenario:** 60% retrofit rate by 2030
- **High Uptake Scenario:** 100% retrofit rate by 2030

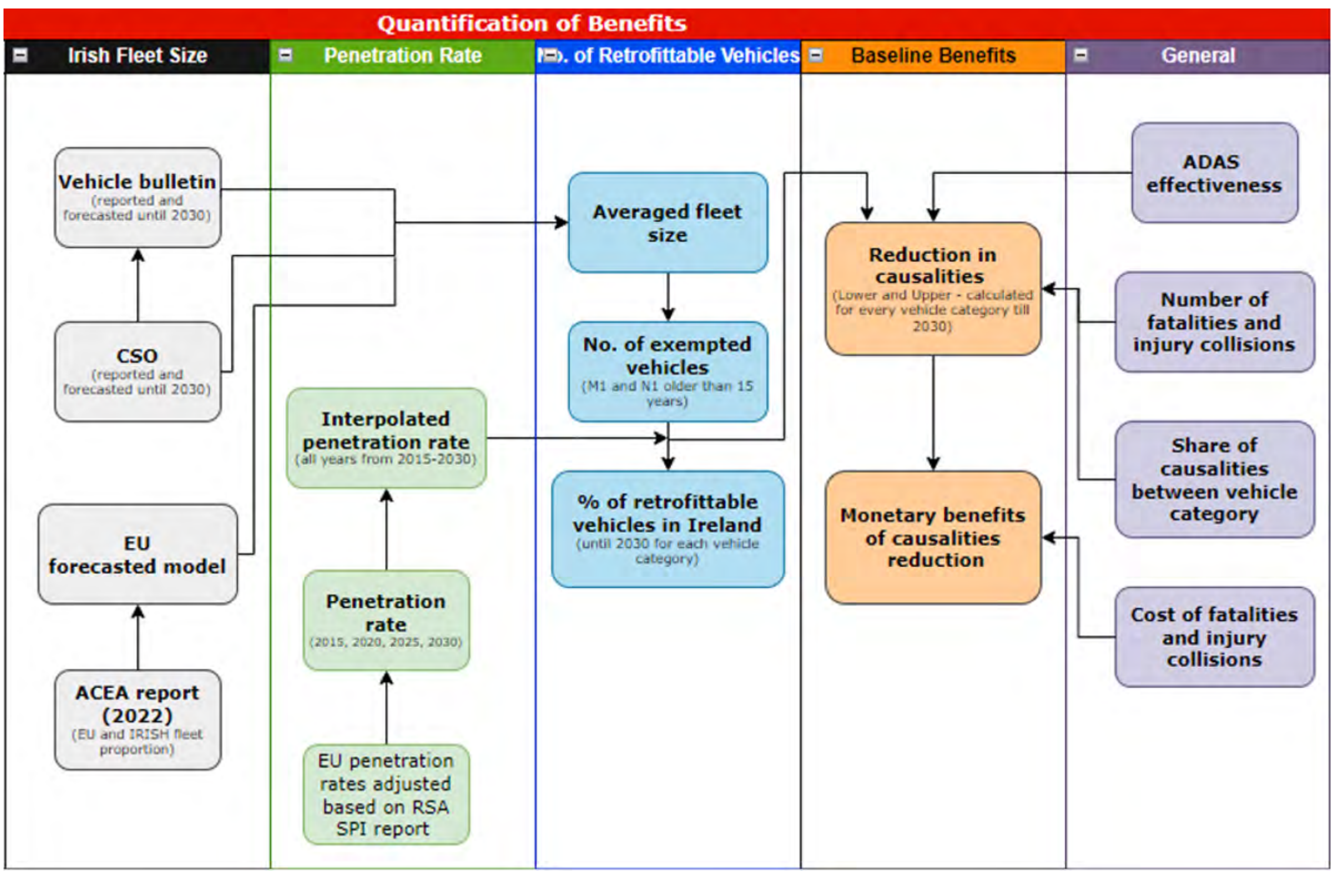
Each scenario will be incrementally applied to the retrofittable vehicle fleet, with annual retrofit rates increasing progressively to achieve the specified targets by 2030.

2.2. QUANTIFICATION OF BENEFITS

The methodology for quantifying benefits assesses ADAS safety impacts by building upon the EU study on the feasibility, costs and benefits of retrofitting advanced driver assistance to improve road safety by the (European Commission, 2020) and adapting it to reflect Ireland's transport environment. This approach was developed recognising that evaluating advanced vehicle technologies requires a comprehensive analytical process considering multiple interconnected factors. Figure 1 illustrates the analytical stages and data sources employed in this assessment framework.

FIGURE 1

Overview of the benefit quantification methodology



2.2.1. Fleet Size and Market Penetration Estimation

The fleet size forecasting analysis drew from two primary sources: the Irish Vehicle Bulletin's total taxed vehicle records (1985-2021) and the Central Statistics Office (CSO) data on vehicle population and kilometres (2008-2020). The analysis focused on 2015-2019 for projections, as this period provided consistent vehicle uptake patterns, avoiding both pre-2015 data variations and COVID-19 impacts.

For forecasting from 2020 to 2030, the analysis applied the average annual change observed between 2015 and 2019 to both datasets. Vehicle counts were determined by averaging figures from both the Irish Vehicle Bulletin and CSO sources, except for buses and coaches where only CSO data was available. The goods vehicle category was subdivided based on EU study (European Commission, 2020) proportions, with LGVs representing 80% and HGVs 20% of the total fleet.

Market Penetration Rates (MPR) were calculated in two steps: first establishing baseline MPRs for factory-fitted ADAS systems, then determining additional MPRs for each retrofit scenario. For Bundle 1, the baseline analysis began with a 1% fleet penetration rate in 2015. Market data from research firms (Gallagher, 2023) & (Canalys, 2021) showed rapid adoption in new vehicle registrations, rising from 25% in 2019 to 95% by 2025, reaching full market coverage by 2030. These baseline figures were applied to the total fleet size to determine vehicles already equipped with ADAS. The study then calculated additional MPRs for each retrofit scenario (10%, 40%, 60%, and 100%) to achieve their respective target rates by 2030.

Bundle 2's baseline calculation reflected HGVs' distinct technological adoption patterns. Starting from 1% fleet penetration in 2015, SIMI data showed new vehicle registrations with ADAS increasing to 30% in 2022, 60% in 2024, 75% in 2025 and 100% by 2030. After establishing this baseline, the study determined additional MPRs needed to meet each retrofit scenario's 2030 targets, accounting for HGVs' modular nature and longer update cycles.

The calculation of retrofittable vehicles began by identifying the total potential fleet for ADAS implementation in each year. This was determined by taking the total fleet size and subtracting two specific groups: vehicles already equipped with factory-fitted ADAS systems (identified through the Market Penetration Rate analysis) and vehicles deemed too old for economically viable retrofitting. Based on age analysis from the ACEA report, the study excluded 6% of passenger cars, 10% of LGVs, and 8% of HGVs from the retrofit pool due to age considerations exceeding 15 years.

This calculation established the total retrofittable fleet - vehicles that could feasibly receive ADAS upgrades. The study's adoption scenarios (10%, 40%, 60%, and 100%) were then applied to this retrofittable fleet number. For example, in the 10% scenario, the target was to retrofit one-tenth of all eligible vehicles by 2030, while the 100% scenario aimed to upgrade all retrofittable vehicles by the same date. This approach ensured that scenario targets were based on realistic vehicle numbers by excluding both vehicles already equipped with ADAS and those too old for practical upgrading.

2.2.2. ADAS Effectiveness Quantification

ADAS effectiveness parameter provides a critical quantitative assessment of potential reductions in fatalities and injury collisions across vehicle categories. For Bundle 1, the effectiveness figures were derived directly from the EU feasibility study (European Commission, 2020). The analysis uses a fatality reduction range of 12.90% to 27.20%, with corresponding injury collision reductions between 8.40% and 23.40%. Bundle 2 drew its effectiveness metrics from supplier trials, which demonstrate a fatality reduction range of 15.00% to 29.10%, with injury collision reductions spanning 9.77% to 25.04%.

2.2.3. Analysis of Collision Data

The analysis incorporates road traffic fatality and injury collision data from 2018 to 2023, sourced from the RSA, with projections maintained at constant 2023 levels through 2040. This conservative approach prevents potential overestimation or underestimation of ADAS retrofitting benefits. The dataset excludes single-vehicle collisions involving only pedal cycles or motorcycles, as ADAS implementation would not have an impact on these incidents. However, it includes single-vehicle collisions involving M1, M2, M3, N1, N2, and N3 vehicle categories.

The data reveals annual fatalities ranging from 126 to 171 between 2018 and 2023, whilst injury collisions fluctuated between 4,115 and 5,915 during the same period. From 2023 onwards, the figures are projected at 171 fatalities and 5,600 injury collisions annually.

Vehicle category analysis shows that M1 vehicles account for most incidents, representing 74% of fatalities and 86% of injury collisions. Heavy goods vehicles (N2 and N3) contribute to 13% of fatalities but only 3% of injury collisions. For incidents involving vulnerable road users, M1 vehicles maintain similar involvement rates, whilst heavy goods vehicles show higher fatality involvement at 18%.

2.2.4. Monetised Benefits Calculations

The study developed the following formula for calculating averted fatalities and injury collisions that integrates multiple critical variables:

Averted Fatalities/Injury Collisions = MPR of retrofitting ADAS × ADAS Effectiveness × Share of Vehicle Category in fatalities and injury collisions × Number of fatalities/Injury Collisions

This allows for a precise assessment of potential safety improvements across different ADAS technologies and vehicle categories. The formula was systematically applied across various years, enabling a detailed analysis of each ADAS system and bundle.

The anticipated number of averted fatalities and injury collisions was then monetised by multiplying the calculated reductions with the annual cost per fatality or injury collision. These economic valuations drew from the Common Appraisal Framework for Transport Projects and Programmes (Department of Transport - Ireland, 2023), which provides a comprehensive approach to assessing road safety economic impacts.

The economic analysis considered two primary cost components:

1. Casualty-related costs, encompassing human expenses, lost output and medical treatment
2. Collision-related costs, addressing material and administrative expenses from road traffic incidents

Cost indexing was performed using forecast growth in Gross National Product per person employed, ensuring a dynamic and contextually relevant economic assessment.

A critical aspect of the methodology is its extended timeframe. While the primary retrofitting activity is concentrated between 2025 and 2030, the safety benefits are projected to be realisable until 2040. This approach accounts for the continued presence of retrofitted vehicles in the transportation network, providing a comprehensive long-term perspective on potential safety improvements.

2.3. QUANTIFICATION OF COSTS

This analysis examines the unit cost calculation considering two primary cost components: initial purchase and installation costs. The total programme cost is calculated by multiplying the unit cost by the number of vehicles requiring retrofitting per year, specific to each ADAS system and vehicle category.

Initial costs encompass both equipment purchase and professional installation, with installation calculated using the standard EU labour rate of €49 per hour, according to the EU Feasibility study (European Commission, 2020). A market survey of Commercial Off-The-Shelf (COTS) products informed the pricing structure, with 2018 values adjusted to 2040 using a 4.25% inflation rate. The 2024 costs for Bundle 1 and Bundle 2, including installation considered in this study, are €748 and €1,673 respectively.

The analysis anticipates price reductions through economies of scale, projecting a 1.5% annual decrease from 2025 onwards in retrofit scenarios, aligned with Irish road safety strategy targets for 2030. The baseline scenario maintains stable prices, consistent with EU feasibility assessments (European Commission, 2020).

3. Results and Discussions

This section examines the outcomes of ADAS retrofit implementation across the vehicle fleet, presenting key findings on safety improvements, economic benefits, and cost sensitivities from 2025 to 2040.

3.1. PREVENTION OF FATALITIES AND INJURY COLLISIONS

Based on Ireland's 2023 baseline of 171 fatalities, the analysis projects that full implementation of Bundle 1 in passenger vehicles could prevent between 7.2 - 15.1 fatalities in total by 2030, as demonstrated in Table 1. This represents a reduction of 4.2% to 8.8% depending on ADAS efficiency. Similarly, from a baseline of 5,600 injury collisions, Bundle 1 implementation could prevent between 177 - 494 injury collisions, corresponding to a reduction of 3.2% to 8.8%. These projections specifically reflect retrofit efforts, excluding benefits from factory-fitted systems.

TABLE 1

Number of prevented fatalities and injury collisions due to the uptake of Bundle 1- Category M1

Uptake Scenarios	In 2030		Cumulative (2025-2040)	
	Fatalities Avoided (Low to High Effect.)	Injury Collisions Avoided (Low to High Effect.)	Fatalities Avoided (Low to High Effect.)	Injury Collisions Avoided (Low to High Effect.)
10%	0.7 – 1.5	18 – 49	8.0 - 17.0	198 – 550
40%	2.9 – 6.0	71 – 198	32.0 - 67.0	783 – 2180
60%	4.3 – 9.1	106 – 297	47.0 - 100.0	1170 – 3259
100%	7.2 – 15.1	177 - 494	78 - 165.0	1937 - 5397

LGV implementation of Bundle 1 could prevent 1.1 to 2.2 fatalities and 19 to 52 injury collisions. This represents a 0.6% to 1.3% improvement on forecast fatalities for 2030. For HGVs, Bundle 2 implementation at 100% penetration could reduce annual fatalities by 2.2 to 4.3 (1.3% to 2.5% decrease) and prevent 11 to 33 injury collisions by 2030. As with passenger vehicles, lower penetration rates yield proportionally reduced benefits, with impact variations closely tied to both ADAS efficiency and market uptake levels.

3.2. MONETISED BENEFIT OF FATALITIES AND INJURY COLLISIONS

The monetisation of safety benefits reveals significant potential across all vehicle categories. Passenger vehicles demonstrate the highest absolute benefits, ranging from €5.4M-€131M in 2030 across different uptake scenarios, as demonstrated in Figure 2 and Figure 3.

FIGURE 2

Monetary benefit due to reduction in fatalities and injury collisions (Low Effectiveness ADAS) - Category M1

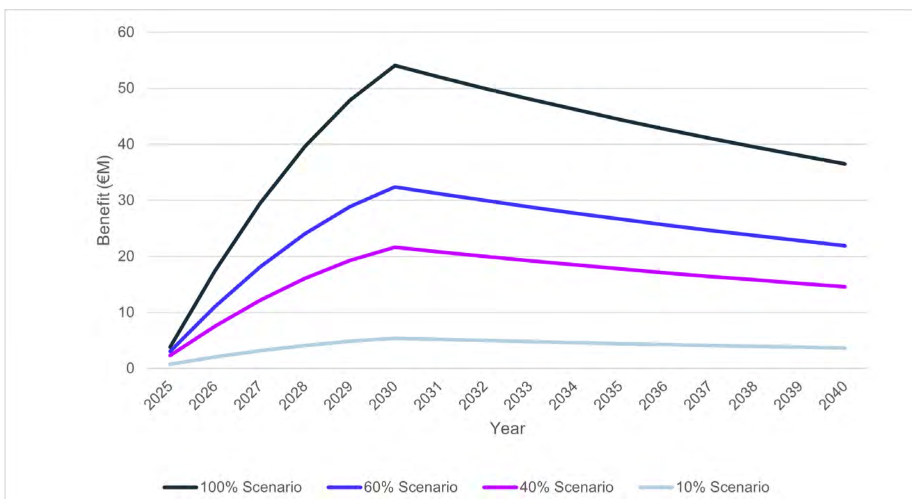
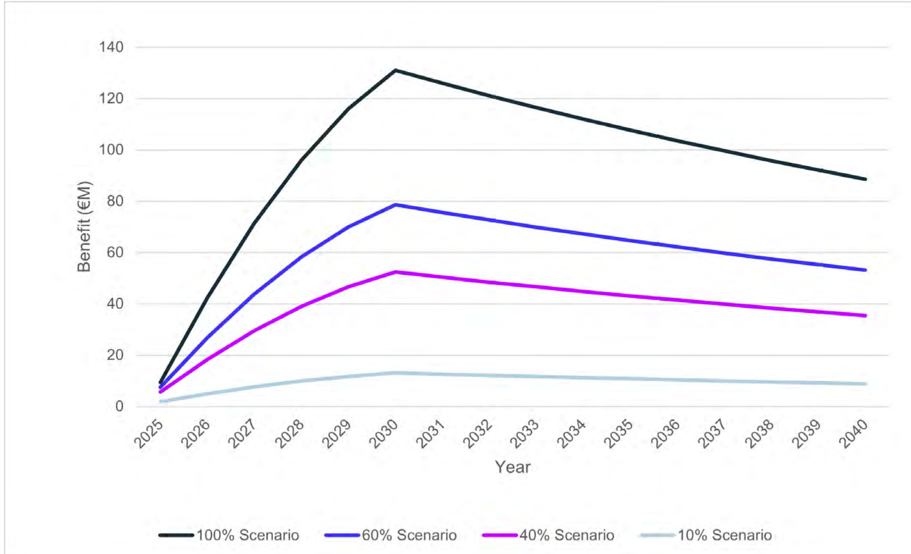


FIGURE 3

Monetary benefit due to reduction in fatalities and injury collisions (High Effectiveness ADAS) - Category M1



LGVs show more modest but still substantial benefits between €0.7M-€16.4M, while HGVs demonstrate benefits ranging from €1.05M-€22M. These variations correspond to different uptake rates (10-100%) and effectiveness levels, with higher uptake scenarios consistently showing proportionally greater benefits.

3.3. CUMULATIVE COST VS MONETISED BENEFITS

The cost-benefit analysis reveals that low-effectiveness ADAS systems fail to justify implementation costs across all vehicle categories. However, systems with higher effectiveness levels demonstrate significant positive net benefits, particularly in scenarios with optimal performance.

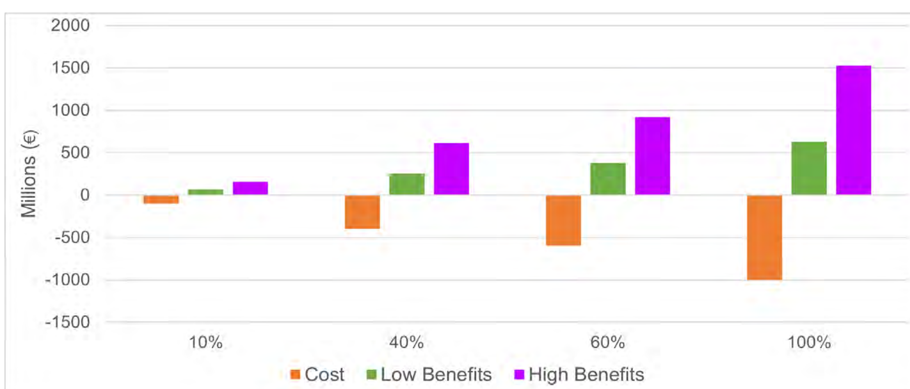
In Figure 4, the economic analysis demonstrates varying investment requirements and returns across different vehicle categories:

- **Passenger vehicles:** These require an investment ranging from €100 million to €1 billion, with benefits ranging from €64.1 million to €1.5 billion under different effectiveness scenarios, as demonstrated in Figure 4.
- **Light goods vehicles:** Implementation costs range from €12.7 million to €128 million, with benefits spanning €7.1 million to €166 million.
- **Heavy goods vehicles:** These require investments from €12 million to €120.9 million, while generating benefits between €11.2 million and €231.2 million.

The analysis considers implementation costs from 2025-2030 against cumulative benefits from 2025-2040, providing a comprehensive view of long-term economic implications. This extended timeframe captures the full trajectory of returns, revealing that scenarios with lower benefit estimates fail to achieve cost recovery, while high-benefit scenarios yield a positive benefit-cost ratio.

FIGURE 4

Cumulative cost vs monetised benefits (2025 – 2040) for passenger cars (M1)



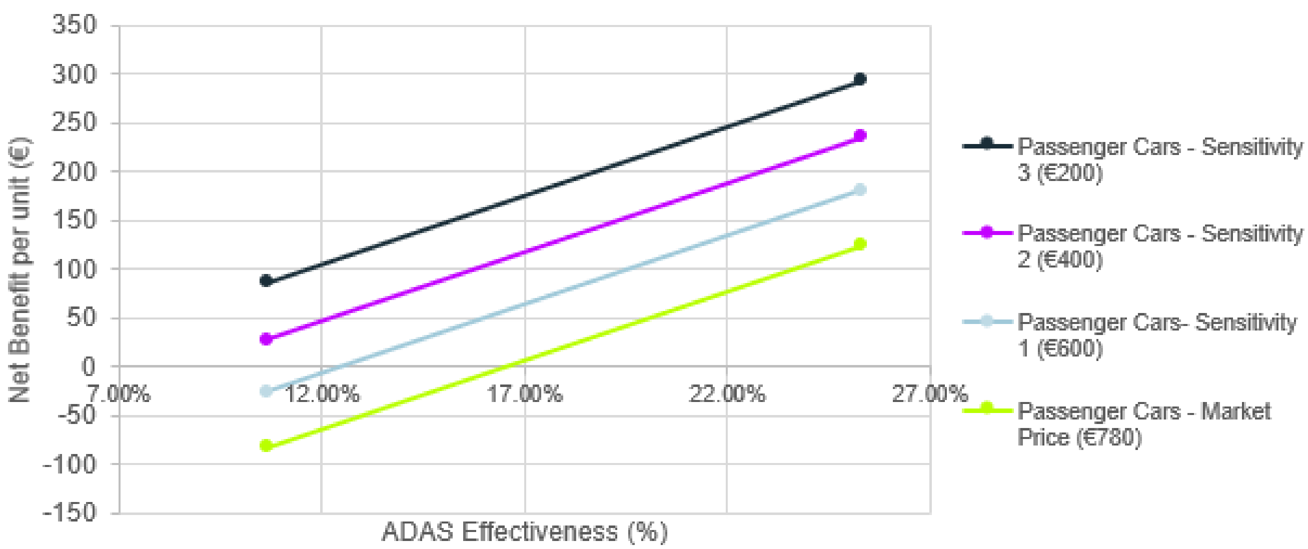
3.4. SENSITIVITY ANALYSIS FOR UNIT COST

The sensitivity analysis of unit costs and net benefits for ADAS across different vehicle categories reveals compelling insights about the economic viability of ADAS implementation. Figure 5 illustrates the relationship between unit costs and net benefits for passenger vehicles (M1), demonstrating that net benefits are highly responsive to cost variations, particularly when ADAS effectiveness is at lower levels. The graph clearly shows that whilst lower unit costs generate positive net benefits, these benefits diminish and eventually become negative as costs increase. This relationship underscores the critical importance of cost management in ADAS implementation strategies. The figure further demonstrates that although increased ADAS effectiveness improves the net benefit profile, the impact of cost remains a dominant factor in determining overall economic viability.

When examining the broader vehicle category landscape, LGVs exhibit characteristics that suggest greater resilience to cost escalation compared to passenger vehicles, albeit with lower total benefits due to their smaller fleet size. Most notably, HGVs emerge as the most promising category for ADAS implementation, demonstrating robust positive benefits even at elevated cost levels. This analysis suggests that whilst cost management remains crucial across all vehicle categories, the economic case for ADAS retrofitting strengthens significantly in the commercial vehicle sector, with HGVs presenting the most compelling opportunity for investment and returns.

FIGURE 5

Net benefit per unit for passenger vehicles (M1)



4. Conclusions

This study provides compelling evidence that retrofitting ADAS in Ireland's existing vehicle fleet can deliver substantial safety and economic benefits. Under high-effectiveness scenarios, full implementation of Bundle 1 in passenger vehicles could prevent up to 165 fatalities and over 5,000 injury collisions by 2040. Light goods vehicles and heavy goods vehicles also show meaningful reductions in road trauma, with HGVs demonstrating particularly strong cost-benefit performance.

The economic analysis confirms that while low-effectiveness systems may not justify investment, high-effectiveness ADAS retrofits yield positive net benefits—especially in commercial vehicle sectors.

These findings support a strategic shift towards proactive retrofitting policies, complementing factory-fitted adoption and accelerating progress towards Ireland's 2030 road safety targets in line with EU objectives.

To realise these benefits, a coordinated national strategy is essential. This should include:

- **Targeted financial incentives** to support early adopters.
- **Clear regulatory timelines** for mandatory retrofitting in high-risk vehicle categories.
- **Robust monitoring frameworks** to track adoption and safety outcomes.
- **Public education and technical training** to ensure effective implementation and maintenance.

By acting now, policymakers can accelerate progress toward halving road fatalities and injuries and build a more resilient, technologically advanced mobility system. This approach also offers a scalable model for other countries with ageing fleets and evolving safety standards.

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02: Safer Drinking Water through Advanced Digital Simulations: Optimizing Urban Reservoir Performance

Significance Statement

Reservoirs keep our drinking water safe, but when they are repaired or upgraded, sections must stay in service to maintain supply. This creates temporary layouts that can trap water and weaken disinfection—risks invisible to the naked eye. Our work uses advanced digital simulations to "see inside" the reservoir, revealing how water really moves and where problems form. We showed that small, low-cost changes to flow paths can cut water age by half, reducing the need for flushing. For clients and communities, this means safer water, smarter spending, and greater confidence during critical infrastructure projects.

Énoncé d'importance

Les réservoirs assurent la salubrité de notre eau potable, mais lorsqu'ils doivent être réparés ou améliorés, certaines sections doivent demeurer opérationnelles pour maintenir l'approvisionnement. La mise en place de circuits temporaires peut engendrer des soucis de stagnation de l'eau et de désinfection inadéquate – des risques qui sont invisibles à l'œil nu. Notre méthode fait donc appel à des simulations numériques avancées, qui permettent en quelque sorte de « voir à l'intérieur » du réservoir pour déterminer comment l'eau s'écoule exactement et où les problèmes surviennent. Nous avons démontré comment de petits changements aux circuits peu coûteux peuvent réduire de moitié le temps d'écoulement de l'eau vers l'utilisateur, réduisant ainsi le besoin de vidange. Pour les clients et les collectivités, cela signifie une meilleure salubrité, des dépenses plus judicieuses et une plus grande sérénité lors de projets impliquant des infrastructures essentielles.

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Abstract

When urban reservoirs undergo rehabilitation, the work is typically phased, with sections closed for construction while others remain in operation to maintain supply. These temporary layouts can alter flow patterns, creating risks such as stagnation, uneven disinfectant distribution, and higher water age. This paper shows how Computational Fluid Dynamics (CFD) supports managing these risks with decision-grade evidence. Using OpenFOAM®, a four-cell reservoir was simulated with a dynamic free surface driven by a 24-h hydrograph and advanced over ten cycles to a statistically periodic state. Water age and inferred chlorine decay were mapped under baseline conditions, revealing a recirculation zone with elevated age in one cell. A layout adjustment that removed a flow shortcut and enforced serial passage through all cells reduced stagnation and cut maximum water age by ~50%, meeting operational criteria. The results demonstrate how CFD helps utilities validate rehabilitation layouts, protect water quality, and avoid costly trial-and-error.

KEYWORDS

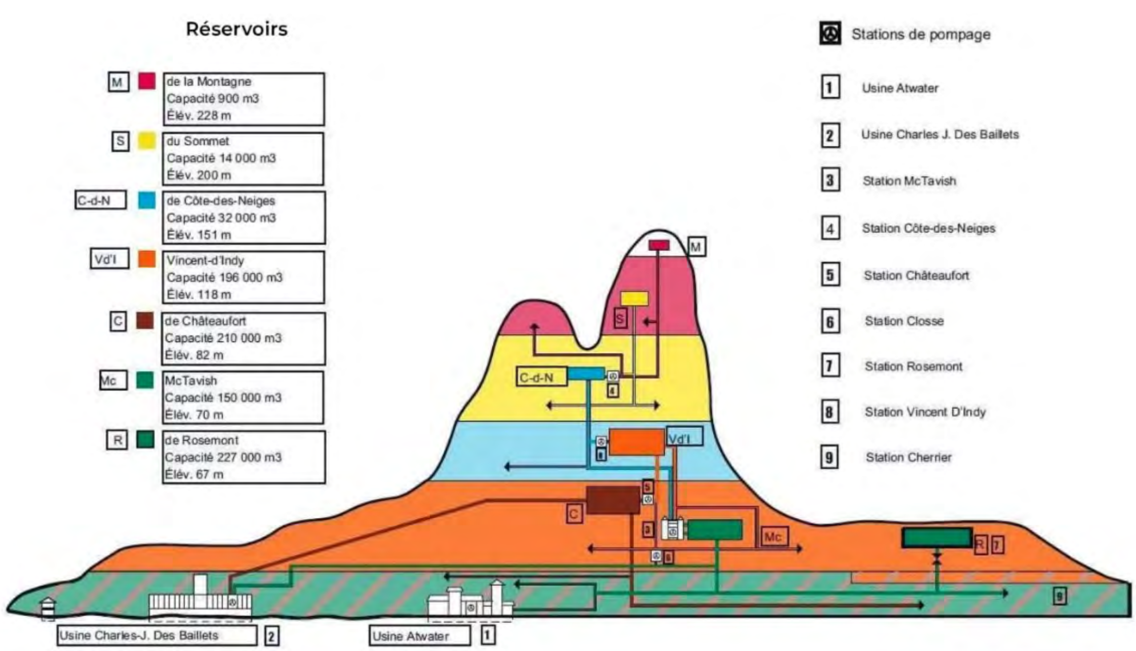
Computational fluid dynamics (CFD); Urban water reservoirs; Water quality optimization; Hydraulic infrastructure; Data-driven decision making

1. Introduction

Urban reservoirs (including treated water storage tanks and impounding reservoirs) are crucial components of municipal water supply systems worldwide. They provide buffer storage to balance supply and demand, maintain stable pressure, and ensure a continuous supply during peak usage or emergencies (Clark, Abdesaken, Boulos, & Mau, 1996). Reservoirs also serve as the final point where water quality can be monitored and adjusted before distribution to consumers (Kruger, 2001). A well-managed reservoir helps guarantee that safe, clean drinking water is delivered reliably to millions of urban residents. At AtkinsRéalis, the Water Infrastructure department and the Simulation and Modeling team support clients in achieving these objectives by providing expertise in the design, operation, and optimization of reservoir systems. Figure 1 offers a visual overview of Montréal's water distribution infrastructure as an example, including the pumping stations and reservoirs served by the Charles-J.-Des Baillets and Atwater treatment plants and Atwater treatment plants (Lussier 2013).

FIGURE 1

Water distribution infrastructure and underground pipelines in Montréal.



1.1 CHALLENGES IN AGING RESERVOIRS

Urban water reservoirs are essential for ensuring a reliable and safe water supply. However, many of these critical structures are aging and require rehabilitation to address issues like structural deterioration, leaks, and outdated designs.

- **Maintaining Operations During Rehabilitation:** A key challenge during reservoir rehabilitation is maintaining uninterrupted water supply. Often, these reservoirs cannot be taken entirely offline due to their critical role in the distribution system. Consequently, renovations are conducted in phases, with sections of the reservoir temporarily closed for construction while other parts remain operational. This phased approach demands meticulous planning to ensure water quality is not compromised during construction activities.
- **Testing Temporary Layouts to Ensure Water Quality:** Operating a reservoir in a partially closed state can alter water flow patterns, potentially leading to issues such as stagnation, uneven disinfectant distribution, and increased water age in certain areas. These impacts on water quality require thorough validation of temporary operational layouts before implementation. Computational Fluid Dynamics (CFD) simulations serve as a valuable tool in this context, allowing engineers to model different scenarios, predict potential problem areas, and adjust plans accordingly to maintain optimal water quality throughout the renovation process.

1.2 FROM TRIAL-AND-ERROR TO CFD SIMULATION

Traditionally, water utilities have managed reservoir performance through experience-based methods—adjusting pump schedules, performing periodic flushing, or installing mixers based on general guidelines or trial-and-error. Although sometimes effective, these strategies lack precision. Operators typically rely on limited field measurements or routine sampling, which provide only partial insight into what is actually happening inside a large reservoir. As a result, problems like water stagnation, short-circuiting, or chlorine decay may go undetected until after customer complaints or water quality violations occur (Clark & Grayman, 1998).

Computational Fluid Dynamics (CFD) has significantly advanced the analysis of hydraulic behavior within storage tanks. It allows engineers to visualize internal currents, identify stagnant zones, and estimate water age or disinfectant decay across the entire tank. This level of detail is nearly impossible to capture with manual testing alone. With CFD, engineers can explore "what-if" scenarios—such as closing part of the reservoir for maintenance, changing inlet/outlet locations, or adding a temporary pump—and see the effects before making any physical changes (Yi et al., 2020). This predictive capability greatly reduces risk, saves time, and supports smarter infrastructure planning. Instead of costly field tests or uncertain trial configurations, utilities can quickly evaluate multiple scenarios using digital simulations. As digital engineering tools become more accessible, CFD is increasingly recognized as a key solution for modern water quality management, especially during construction or rehabilitation when temporary layouts must be validated (Interdepartmental Water Quality Training Board (Canada), 2009).

1.3 GLOBAL PERSPECTIVE AND STRATEGIC RELEVANCE

Globally, ensuring high-quality drinking water has become a key priority for urban infrastructure management. Water storage reservoirs are recognized worldwide as critical points where water quality must be carefully monitored and controlled. This paper aims to demonstrate how advanced CFD simulations can significantly enhance water quality management in urban reservoirs by accurately modeling flow patterns, identifying areas prone to stagnation, and optimizing disinfectant distribution. These insights enable proactive, data-driven decisions, which align directly with global best practices and regulatory requirements, such as those outlined by the EPA (U.S.) and European water standards. Applying CFD during reservoir rehabilitation or routine operation adjustments thus supports safer, more efficient, and resilient water systems, aligning strategically with infrastructure modernization, climate change resiliency, and digitally enabled service goals.

2. Understanding the Methodology

To explore how temporary changes in reservoir layout affect water quality, we can develop a series of detailed CFD simulations. Here we use OpenFOAM®, a widely used engineering software. These simulations allowed us to virtually test different operational scenarios—such as closing certain reservoir sections or adding temporary pumps—before any physical changes were made.

2.1 MODELING THE RESERVOIR

The reservoir is digitally recreated using a high-resolution mesh, which breaks the space into millions of small blocks. This mesh helps the software calculate how water flows through each part of the reservoir. We pay special attention to areas where water might slow down or stagnate, as these are often linked to poor water quality.

Figure 2 presents a simplified mock-up of the reservoir used for this study. It consists of four cells with different shapes, with the mesh structure clearly shown. The figure also indicates the locations of two intake points and one outtake.

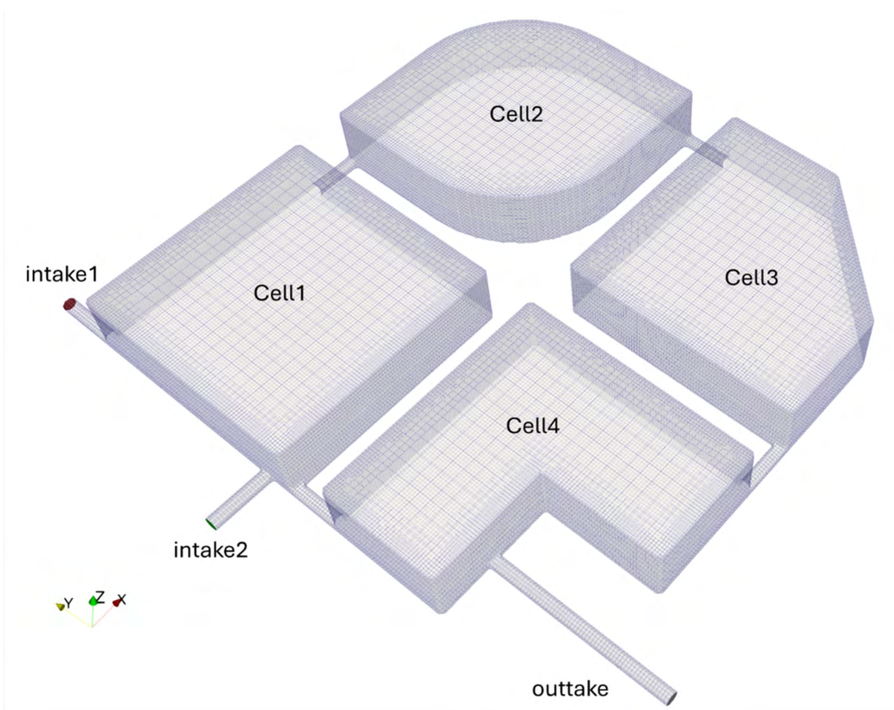


FIGURE 2

Mock-up reservoir model with mesh structure, intakes, and outtake.

To simulate realistic conditions, we include:

- **Water age tracking:** This shows how long water stays in one place. Older water tends to lose chlorine and may pose health risks.
- **Chlorine estimation:** We use water age to estimate how chlorine levels would decline over time.
- **Dynamic water levels:** The mesh adapts to changing water levels, reflecting how reservoirs operate in real life.

We usually assume the water temperature stays relatively constant, which is typical for shallow urban reservoirs that are refreshed daily. This simplification helps focus the analysis on flow patterns and disinfectant behavior.

2.2 INITIAL SIMULATION: IDENTIFYING THE PROBLEM

This paper includes two simulations. The first simulation models a reservoir with four interconnected cells, each with a unique shape and volume. Inlet and outlet locations are defined to reflect typical operational conditions during partial closure.

The results show that most areas had good circulation. However, one cell has relatively elevated water age, indicating stagnation and suggesting a risk of chlorine decay and reduced water quality.

2.3 ENHANCED SIMULATION(S): SOLVING THE PROBLEM

In general, the mitigations usually include:

- Additional outtake points to improve water removal.
- A temporary circulation pump in the downstream cell to boost flow.
- Dual jet streams from an upstream cell to increase mixing.
- Temporary flexible baffles/curtains to lengthen the flow path and reduce short-circuiting.
- Inlet/outlet reconfiguration (e.g., drop pipes or perforated diffusers) to target depth and distribute inflow evenly.

These changes are designed to be practical and reversible—ideal for temporary use during construction.

In this case study, we ran a second simulation with modified inter-cell connections. The results are clear: water age dropped significantly across all cells, and the previously stagnant zone showed uniform circulation. This confirmed that even modest operational adjustments, when guided by CFD insights, can significantly improve water quality.

2.4 PRACTICAL TARGETS AND DECISION CONFIDENCE

The primary objective is to keep water age below the agreed criteria (e.g., ≤5 days, a common benchmark for safe water). The simulations can be calibrated with field data, and they can provide reliable comparisons between different layouts. This helps identify the most effective strategies for maintaining water quality during temporary disruptions.

3. Results: Making Reservoirs Perform Better

Both scenarios were driven by the same 24-hour inflow-outflow pattern and advanced for ten full cycles. We assessed results only after the system reached a statistically steady periodic state, then traced scalar quantities (water age and chlorine concentration inferred from age) to evaluate water quality. Figure 3 presents the 24-hour inflow-outflow hydrograph used in both simulations, confirming cycle-wise mass balance, while Figure 4 shows the corresponding free-surface fluctuations over one cycle—reproduced by the dynamic mesh—to capture daily drawdown and recovery without net storage drift across cycles.

FIGURE 3

Inflow-outflow balance over a 24-hour cycle (mass-balanced hydrograph)

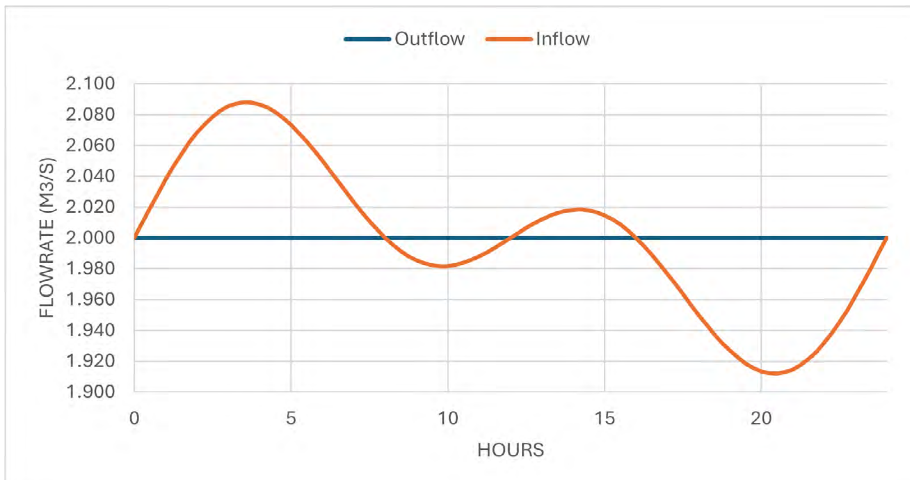
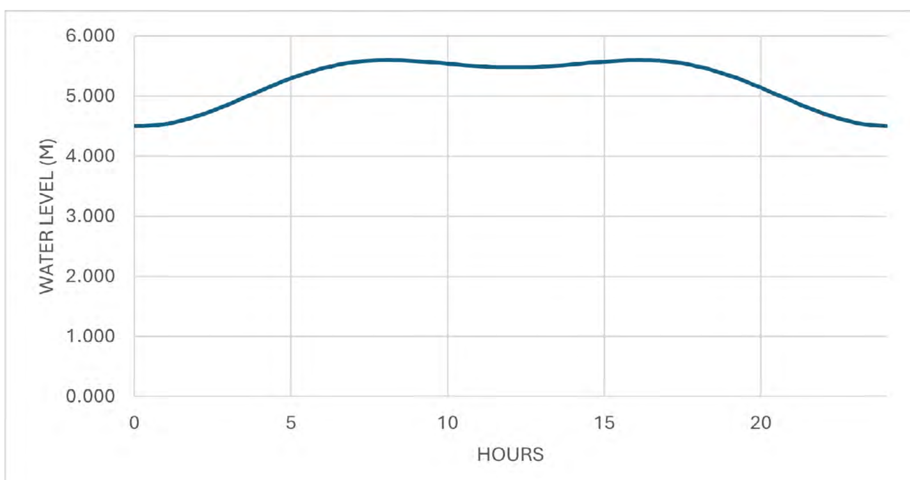


FIGURE 4

Water-surface fluctuation over a 24-hour cycle



3.1 SIMULATION 1 (BASELINE): WHERE THE WATER LINGERS

The reservoir is made up of four connected cells. Two intake pipes feed into Cell 1, and one outlet pipe draws water from Cell 4. During a typical 24-hour cycle, the flow pattern at a representative moment is shown in Figure 5. Fast-moving jets enter Cell 1 and follow the walls and narrow passages, but the center areas of the cells are much slower. In Cell 2, the curved shape creates a large swirl that doesn't mix well with the main flow—this is visible as a smooth, low-speed zone away from the faster paths.

The water age map at the end of the cycle (Figure 6) confirms this pattern. Water near the intakes in Cell 1 is fresh, but it gets older as it moves through the reservoir. In Cell 2, old water builds up in the same area as the swirl, showing poor mixing. More aging appears along the lower path to Cell 4. This pattern flags a mixing deficiency and motivates the layout change tested in Simulation 2.

FIGURE 5

Simulation 1 - Plan-view velocity magnitude

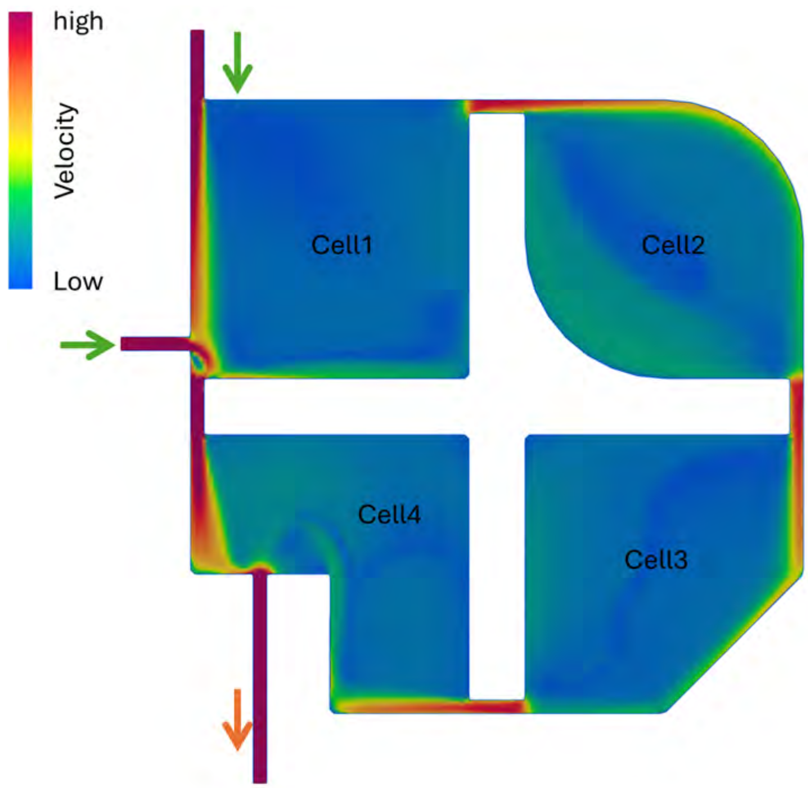
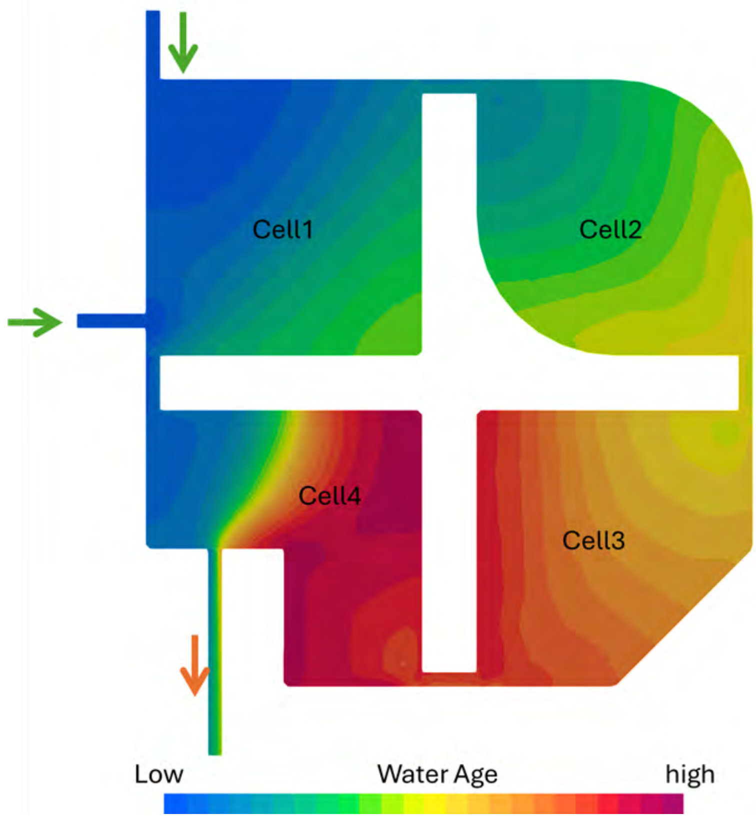


FIGURE 6

Simulation 1 - Water age at the end of cycle 10



3.2 SIMULATION 2 (LAYOUT ADJUSTMENT): TURNING FLOW INTO TURNOVER

In the updated design, Cell 1 is no longer directly connected to Cell 4. This change removes a shortcut and forces water to pass through all four cells. The flow snapshot in Figure 7 shows a more organized movement: fast flow follows the edges and reaches the outlet, while the center areas no longer trap slow-moving water like before. In Cells 3 and 4, water is guided along the boundary toward the outlet, reducing the chance of stagnation.

The water age map in Figure 8 shows the improvement. The old water zones seen in Simulation 1 are gone, and the age is more evenly spread. The maximum water age drops by 50%. Cell 1 still has the freshest water near the intakes, but Cells 3 and 4 now show smoother age patterns that follow the outlet path. Overall, Simulation 2 shows that the new layout improves mixing, reduces stagnation, and helps maintain water quality more effectively.

FIGURE 7

Simulation 2 - Plan-view velocity magnitude

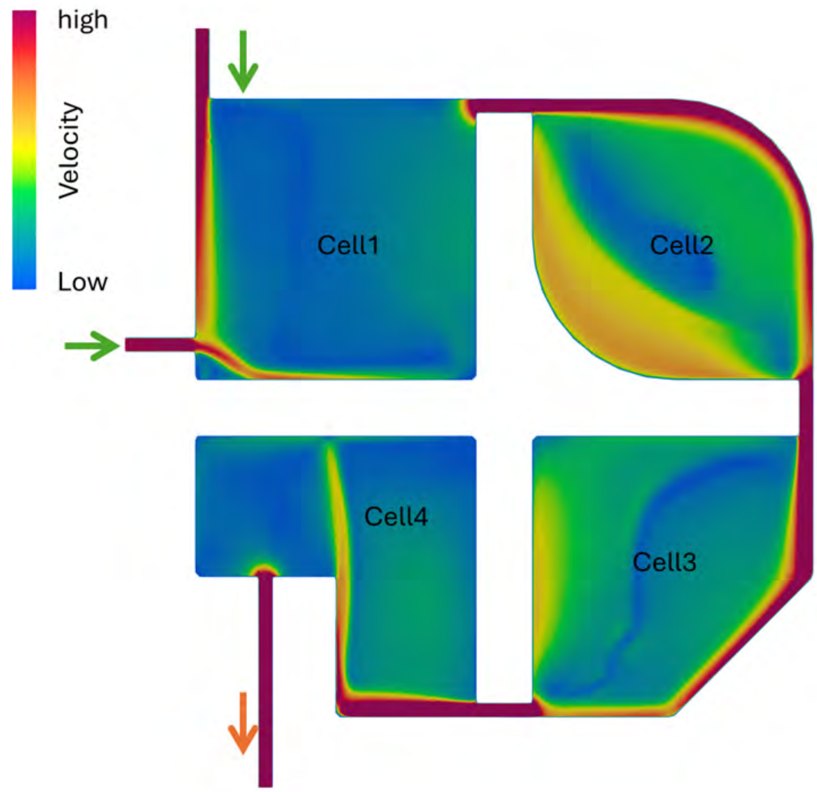
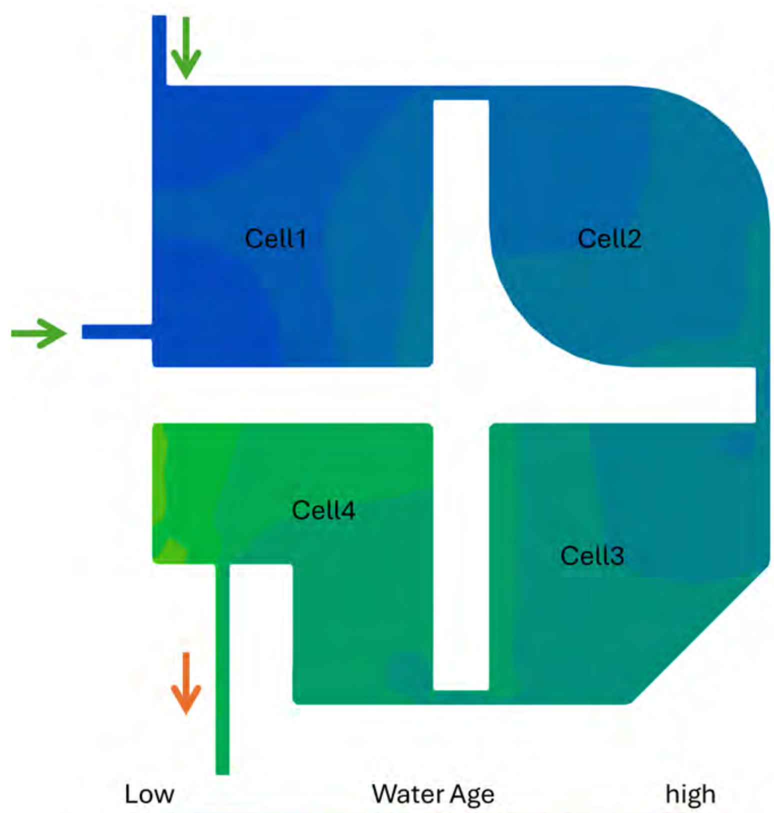


FIGURE 8

Simulation 2 - Water age at the end of cycle 10



4. Practical Benefits and Strategic Alignment

In practice, CFD turns complex hydraulics into clear options with quantified trade-offs. For clients, that means informed decisions, cleaner regulatory submissions, and focused spend on what truly moves the needle. For peers, a shared, repeatable workflow aligns hydraulics, process, structural, and operations, lifting technical capacity across the team. Communities see steadier water quality and fewer, shorter service interruptions. For projects, the approach de-risks phasing and accelerates refurbishment and maintenance by targeting the highest-impact temporary works.

This is also AtkinsRéalis in action. It operationalizes digitally enabled services through calibrated models and decision-ready visuals; helps decarbonize the built environment by replacing blanket flushing and unnecessary physical interventions with targeted measures; strengthens climate resiliency and long-term asset sustainability by stress-testing seasonal and demand scenarios; and brings cross-sector analytical methods that transfer to nuclear and other regulated systems.

5. Conclusion and Next Steps

CFD turns a black box into a dashboard. In this study, it revealed where water lingered, showed how simple, temporary changes reshape circulation, and quantified the impact—lower water age and more uniform residuals—before anyone moved a valve. The takeaway is straightforward: simulation-led choices deliver safer water with less disruption, less guesswork, and better use of budget.

To embed this value, make CFD a standard check for any reservoir rehabilitation or operating change. Use calibrated models with clear acceptance criteria, keep a library of reusable templates for common layouts, and pair results with simple visuals and one-page option matrices for quick, defensible decisions. Build light-touch QA (mesh checks, sensitivity runs) into the workflow so findings are consistently "decision grade" across projects and teams. Not only do these tools strengthen our solutions for reservoir-related projects and add immediate value for clients, but they also establish a framework that extends to other AtkinsRéalis services, including wastewater treatment, tailings management, and surface water contamination control.

Looking ahead, several opportunities exist to enhance operational planning and system resilience:

- Real-time, data-integrated models (e.g., SCADA ingestion) to support predictive "what-if" scenario analysis.
- Automated scenario sweeps and optimization techniques to balance water quality, energy consumption, and chemical usage.
- Expanded stress testing protocols—including seasonal variability, emergency response, and partial system outages—to improve robustness under uncertainty.
- A continuously growing case library to benchmark performance expectations and facilitate approval processes.

In summary, the objective is to visualize hydraulic behavior, evaluate operational alternatives, and identify the optimal solution prior to implementation.

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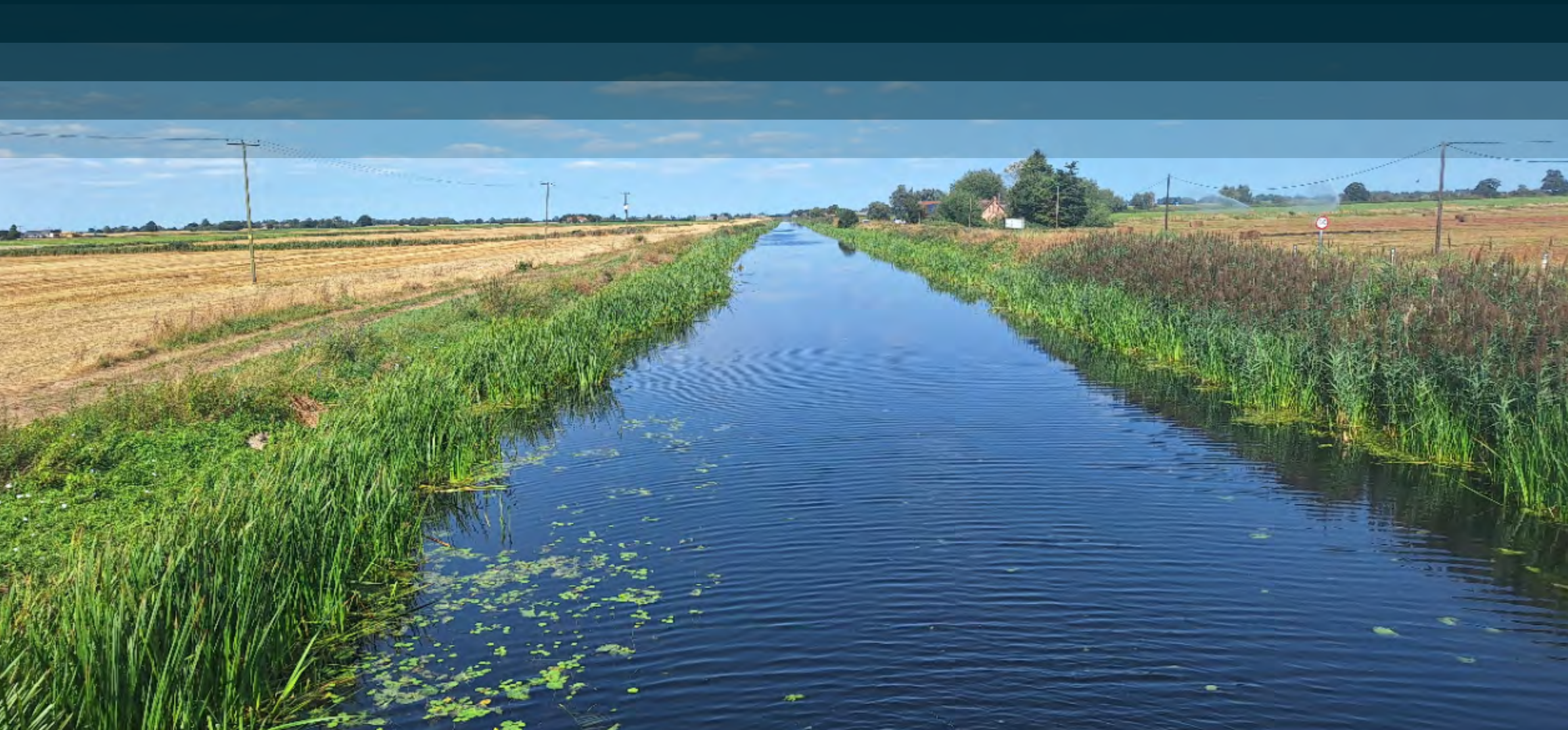
03: Algorithmic Thinking and Agile Delivery in Linear Infrastructure

Significance Statement

Algorithmic design tools helped accelerate flood protection planning in England. Engineering expertise was adopted into logical processes to analyse 178 km of riverbanks, completing key project goals three months early. The approach revealed that the scale of the work was much greater than first expected, helping stakeholders plan more effectively. By replacing manual methods with computational and logic driven design workflows, the project became faster, more flexible, and easier to adapt. This new way of working offers a model for future infrastructure projects, especially those involving long stretches of land like rivers, railways, power lines, pipelines, or transport routes.

Énoncé d'importance

Des outils de conception algorithmique ont permis d'accélérer et de clarifier l'étendue de la planification de la protection contre les inondations en Angleterre. L'expertise en ingénierie a été intégrée aux processus logiques pour analyser 178 km de berges, permettant ainsi d'atteindre les objectifs du projet avec trois mois d'avance. Cette approche a révélé que l'ampleur des travaux était plus grande que prévu. Ce constat précoce a aidé les parties prenantes à planifier de manière plus efficace. En substituant aux méthodes manuelles une démarche de conception s'appuyant sur la logique et des calculs avancés, le projet a gagné en vitesse, en flexibilité et en adaptabilité. Cette nouvelle façon de faire constitue un modèle potentiel pour des projets d'infrastructure futurs, notamment ceux qui s'étendent sur de grandes distances comme le long de rivières, de voies ferrées, de lignes électriques, de pipelines ou de voies de transport.



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Abstract

This paper presents a technical case study of the Middle Level System River Management Scheme (MLSRMS), a nationally significant flood risk infrastructure programme in the UK. The project involved the assessment and design of flood defence interventions across 178 km of watercourses within a constrained budget and timeline. To meet these challenges, the authors adopted a computational design framework and agile delivery model, leveraging parametric modelling, geospatial data integration, and visual programming.

These methods enabled the automation of embankment analysis, early cost forecasting, and scalable stakeholder engagement. The approach accelerated the concept design phase by over three months, delivering actionable insights to the client ahead of schedule. This paper documents the engineering logic, digital workflows, and agile practices that underpinned the project, offering a replicable model for data-driven linear infrastructure delivery. The findings demonstrate how computational methodologies can enhance design assurance, reduce programme risk, and support strategic decision-making in flood resilience planning.

KEYWORDS

Computational Design; Agile Delivery; Parametric Modelling; Flood Risk Infrastructure; Visual Programming

1. Introduction

The Middle Level System River Management Scheme (MLSRMS), referred to as "The Project," is a nationally significant flood risk infrastructure programme. AtkinsRéalis was appointed by Balfour Beatty as the design consultant for this contract. The scheme addresses the long-term resilience of critical watercourses within the Middle Level System (MLS), a low-lying catchment between the River Nene and the Great Ouse in Cambridgeshire, UK. This region, encompassing an area of over 690 km², is highly dependent on engineered drainage infrastructure, including embankments, pumping stations, navigable channels for flood protection, water level management, and agricultural viability [1][2].

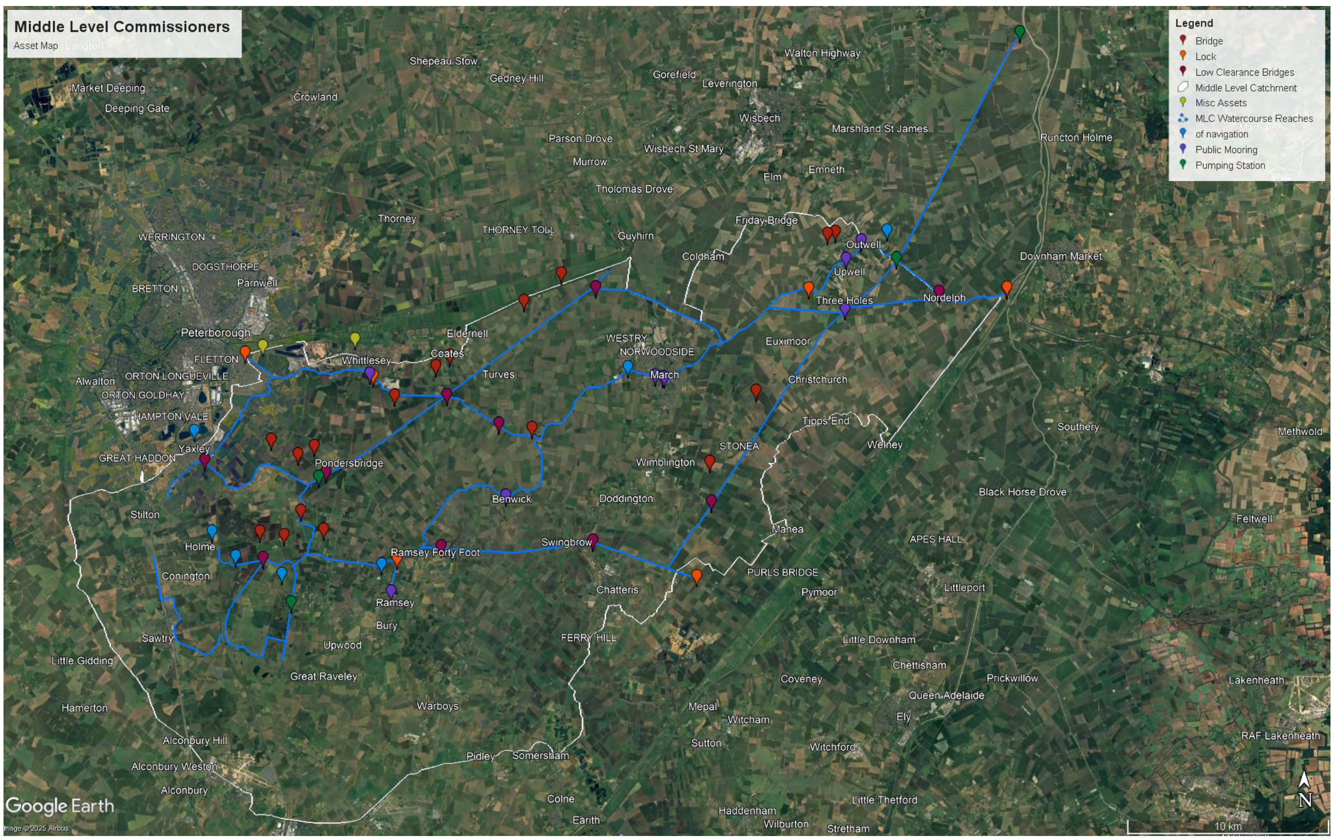
Middle Level Commissioners secured funding from UK government as part of the Environment Agency's 2021–2027 flood and coastal erosion risk management capital programme, specifically Department for Environment, Food and Rural Affairs (Defra) Flood Defence Grant in Aid (FDGiA) funding [5]. The scheme aims to deliver a 1.5% Annual Exceedance Probability (AEP) standard of protection to the 2050s, aligned with the Fens 2100+ adaptive strategy [3][4].

The traditional design workflow would have protracted the concept design phase or postponed critical insights until the detailed design stage, increasing the risk of late-stage rework and budget misalignment. To overcome this, AtkinsRéalis, implemented a computational design framework and agile delivery model. This digital-first approach leveraged parametric modelling, geospatial data integration, and visual programming to automate embankment analysis and forecast costs early.

By accelerating the concept design phase, the team delivered actionable insights to the client by September 2024, three months ahead of the project programme. This enabled the client to strategically pause the project and initiate funding discussions, informed by a cost estimate exceeding £100 million. Such foresight would have been unattainable under conventional methods.

FIGURE 1

MLC Asset Map

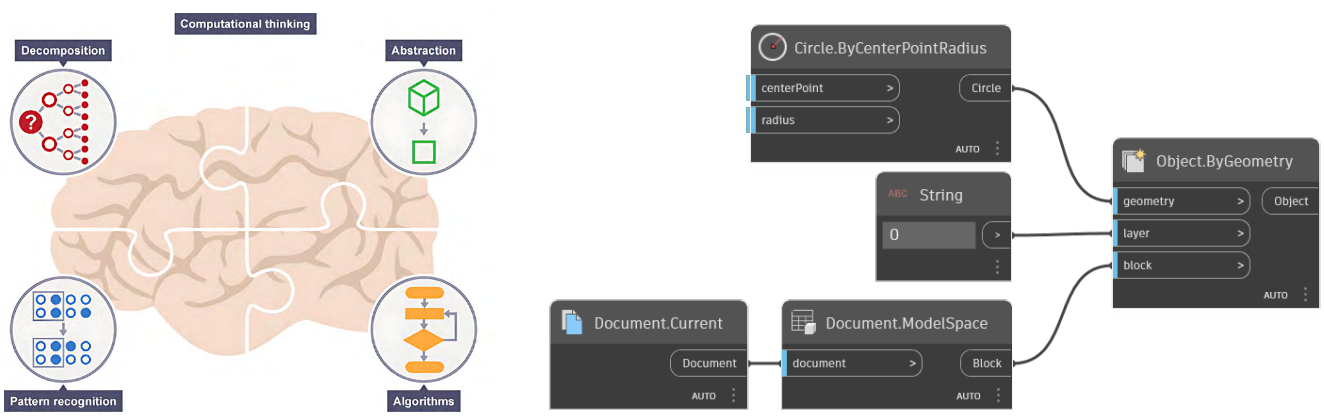


1.1 UNDERSTANDING COMPUTATIONAL THINKING, COMPUTATIONAL DESIGN, AND VISUAL PROGRAMMING

In the context of linear infrastructure, where complexity, scale, and precision converge, the ability to think algorithmically is becoming indispensable. **Computational thinking** provides the foundational mindset emphasising decomposition, abstraction, and algorithmic logic. **Computational design** builds on this by translating abstract reasoning into structured, rule-based workflows that automate and optimise design processes. **Visual programming tools** like **Dynamo** and **Grasshopper** serve as the practical interface, enabling engineers to implement these workflows through intuitive, code-free environments.

FIGURE 2

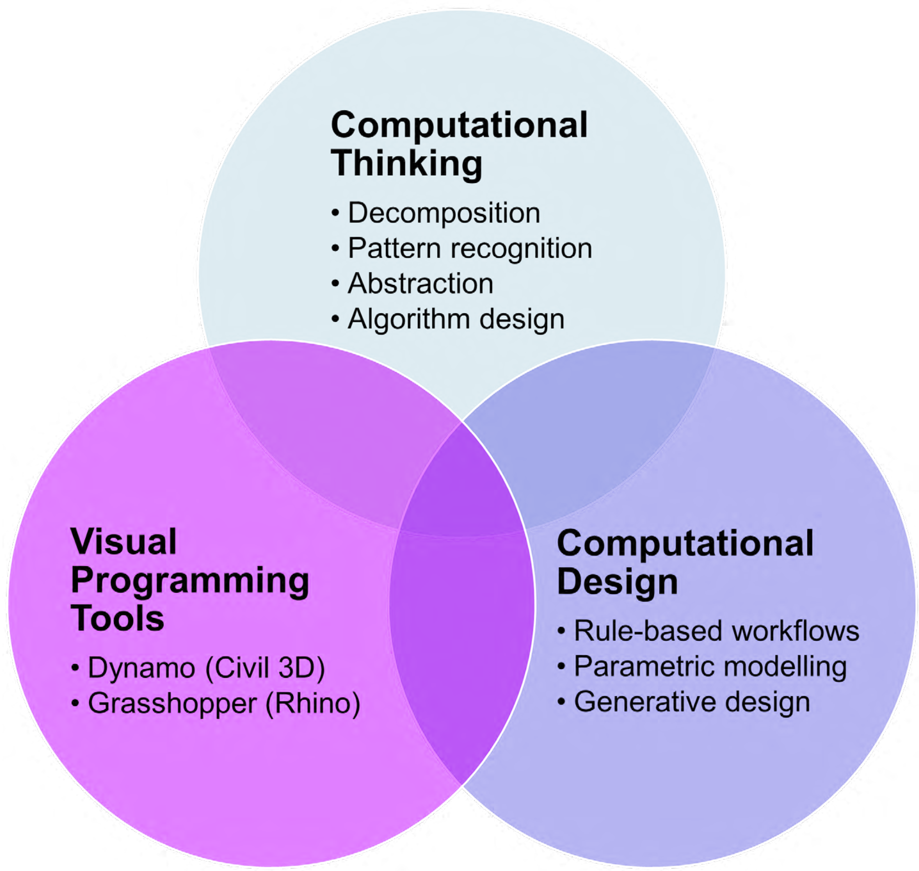
Computational Thinking (Left) and Visual Programming in Dynamo (Right)



The overlap between computational thinking and design enables logic-driven strategies and algorithmic problem-solving. The intersection of design and visual programming enables parametric automation and modular scripting. Meanwhile, the synergy between thinking and visual tools supports intuitive logic construction and broad accessibility. At the centre of this continuum lies an integrated, agile, and scalable approach to infrastructure delivery and enable abstract ideas into tangible, high-impact outcomes.

FIGURE 3

Computational Relationship



2. Computational Framework for Algorithmic Design

2.1 APPLYING THE PROCESS OF COMPUTATIONAL THINKING

Computational thinking comprises of decomposition, pattern recognition, abstraction, and algorithm design. These steps form an iterative loop that refines both problem understanding and solution logic.

These principles guided the MLSRMS project's shift from traditional workflows to a logic-driven, iterative design process.

- **Decomposition** enabled the breakdown of complex workflows into manageable components, revealing that incremental improvements were insufficient. This led to a systemic redesign of the input-to-output transformation using parametric and generative methods.
- **Pattern recognition** helped identify recurring design challenges and stakeholder requirements, informing the creation of reusable templates and computational (algorithmic logic) modules.
- **Abstraction** allowed the team to focus on essential variables such as geometry, materials, and environmental constraints while omitting non-critical details, enabling the development of generalised algorithms.
- **Algorithm design** translated engineering logic into executable scripts that automated design iterations and performance simulations. Generative algorithms produced thousands of design alternatives, evaluated against criteria like cost and constructability. [9][10][11]

While the theoretical framework suggests a linear progression through these steps, practical application within the Project revealed a more fluid and cyclical process. Feedback from simulations, stakeholder reviews, and environmental analyses, necessitated revisiting and refining decompositions, adjusting abstractions, and recalibrating algorithms. This iterative loop was essential for aligning computational outputs with real-world constraints and stakeholder expectations. The mapping of the computational thinking steps to these constructs is illustrated below:

TABLE 1

Computational Thinking Breakdown

Foundational breakdown of Computational thinking	**Mapping to Computational framework**
Decomposition	Computational Thinking
Pattern Recognition	Computational Thinking & Computational Design
Abstraction	Computational Thinking & Computational Design
Algorithm Design	Computational Design & Visual programming

This structured yet flexible approach enabled the Project to adapt to the practical realities of live projects, where iterative refinement and interdisciplinary collaboration unlocked the full potential of computational methodologies.

2.2 COMPUTATIONAL DESIGN – TRANSLATING MANUAL DESIGN PROCESS INTO COMPUTATIONAL LOGIC

The application of computational design in linear infrastructure projects necessitates a fundamental shift **from tacit, experience-driven engineering practices to explicit, logic-based workflows. Traditional design methodologies in civil engineering often rely on the accumulated intuition and situational judgment of experienced practitioners. These manual processes, while effective in context, are inherently non-linear, adaptive, and undocumented. It poses significant challenges when attempting to codify them into computational routines.**

The MLSRMS project adopted a computational design strategy to convert undocumented, experience-driven engineering practices into deterministic, logic-based workflows. This began with decomposing manual processes, typically reliant on visual inspection into discrete, sequenced phases, then encoding them using the **Dynamo visual programming environment within Autodesk Civil 3D**.

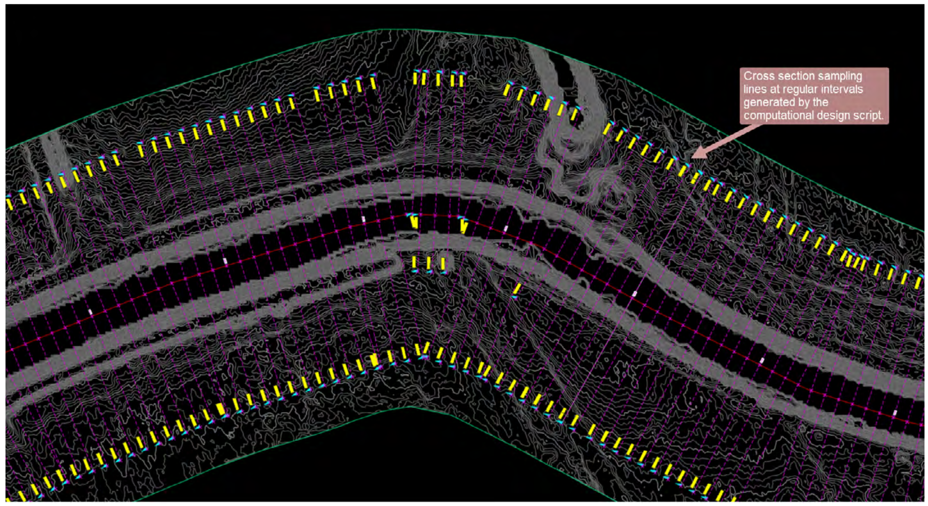
A key example was the automation of **cross-section analysis** along open channel networks as shown in Figure 4 and the Digital Model in Figure 5 using **LiDAR-derived TIN surfaces**. Traditionally, engineers selected cross-section locations based on visual cues. Instead, the computational approach generated sections at **fixed 5 m intervals**, increasing granularity and eliminating subjective decision-making.

FIGURE 4

Site Image - MLSRMS Watercourse

FIGURE 5

Civil 3D Extract of Model Alignment setup



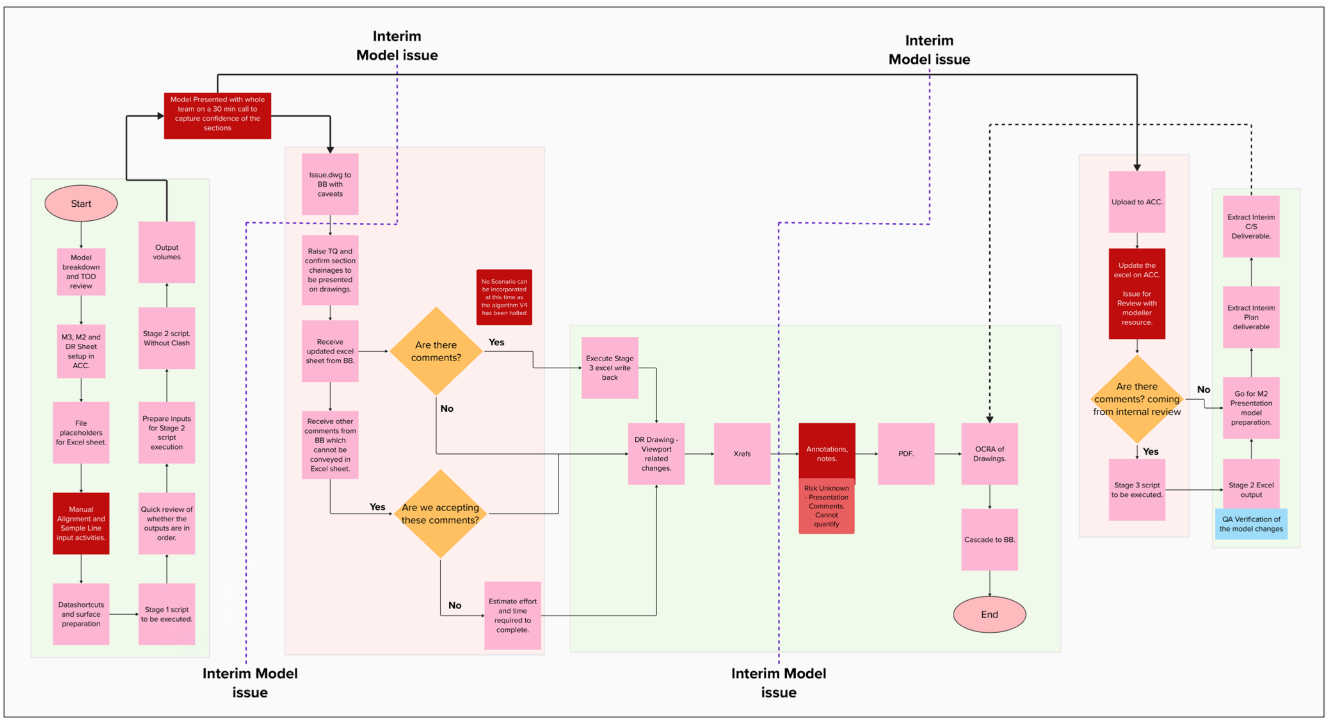
The automation script evolved through iterative development:

- **Initial logic:** Detected top and bottom of channel banks using slope thresholds.
- **Top-N slope analysis:** Isolated significant slope transitions to improve robustness against terrain noise in **National LiDAR Programme** data.
- **Excel-based parameter control:** Enabled dynamic adjustment of berm widths, slope thresholds, and top-of-defence levels.
- **Clash detection:** Incorporated logic to identify conflicts with adjacent infrastructure.
- **User override system:** Allowed manual input via structured Excel sheets, **with write-back functionality** to update Civil 3D models.

These scripts created **surfaces, and cross-sections** directly within the design environment, enabling seamless integration with existing workflows. The development process began with collaborative brainstorming, as pictured in Figure 6, followed by development sprints with iterative handovers between computational developers and engineers to validate outputs and refine logic.

FIGURE 6

Computational Thinking and Computational Design overlaid onto Project delivery workflow



A critical insight was that not all manual behaviours needed replication. Instead, the design logic was simplified where appropriate, e.g., exhaustive sectioning of watercourses replaced subjective selection of sections resulting in scalable, repeatable, and traceable outputs.

2.3 STRUCTURING LOGIC FOR AGILE DELIVERY AND IMPLEMENTATION

To support agile delivery, the MLSRMS project broke computational logic into modular, standalone components. Each, like corridor alignment or cross-section extraction, was delivered incrementally for immediate validation. Dynamo in Autodesk Civil 3D enabled modular logic, allowing the authors to build and refine workflows visually and in parallel. Flexible odules absorbed stakeholder feedback and regulatory changes through spreadsheet controls, with real-time parameter updates feeding directly back into the model. By applying parametric and generative principles, the system remained adaptable for different project needs without requiring core script changes.

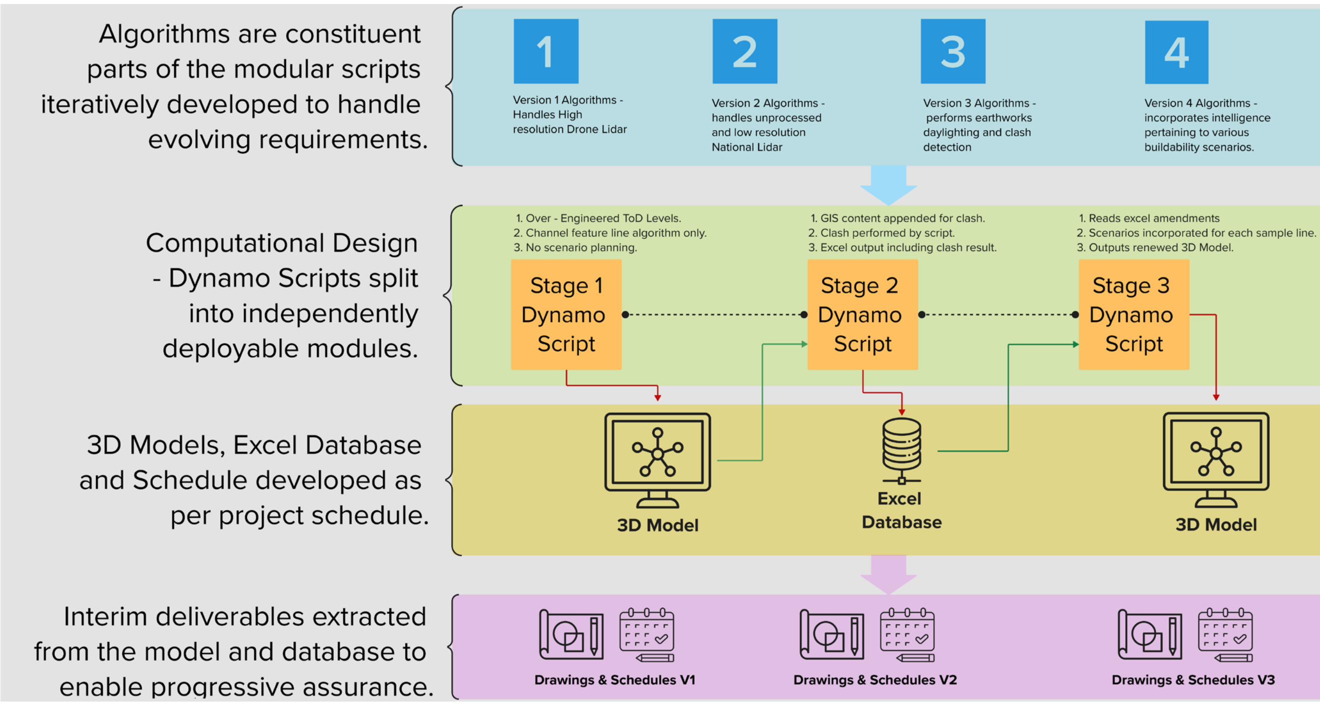
2.3.1 Strategic Linear Infrastructure recommendations for Agile Computational Design

Drawing from practical implementations and theoretical frameworks, the authors propose the following recommendations for structuring computational design logic in agile delivery contexts:

- **Assume concurrency:** Design logic with the understanding that the project team is already active and dependent on timely outputs.
- **Modularise aggressively:** Decompose logic into independent units that can be developed and deployed incrementally.
- **Anticipate change:** Build flexibility into the system to accommodate evolving requirements and stakeholder feedback.
- **Enable feedback loops:** Establish mechanisms for continuous review and refinement of outputs.
- **Design for adaptability:** Ensure that the system can evolve without requiring wholesale redesign.

FIGURE 7

Project Delivery Breakdown
and Implementation



While the MLSRMS project applied computational logic during concept design, it is important to recognise the value of introducing computational thinking principles even at the bid stage. Applying decomposition, pattern recognition, and abstraction during bidding can help teams rapidly frame the scope, identify scalable logic structures, and propose more robust, data-driven solutions. This early application positions the bid to offer differentiated, value-adding strategies to the client. [12][13][14]

2.4 RETHINKING DELIVERABLES

The MLSRMS project redefined deliverables by shifting from static drawings to **data-centric outputs** that left-shifted decision-making and assurance. This transformation was driven by the volume and granularity of data generated through computational design.

For example, cross-sections were originally produced at 500 metre intervals due to project programme constraints using the manual drafting process. Using automation, the team generated cross-sections at **5 metre intervals** across 178 km of watercourses. Rather than producing thousands of drawings, the outputs were structured as **Excel-based datasets and dashboards**, enabling scalable review, early earthworks estimation, and cost forecasting.

FIGURE 8

Excel Based Spreadsheets with Data extracted from the model

Middle Level Commissioners

Middle Level System River Management System - (MLSRMS)

River Channel Alignment & Corridor output date

River Name -
Project Naming Convention Code -
Upstream Node -
Downstream Node -
Length - 1541.528 m
Model File name - MLSRMS-ATK-XX-FF15-M3-C-0001.dwg
Alignment Name - ALG - Forty Foot Drain 1.5
Start Chainage - 0
End Chainage - 1541.528
Extracted on - 19-09-2024 19:03

Legend & Colouring scheme

Colour / font	*Hex*	*Description*
	#FFC319	*Channel Top offset has been selected further away from the channel than average.*
	#8BD8FF	*Channel Top offset has been selected closer to the channel than the average.*
1.234	*#808080*	*Default override value same as the original associated value as output by Dynamo.*
1.234	*#C00000*	*Default value overriden by the user.*
	#E2EFDA	*Channel Top elevation is higher or equal to ToD and hence no works are required. (Values still exist underneath, but they are shaded out).*

Left Hand Side (LHS) Channel Data															Chainage	
Manual Entry		Manual Entry			Manual Entry		Manual Entry		Manual Entry		Manual Entry		Manual Entry			
Works Status Override	**Works Status**	**Ret. Soln Offset Override**	**Ret. Soln Offset**	**Clash reported?**	**Berm Width Override**	**Berm Width (from TOD Top)**	**Bench Width Override**	**Bench Width (From Channel Top)**	**ToD Top Elevation Override**	**Current ToD Top Elevation (From Featureline)**	**ToD Requirement**	**Channel Top Elevation**	**Channel Top Offset Override**	**Channel Top Offset**	**LHS Chainage**	**RHS Chainage**
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	0.133	-47.5	-47.5	0	0
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	-0.502	-41.5	-41.5	5	5
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	-0.462	-39.5	-39.5	10	10
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	-0.444	-38	-38	15	15
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	-0.48	-27	-27	20	20
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.392	-21	-21	25	25
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	2.248	1.66	2.248	-16.5	-16.5	30	30
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	2.178	1.66	2.178	-13	-13	35	35
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	2.168	1.66	2.168	-12	-12	40	40
	No Works - Flat Ground Scenario 1/4/6			FALSE	-5	-4.981	0	0	1.66	1.966	1.66	1.966	-11.473	-11.473	44.005	45
	No Works - Flat Ground Scenario 1/4/6			FALSE	-5	-5	0	0	1.66	1.916	1.66	1.916	-11	-11	50	50
	No Works - Gradual down slope Scenario 2/6			FALSE	-5	-5	0	0	1.66	1.935	1.66	1.935	-11.5	-11.5	55	55
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.76	1.66	1.76	-13.5	-13.5	60	60
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.677	1.66	1.677	-10.5	-10.5	65	65
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.737	1.66	1.737	-10.5	-10.5	70	70
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.847	1.66	1.847	-10	-10	75	75
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.896	1.66	1.896	-10.5	-10.5	80	80
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.818	1.66	1.818	-10.5	-10.5	85	85
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.832	1.66	1.832	-10.5	-10.5	90	90
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.625	-10.5	-10.5	95	95
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	2.905	1.66	2.905	-18	-18	100	100
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	2.706	1.66	2.706	-14.5	-14.5	105	105
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.869	1.66	1.869	-10.5	-10.5	110	110
	Works - Steep down slope			FALSE	-5	-5	0	0	1.66	1.751	1.66	1.751	-10.5	-10.5	115	115
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.626	-10.5	-10.5	120	120
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.544	-10.5	-10.5	125	125
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.587	-11	-11	130	130
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.57	-10.5	-10.5	135	135
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.532	-10.5	-10.5	140	140
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.537	-10.5	-10.5	145	145
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.575	-10.5	-10.5	150	150
	Works - Bank Improvement Scenario 3			FALSE	-5	-5	0	0	1.66	1.66	1.66	1.45	-11	-11	155	155
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.431	-11.5	-11.5	160	160
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.403	-11.5	-11.5	165	165
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.468	-11.5	-11.5	170	170
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.478	-11.5	-11.5	175	175
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.495	-11	-11	180	180
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.506	-11.5	-11.5	185	185
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.644	-11	-11	190	190
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.445	-11.5	-11.5	195	195
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.56	-11	-11	200	200
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.428	-11.5	-11.5	205	205
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.524	-11.111	-11.111	210	210
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.443	-11.111	-11.111	215	215
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.444	-11.111	-11.111	220	220
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.534	-11.111	-11.111	225	225
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.454	-12.121	-12.121	230	230
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.556	-11.111	-11.111	235	235
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.541	-10.606	-10.606	240	240
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.538	-11.616	-11.616	245	245
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.474	-10.606	-10.606	250	250
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.576	-10.606	-10.606	255	255
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.547	-10.606	-10.606	260	260
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.66	1.66	1.606	-10.101	-10.101	265	265
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.721	1.66	1.721	-10.101	-10.101	270	270
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.739	1.66	1.739	-10.101	-10.101	275	275
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.756	1.66	1.756	-10.101	-10.101	280	280
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.715	1.66	1.715	-10.606	-10.606	285	285
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.741	1.66	1.741	-10.606	-10.606	290	290
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.754	1.66	1.754	-10.606	-10.606	295	295
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.825	1.66	1.825	-11.616	-11.616	300	300
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.859	1.66	1.859	-12	-12	305	305
	Hard Retaining Soln.			TRUE	-5	-5	0	0	1.66	1.889	1.66	1.889	-12	-12	310	310

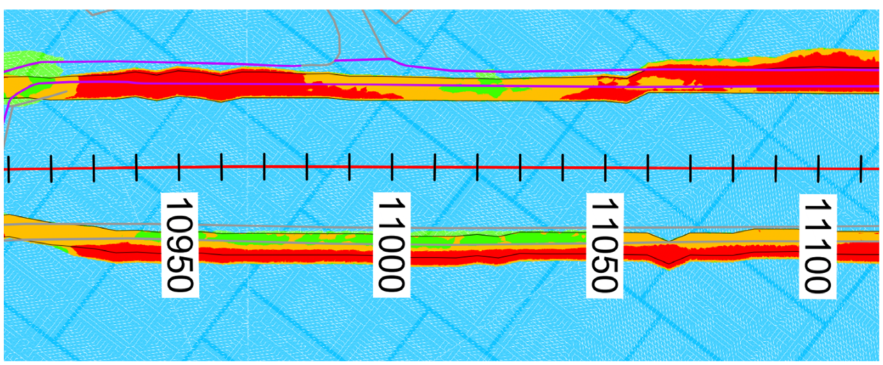
In embankment analysis, the system automatically flagged sections requiring intervention based on slope thresholds and top-of-defence level criteria. These were reviewed using **tabular logic** rather than visual inspection, significantly reducing review time and improving traceability. These structured data formats enabled **write-back functionality**, where user overrides could be captured in Excel and reflected back in the model, reducing rework.

Visual outputs were also optimised for clarity. Instead of full-colour elevation heatmaps, the team used traffic light-style visualisations (red, amber, green) focused on critical zones. This allowed contractors to quickly identify high-intensity work areas, aiding construction sequencing. [15][16][17]

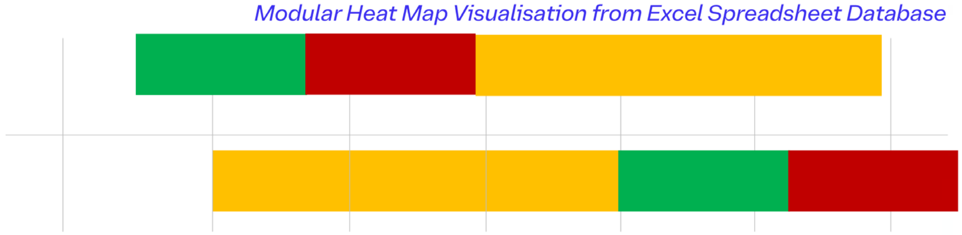
FIGURE 9

Optimised Visual Representation from the Spreadsheet Data

Traditional Heat Map Visualisation



Modular Heat Map Visualisation from Excel Spreadsheet Database



This approach of rethinking deliverables is highly transferable. By prioritising structured, logic-driven outputs over traditional documentation, future projects can benefit from:

- Faster assurance cycles
- Early-stage scenario testing
- Scalable stakeholder engagement
- Reduced drawing production overhead

2.5 DATA MANAGEMENT AND DATA STRUCTURES

Computational design workflows for linear infrastructure, the management and structuring of data are foundational pillars, as infrastructure projects increasingly adopt automation and logic-driven design methodologies, data becomes an active enabler, interlinking scripts, algorithms, through design stages across interoperable formats.

2.5.1. Data as the Backbone of Computational Logic

Within Dynamo for Autodesk Civil 3D, data flows continuously between nodes, scripts, and external sources, requiring robust data structures for storage, retrieval, and transformation. The authors leveraged, chainage-based sampling along a 178 km of watercourses by extracting, manipulating and retrieving X, Y, and Z coordinates at high frequency intervals (e.g., every metre), dramatically increasing data volume and complexity.

This data was used for geometric representation and also integrated with GIS shapefiles to enable clash detection. The interoperability of these datasets across platforms and disciplines was critical to maintaining continuity in design logic and ensuring that outputs remained coherent and actionable.

2.5.2. Structuring Data for Efficiency and Integrity

Three primary constructs of lists, dictionaries, and tuples, were employed to organise and manipulate data efficiently:

- **Lists (Arrays):** Fundamental to visual programming, lists, store sequences of values such as chainage points or elevation profiles. Operations like querying, transposing, and mathematical manipulation are routine and essential. For instance, in the bank raising algorithm, lists were used to store slope values extracted from LiDAR cross-sections, enabling threshold-based detection of channel banks.
- **Dictionaries:** These nested structures associate unique keys with complex data sets. Each chainage point could serve as a key, with associated values including coordinates, elevation, bearing, and hydraulic data. This structure facilitated the dynamic "write-back" functionality (discussed in 2.7), allowing users to override algorithmic outputs and update model files via Excel sheets containing up to 32 columns of structured data.
- **Tuples:** Used for storing immutable pairs such as coordinate sets, tuples offer a lightweight and reliable format for spatial data. Their immutability ensures consistency in referencing fixed points, such as alignment nodes or benchmark locations.

The use of these structures pictured in Figure 10, enabled the project to maintain data integrity across iterative design cycles, support dynamic user input, and facilitate modular development of computational tools.

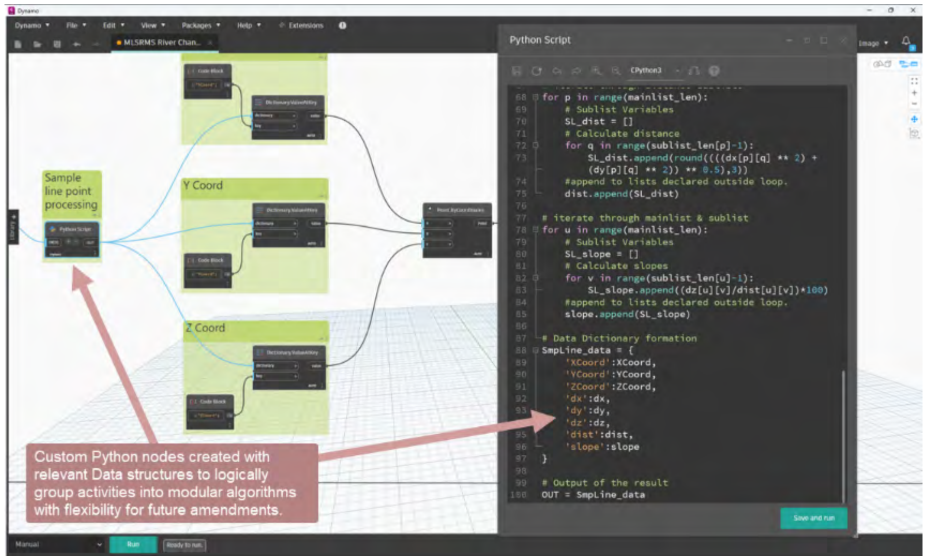


FIGURE 10

Dictionary processing inside the Python Programming node Inside Dynamo

2.5.3. Data Interoperability and Format Diversity

Linear infrastructure projects demand the ingestion and processing of data from diverse sources and formats. The project dealt with data in Civil3D Entities, CAD survey data, National Grid coordinates, local grid systems, GIS shapefiles, Lidar and spreadsheets. LiDAR datasets from drone surveys and national programmes were integrated to generate terrain models and detect slope transitions, while Civil 3D alignment data provided the geometric backbone for sample line generation and cross-section analysis.

Seamless integration of these formats was achieved through interconnected Dynamo scripts and algorithms, daisy-chained together as the centralised platform for managing spatial, geometric, and tabular data.

2.5.4. Data as a Conduit for Modular Algorithmic Workflows

Computational workflows were developed to connect compartmentalised scripts and algorithms. As an example on the project, a script generates cross-sections along chosen alignment, followed by a script to extract elevations and the third performs geometric assessments and design of flood alleviation. The structured exchange of data between these scripts, enabled a modular automation pipeline with continuity in logic and coherence in outputs.

Upon execution of the workflows, the output of the pipeline was further iterated by utilising user overrides and emerging requirements through a write back process wherein tabular data was processed by Dynamo script and then "written back" into the Civil 3D model, enabling iterative refinement without manual intervention.

2.5.5. Implications for Linear Infrastructure Design

The complexity of linear infrastructure projects necessitates a high degree of data interoperability and structural robustness. Data must be ingested from multiple sources, processed through computational logic, and output in formats suitable for downstream applications such as drawing production, quantity estimation, and stakeholder review. The use of structured data constructs, particularly dictionaries and tuples, enabled the development of scalable and adaptable design solutions that could respond to evolving client requirements and site conditions.

2.6 COORDINATE GEOMETRY, TRIGONOMETRY AND NUMERICAL ANALYSIS

2.6.1. Mathematical Foundations for Spatial Automation

The application to coordinate geometry and trigonometry in linear infrastructure design underpins the transition from manual drafting to algorithm-driven design. These mathematical disciplines provide the structural logic to translate spatial relationships, enabling precise modelling and manipulation of geometric entities within computational environments. In particular, the Cartesian coordinate system remains the dominant framework for representing two- and three-dimensional infrastructure geometries, offering a consistent basis for defining alignments, offsets, and elevations across extensive linear assets.

In the context of algorithmic design, coordinate geometry facilitates the decomposition of complex spatial problems into programmable logic. For example, the generation of cross-sections along river channels involved calculating perpendicular offsets from a baseline alignment, determining intersection points with terrain surfaces, and extracting elevation data. These operations, while intuitive in manual CAD workflows, required explicit mathematical formulations, such as vector normalisation, dot product calculations, and the application of the Pythagorean theorem, to be executed reliably in a computational setting.[18][19][20][21]

Trigonometry complements this framework by enabling the resolution of angular relationships critical to infrastructure geometry. Functions such as sine, cosine, and tangent are employed to compute and maintain correct orientation of various design entities relative to the alignment.

Trigonometric functions (sine, cosine, tangent) were embedded in scripts to compute:

- Bearings and deflection angles for alignment geometry.
- Slope gradients for embankment stability.
- Angular relationships for feature placement (e.g., berms, benches, and top-of-defence lines).

These calculations were implemented within bespoke **Python Dynamo nodes**, allowing automated generation of hundreds of cross-sections with consistent spatial referencing using chainage, station, offset, and elevation data.

2.6.2. Numerical Analysis for Terrain Interpretation

To assess embankment conditions, the team used **numerical methods** to analyse terrain data extracted from LiDAR-derived surfaces:

- Slope analysis was performed by sampling elevation points and computing gradients to flag steep or unstable slopes.
- Top-N slope analysis identified the most significant terrain transitions, improving robustness against noise in lower-resolution LiDAR datasets.
- Statistical operations (mean, median, standard deviation) were used to detect anomalies and validate terrain profiles.

These analyses enabled the system to automatically identify sections requiring intervention, reducing manual inspection and accelerating early-stage design decisions.

2.6.3. Engineering Logic and Mathematical Translation

Engineering heuristics were formalised into **conditional logic** and **threshold-based rules**. For example:

- "No work required if ground level exceeds design level" was encoded as a Boolean condition.
- Tolerances were applied to slope and elevation comparisons.
- Clash detection logic was used to identify conflicts with existing infrastructure.
- Where traditional earthworks were not feasible, the algorithm proposed alternatives (e.g., sheet pile walls) based on proximity and geometric constraints.

2.7 CONDITIONAL LOGIC, THRESHOLDS, AND ERROR HANDLING IN COMPUTATIONAL DESIGN

The application of conditional logic within computational design frameworks plays a pivotal role in enabling intelligent automation, particularly in the context of linear infrastructure projects where terrain variability and data ambiguity challenge deterministic modelling. In such environments, the translation of engineering judgement into codifiable logic is essential for achieving scalable, repeatable, and adaptable design solutions.

2.7.1. Stage-Gated Logic for Design Decisions

The core scripts used **Boolean logic** to implement stage-gated processing. For example, embankment raising was only triggered if the existing ground level was below the required top-of-defence (ToD) elevation. This prevented unnecessary computations and ensured that only relevant interventions were processed.

These logic gates were structured as **if-then-else conditions** within Dynamo scripts, enabling deterministic execution of design rules and reducing manual oversight.

2.7.2. Threshold-Based Interpretation of Continuous Data

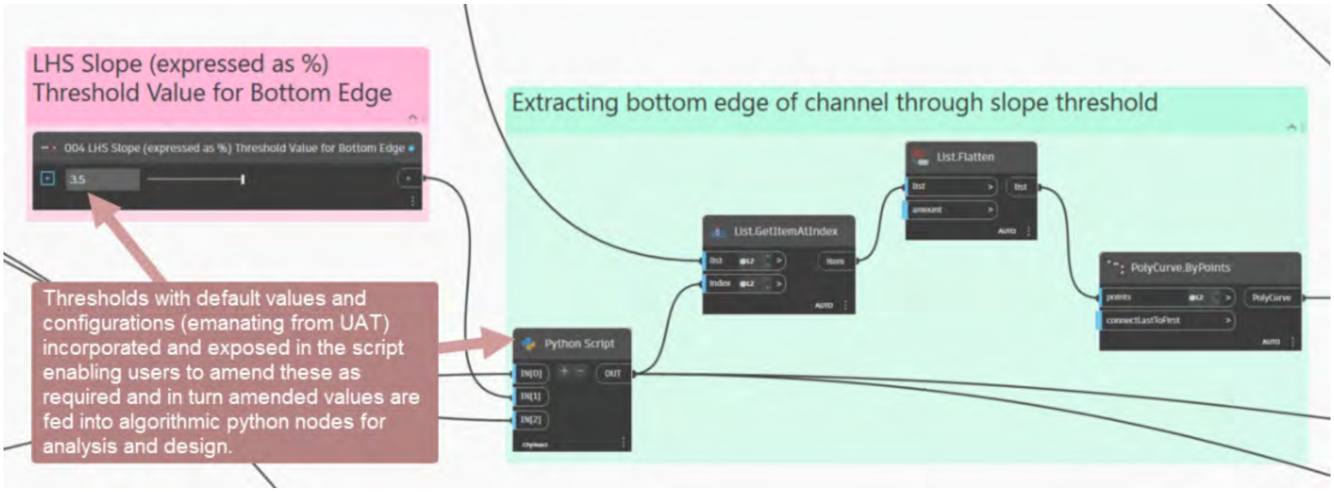
Many design decisions required interpreting continuous data - such as slope gradients or elevation differences into actionable categories. This was achieved through **threshold-based logic**, where parameters like slope steepness (e.g., 35%–50%) were used to classify terrain conditions.

These thresholds as shown in Figure 11 were:

- **User-configurable** via UI sliders in Dynamo and Excel-based control sheets.
- **Adjusted dynamically** based on data resolution (e.g., tighter thresholds for drone LiDAR, broader for national datasets).
- **Embedded in scripts** to drive decisions such as whether to raise banks or propose alternative interventions.

FIGURE 11

User-Controlled Parameters to enable fine tuning of the algorithms



2.7.3. Error Handling and Data Robustness

To ensure resilience, the scripts included **pre-emptive validation checks** and **fallback logic paths**. These handled:

- Missing or inconsistent elevation data.
- Misaligned geometry due to coordinate system discrepancies.
- Unexpected terrain anomalies.

When errors were detected, the system either halted execution with informative messages or rerouted data through alternative logic (e.g., using Top N slope analysis to filter out noise).

2.7.4. User Overrides and Agile Adaptability

The system supported **manual overrides** through structured Excel inputs. Users could adjust berm widths, slope thresholds, or work status flags, which were then re-ingested into the model via a **write-back mechanism**. This allowed for:

- Real-time design adjustments.
- Traceable stakeholder input.
- Agile iteration without script rewrites.

2.8 VISUAL PROGRAMMING FOR COMPUTATIONAL DESIGN IN LINEAR INFRASTRUCTURE

As introduced in 2.1, visual programming tools such as Dynamo (visual programming environment within Autodesk Civil 3D) enable the translation of computational thinking into actionable design logic. This section focuses on their application within the MLSRMS project, demonstrating how modular and scalable workflows were constructed to address the complexities of linear infrastructure.[22][23][24]

2.8.1. Graphical Logic Construction

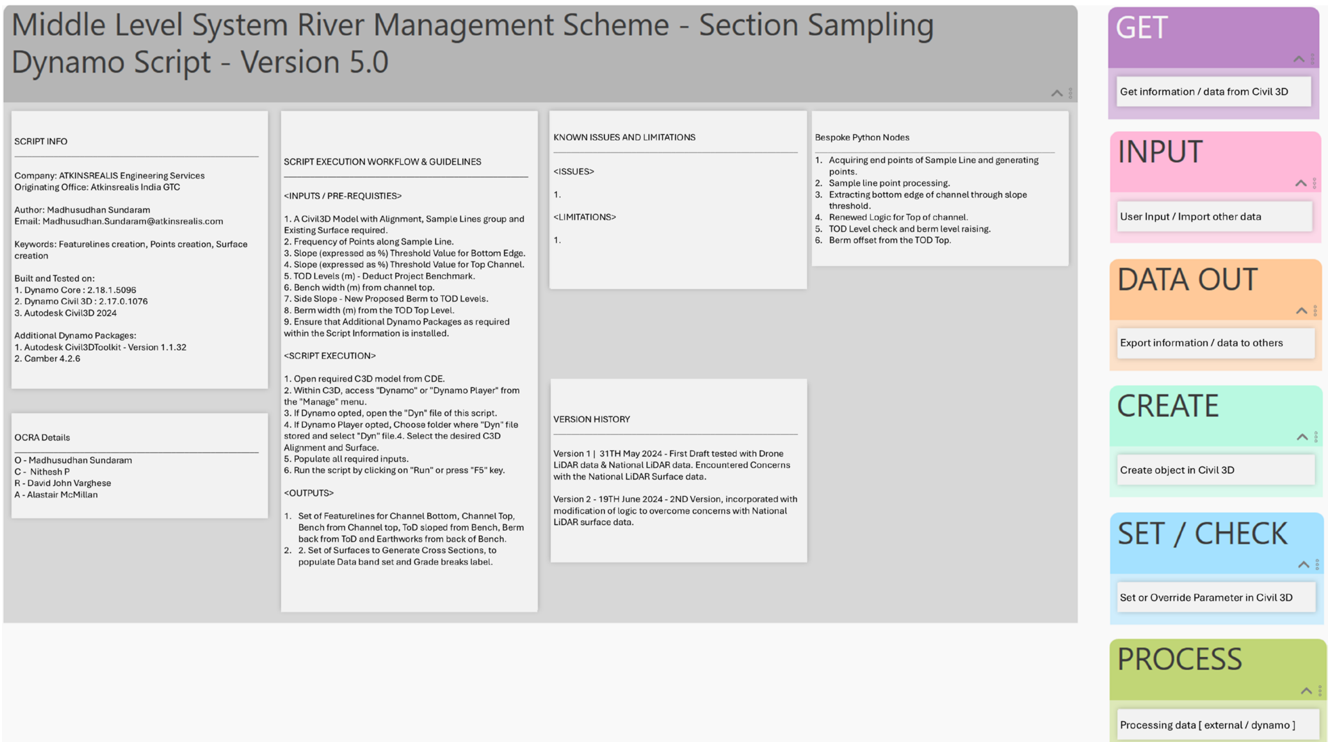
Using **Dynamo**, the team constructed logic flows through node-based interfaces. This allowed:

- Rapid prototyping of design algorithms.
- Intuitive manipulation of geometric and parametric data.
- Real-time feedback during script execution.

Scripts were structured using **graphing standards as show in** Figure 12, color-coded nodes for inputs, processing, and outputs enhancing readability and enabling collaborative development.

FIGURE 12

Dynamo Development Standards Guidance for Script Development



2.8.2. Modular Workflow Architecture

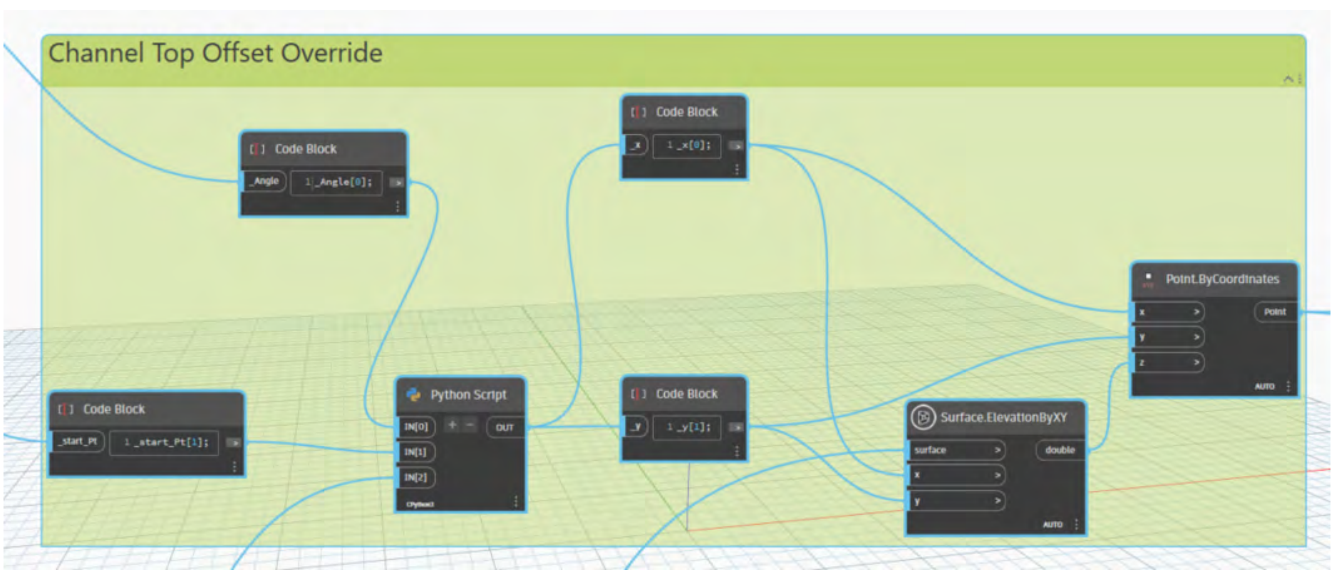
Design logic was decomposed into **modular components**, each addressing a specific task such as:

- Alignment generation
- Corridor modelling
- Quantity extraction

Modules were independently testable and updatable, supporting agile iteration and reducing rework. Manual checkpoints were embedded for validation, ensuring engineering oversight.

FIGURE 13

Dynamo Interface for importing the reviewed Spreadsheet back into the model



2.8.3. Hybrid Logic Integration

For advanced tasks, **Python scripting** was embedded within Dynamo to extend functionality. This hybrid approach enabled:

- Custom algorithms for slope analysis and clash detection.
- Parametric control of geometry based on chainage and offset.
- Dynamic object placement and data validation.

Python's readability and flexibility allowed non-programmers to engage with and adapt scripts as needed.

2.8.4. Documentation and Error Handling

To support adoption and robustness:

- Scripts included tooltips, annotations, and embedded notes for user guidance.
- Pre-execution checks validated inputs and prevented errors.
- Standalone documentation outlined execution protocols and troubleshooting strategies.

These features reduced onboarding time and built confidence among users unfamiliar with computational tools.

2.9 TESTING, FEEDBACK, IMPLEMENTATION, AND TECHNICAL ASSURANCE OF COMPUTATIONAL DESIGN SOLUTIONS

2.9.1. Testing Methodology and Data Representativeness

Scripts were initially tested in **sandbox environments** where logic modules were grouped and executed independently to verify functionality. Once validated, they were deployed in live Civil 3D models with **real-time monitoring** via embedded watch nodes and output visualisations.

To ensure generalisability, test datasets were selected to reflect the **full range of terrain, geometry, and hydraulic conditions** encountered across 178 km of watercourses. This approach mirrored machine learning practices, where diverse training data improves model reliability.

2.9.2. Feedback Integration and Agile Refinement

Feedback was captured through **Excel-based control sheets**, allowing users to:

- Override algorithmic outputs (e.g., berm widths, slope thresholds).
- Flag anomalies or propose localised adjustments.
- Submit comments that were automatically parsed and re-ingested into the model.

This enabled a **closed-loop feedback system**, where each sprint cycle delivered a usable design increment that could be reviewed, refined, and redeployed, supporting agile delivery in a live project environment.

2.9.3. Implementation Strategy and User Acceptance

Implementation followed a **tiered adoption model**:

- 70% (5 users) of users trained for basic execution.
- 20% (2 users) trained for troubleshooting and editing.
- 10% (1 users) trained for advanced development and logic extension.

This ensured broad accessibility while maintaining a core group of technical leads capable of sustaining and evolving the computational framework.

Scripts were version-controlled, with each release tested against real-world data and validated through structured sprint reviews. Backward compatibility was maintained to support rollback and risk mitigation.

2.9.4. Embedded Technical Assurance

Assurance was built into the computational workflow:

- Outputs included **embedded metadata** and **visual cues** for traceability.
- **Automated compliance checks** validated design rules and thresholds.
- **Simulation-based validation** ensured performance under varying conditions.

Deliverables were structured to align with **digital twin principles** such as dynamic data integration, traceability, and real-time feedback in line with **ISO/IEC 30173:2023** and **BSI Digital Twins Framework** [7][8].

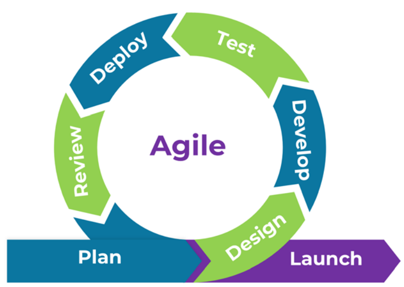
3. Agile Delivery and Iterative Development in Computational Civil Engineering

3.1 AGILE SCRUM AS A PROJECT MANAGEMENT FRAMEWORK

Agile Scrum is an iterative project management framework originally developed for software development. Its structured roles, time-boxed sprints, and regular feedback cycles to deliver incremental value and adapt to evolving requirements. While its adoption in civil engineering has been limited, the increasing use of computational design, automation, and data-driven workflows presents new opportunities for Agile methodologies in infrastructure delivery.[25][26]

FIGURE 14

MLSRMS Algorithm Development Cycle



Plan	Design	Develop	Test	Deploy	Review	Launch
Understanding the Client Scope to inform Algorithm development	Collaborative focus implementing flood defence engineering principles	Incorporating Scrum values - innovation-led environment	Progressive Assurance on working models	Version based release methodology	Client-Centric Collaborative feedback - "Get it right first time"	V1 to V4 Algorithms released - incremental updates to meet evolving Scope.

In particular, the development of digital tools such as parametric design scripts, geospatial analysis algorithms, and automated modelling workflows shares many characteristics with software development:

- Requirements evolve as understanding deepens.
- Outputs are non-physical and can be iteratively refined.
- Feedback from stakeholders is essential to validate assumptions and improve performance.

3.1.1 Why Agile Was Necessary for MLSRMS

The project presented a unique opportunity to apply Agile Scrum methodology within a civil engineering context. The project's objective was to develop a computational algorithm to assess flood defence requirements across a complex network of watercourses. Given the evolving nature of the design logic, the variability of input data, and the need for continuous stakeholder engagement, a traditional linear delivery model was deemed insufficient.

Agile Scrum was adopted to enable iterative development, structured feedback loops, and adaptive planning as show in Figure 14. The methodology facilitated the delivery of incremental improvements to the algorithm, allowing the team to respond dynamically to new requirements, data inconsistencies, and client feedback. This section outlines the implementation of Agile delivery principles and their impact on the project's computational design outcomes.

The following sections detail how Agile Scrum was adapted, implemented, and evolved throughout the MLSRMS project. The aim is to provide a practical reference for engineering teams seeking to apply Agile principles to the development of digital tools and computational workflows within infrastructure projects. [27][28][29]

3.1.2 Agile Framework Adapted for Engineering

The adaptation of Scrum to a civil engineering environment required careful consideration of roles, artefacts, and ceremonies. The project team redefined standard Scrum components to align with engineering workflows:

TABLE 2

Agile Role Ownership

Agile Role	Adapted Role in Project	Responsibilities
Product Owner	Civil Design Team (Including Client input)	Prioritised algorithmic features based on client requirements, engineering logic, and delivery constraints. Acted as the voice of the client within the development cycle.
Scrum Master	Digital Delivery Lead	Facilitated Agile events (e.g., sprint planning, reviews), removed blockers, and ensured adherence to iterative development principles.
Development Team	Cross-functional team of civil engineers with computational expertise	Developed and tested logic modules, integrated outputs into Civil 3D, and collaborated with stakeholders to refine design logic.

Each sprint was structured around the delivery of a "Minimum Viable Design Increment," a validated script module, a new scenario logic, or a refined model output. Sprint planning sessions defined the scope of work, daily stand-ups ensured alignment, and sprint reviews enabled client feedback to be incorporated into subsequent iterations.

The Agile framework was supported by a suite of tools including Civil 3D, Dynamo, Excel-based control sheets, and SharePoint for document management. This hybrid environment allowed the team to maintain engineering rigour while embracing Agile flexibility.

3.1.3 Evolving Scope and Requirements

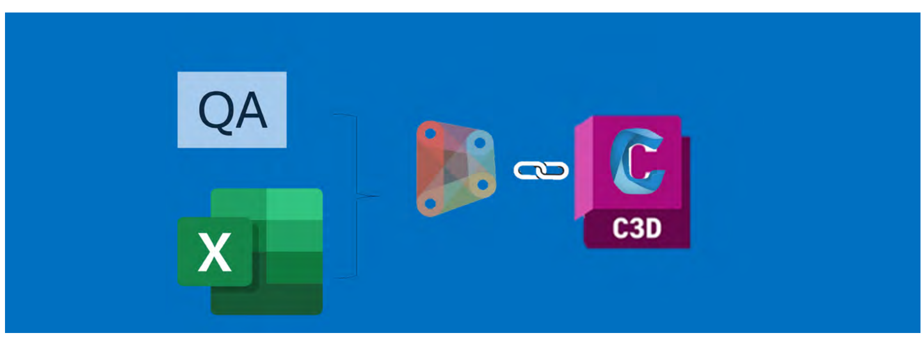
One of the primary drivers for adopting Agile was the recognition that the project scope would evolve significantly over time. Early in the concept design phase, the team encountered ambiguity in the interpretation of bank raising rules across the various locations. Multiple scenarios emerged, each requiring different logic for determining the extent and type of intervention.

The Agile process enabled the team to manage this complexity through structured iteration:

- **Scenario Expansion:** The number of bank-raising scenarios expanded from two to six as the client's understanding matured. These were implemented incrementally across packages, with each version of the algorithm incorporating new logic. Each scenario was unique to the various ground conditions observed throughout the design process.
- **Feedback Integration:** Technical queries triggered sprint reviews and design workshops. These sessions led to the refinement of crest position logic, clash detection, and retaining wall criteria.
- **Write-Back Mechanism:** The fourth iteration of the algorithm introduced a "write-back" feature, allowing the stakeholder comments to be captured in Excel and automatically reflected in the model. This closed the feedback loop and ensured traceability of design decisions.

FIGURE 15

Tech Stack Implementation



By treating scope evolution as a managed process rather than pose a risk of rework to algorithm development, the team-maintained delivery timescales while improving the quality and relevance of the computational outputs.

3.1.4 Operational Model

A key enhancement to the MLSRMS delivery model was the restructuring of the design workflow to enable earlier and more collaborative quality assurance. Originally, client reviews were scheduled post-drawing production, often delaying engagement and increasing the risk of late-stage rework.

This revised approach involved issuing preliminary drawing outputs alongside a structured Excel-based design interface. The spreadsheet contained all key geometric parameters such as crest levels, berm widths, and slope gradients extracted directly from the computational model. This enabled the client to interrogate and validate the design logic well in advance of full drawing production. This allowed the client to interrogate and validate design logic early, with override functionality enabling localised adjustments while maintaining traceability.

To support this delivery model, the project adopted a dual-team operational structure that separated algorithm development from model integration:

- **Development Team:** Focused on authoring scripts, testing logic, and managing version control. They also produced structured Excel-based intermediate deliverables to support early client review.
- **Delivery Team:** Responsible for integrating algorithm outputs into Civil 3D, producing layout plans and cross-sections, and conducting quality assurance.

This structure allowed each team to operate at its own cadence while maintaining alignment through shared sprint goals and coordinated handovers. The modular nature of the workflow also supported parallel progress across multiple design packages, improving resource utilisation and reducing delivery bottlenecks.

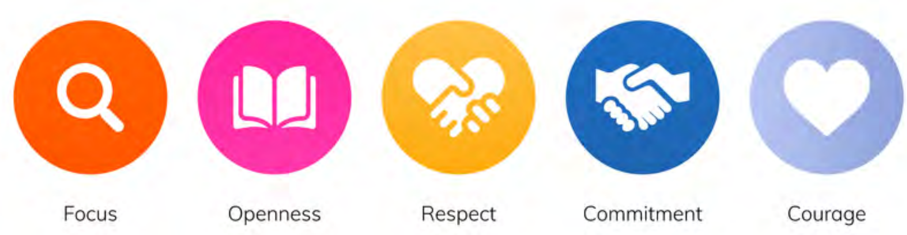
3.1.5 Training and Upskilling

The successful implementation of Agile required a cultural shift and investment in team capability. Several initiatives were undertaken to support this transition:

- **Internal Training:** Focused on the practical application of logic modules, Civil 3D modelling standards, and automation of the model-to-drawing workflow. Sessions covered best practices for script execution, parameter control, and integration of outputs into design documentation.
- **Client Onboarding:** Formal induction sessions were conducted for client stakeholders to introduce the Excel-based interface. Training focused on how to review, modify, and override design parameters, and how those changes dynamically update the Civil 3D model through the write-back mechanism.
- **Documentation and Knowledge Transfer:** Technical notes, version change logs, and user guides were maintained to support transparency and traceability. These artefacts also served as onboarding materials for new team members.

FIGURE 16

Scrum Values



Beyond tools and workflows, the team embraced the core Scrum values Figure 16) as guiding principles reflecting the team's willingness to operate iterating under uncertainty, maintaining transparency, and collaborating across disciplines. This cultural foundation was essential to sustaining Agile practices and enabling a high-performing, adaptive team environment.

3.1.6 Script Versioning and Testing

The embankment assessment workflow was delivered through a structured four-stage process, each stage representing a distinct phase in the computational design lifecycle. Logic modules were developed iteratively to support these stages, with versioning driven by evolving client requirements and feedback.

Delivery Stages

- **Stage 1** – Setup of Civil 3D model, including alignment and section generation.
- **Stage 2** – Evaluation of terrain and generation of the algorithm first-pass embankment geometry and data extraction to excel.
- **Stage 3** – Stakeholder Review and update of design parameters via Excel interface.
- **Stage 4** – Application of reviewed changes back into the Civil 3D model.

TABLE 3

Logic Module (Script) Development Versioning

Version	Delivery Stages	Key Enhancements
Version 1	Stage 1 & 2	Initial logic module using drone LiDAR data to identify top and bottom of bank profiles.
Version 2	Stage 2	Expanded compatibility with National LiDAR and introduced clash detection logic.
Version 3	Stage 2 & 3	Integrated Excel-based parameter control for berm widths, slope thresholds, and top-of-bank levels.
Version 4	Stage 3 & 4	Added write-back functionality, user override scenario options, and expanded scenario logic.

Each version was tested against real-world data and validated through sprint reviews. Stakeholder feedback was captured via structured Excel inputs and incorporated into subsequent iterations, ensuring alignment with engineering intent and project constraints.

This versioning strategy enabled:

- Parallel development across logic modules.
- Decoupling of software logic from delivery workflows.
- Traceable evolution of design automation.
- Risk management through backward compatibility and modular updates.

4. Conclusion

This technical paper has presented a comprehensive framework for embedding computational design and agile delivery into the early stages of linear infrastructure projects, using the Middle Level System River Management Scheme (MLSRMS) as a case study. The approach outlined in this document demonstrates how algorithmic thinking, visual programming, and modular logic development can be operationalised to improve design efficiency, traceability, and stakeholder engagement.

The framework was developed in response to the need for scalable, deterministic workflows that could replace traditional, manual engineering practices. Using parametric modelling, data-driven logic, and structured feedback loops, the project team was able to automate the assessment of over 178 km of watercourses, reduce programme risk, and achieve a three-month reduction in the delivery timeline.

With the full set of technical strategies now documented, this paper serves as a reference for practitioners seeking to implement similar methodologies. The following sections are particularly relevant for targeted reapplication:

- **Section 2.1–2.2:** Introduces the principles of computational thinking and their mapping to computational design and visual programming environments.
- **Section 2.3:** Details the structuring of logic into Minimum Viable Design Increments (MVDIs), enabling modular development and agile iteration.
- **Section 2.4:** Reframes deliverables as structured data artefacts, supporting scalable review and early-stage assurance.
- **Section 2.5–2.6:** Explains the mathematical and spatial logic underpinning the automation, including coordinate geometry, trigonometry, and terrain analysis.
- **Section 2.7:** Describes the use of conditional logic, thresholds, and error handling to manage data ambiguity and ensure robustness.

- **Section 2.8:** Demonstrates how visual programming was used to construct modular, scalable workflows accessible to multidisciplinary teams.
- **Section 2.9:** Outlines the testing, feedback, and assurance strategy, including sandbox testing, stakeholder input, and simulation-based validation.
- **Section 3.1:** Presents the agile delivery model, including adapted Scrum roles, sprint-based development, and a dual-team operational structure.

Together, these sections form a replicable model for computational delivery in infrastructure. The MLSRMS project illustrates that such methods are not theoretical constructs but practical tools that can be deployed in live environments to achieve measurable outcomes. As infrastructure projects grow in complexity and data richness, the ability to structure, automate, and iterate design logic will be essential to delivering resilient, efficient, and future-ready assets.

Acknowledgements

The author extends their gratitude to the Middle Level Commissioners for initiating the MLSRMS project and for their invaluable input during development of the computational design framework and agile delivery model. The extensive knowledge and understanding of the Middle Level System provided by Chief Engineer Nicola Oldfield, Head of Operations & Water Level Management Jonathan Fenn, Civil Engineer Tom Pollendine and Operations Manager Morgan Lakey, were instrumental in ensuring that the automated embankment analysis and conceptual design generation accurately captured the complexities of their infrastructure, delivering practical, real-world value.

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04: Demystifying Carbon: Affecting Real Change Through Qualitative Methods

Significance Statement

Carbon Insights is a user-friendly digital carbon management platform that helps teams reduce carbon emissions in global, multidisciplinary projects, without needing complex calculations. Built on international standards, the qualitative framework empowers teams and individuals, regardless of technical expertise, to identify carbon hotspots, explore reduction opportunities, and track outcomes. By integrating benchmark data, carbon reduction interventions, and optional quantification, it supports brainstorming and implementation. Already used on over 200 projects for 104 clients, it has enabled more than 600 carbon-saving interventions. It represents a scalable solution for embedding carbon thinking into everyday practice, supporting AtkinsRéalis' and its clients' transition to net zero.

Énoncé d'importance

Carbon Insights est une plateforme numérique facile à utiliser pour la gestion du carbone qui aide les équipes à réduire les émissions dans le cadre de projets multidisciplinaires mondiaux, sans avoir recours à des calculs complexes. S'appuyant sur des normes internationales, ce cadre qualitatif permet aux équipes et aux individus, peu importe leur expertise technique, d'identifier les principales sources d'émissions de carbone, d'explorer les possibilités de réduction et d'assurer le suivi des résultats. En intégrant des données de référence, des mesures de réduction et une quantification optionnelle, il facilite la réflexion et la mise en œuvre. Déjà utilisé sur plus de 200 projets au profit de 104 clients, il a généré plus de 600 interventions ayant permis de réduire les émissions carbones. Il constitue une solution évolutive pour intégrer la question du carbone dans les pratiques quotidiennes, et qui vient soutenir la transition d'AtkinsRéalis et de ses clients vers le net zéro.

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Abstract

To ***engineer a better future for our planet and its people***, the carbon impacts of projects should be understood and reduced wherever possible. AtkinsRéalis' carbon experts routinely quantify and actively manage the carbon associated with the design, construction and operation of major infrastructure projects. But full carbon quantification takes time and specialist resource. It is not always prioritised by clients, and not scalable across all global projects.

The premise that ***you don't always need to measure carbon, to reduce carbon*** led to the development of *Carbon Insights*: a digital carbon management platform designed to embed carbon thinking into everyday project decision-making. Developed by AtkinsRéalis, it addresses the limitations of traditional carbon quantification tools by offering an accessible, standards-aligned approach grounded in PAS 2080:2023. 'Demystifying' carbon, it empowers all staff, regardless of technical expertise, to identify carbon hotspots, explore reduction opportunities, and track outcomes on live projects. Now adopted across over 200 live projects for more than 100 clients, it has facilitated the identification and implementation of over 600 carbon reduction interventions. This scalable solution demonstrates how qualitative methods can drive meaningful carbon reductions, support net zero ambitions, and foster a culture of sustainability across the organisation.

KEYWORDS

Carbon Management; Qualitative Framework; PAS 2080; Sustainability; Digital Platform; *Carbon Insights*

1. Introduction

The global imperative to decarbonise is reshaping industries, economies, and societies at an unprecedented pace. As climate change continues to pose existential risks, governments around the world have responded with ambitious net zero targets, aiming to eliminate greenhouse gas emissions within the coming decades. These national and international commitments are not merely aspirational, they are being translated into tangible policies, regulations, and expectations that cascade down to every sector, organisation, and project. For the construction industry, this shift represents both a challenge and an opportunity to redefine its role in a low-carbon future.

Construction is one of the most carbon-intensive industries globally. From the extraction and processing of raw materials to the energy consumed during building operations, the sector contributes significantly to global emissions. According to the United Nations Environment Programme, the built environment accounts for nearly 40% of global carbon dioxide emissions (United Nations, 2023), with construction processes and materials playing a major role. This reality places the engineering and construction industry under intense scrutiny and pressure to evolve. Decarbonisation is no longer a peripheral concern, it is central to how projects are designed, built, and delivered.

The emphasis on reducing carbon emissions in construction is not limited to operational energy use. Increasingly, stakeholders are recognising the importance of embodied carbon, the emissions associated with materials and construction activities throughout a building's lifecycle. This holistic view of carbon impact demands a fundamental shift in how projects are conceived and executed. It requires collaboration across disciplines and across the supply chain. It requires innovation in materials and construction methods, and a commitment to sustainability that permeates every stage of development.

AtkinsRéalis' clients are at the forefront of this transformation. Many have set their own decarbonisation targets, aligned with broader corporate sustainability strategies and regulatory requirements. These targets often span Scope 1 (direct emissions), Scope 2 (indirect emissions from purchased energy), and Scope 3 (all other indirect emissions, including those from the supply chain) as defined by the Greenhouse Gas Protocol (The Greenhouse Gas Protocol, 2004). Project work directly influences all three scopes in one way or another, whether for clients or for AtkinsRéalis' own footprint. The specified materials, recommended construction techniques, and designed operational efficiencies all contribute to clients' carbon footprints. In this context, AtkinsRéalis serves not only as a service provider, but as a strategic partner in the client's journey toward net zero.

The expectations from clients are clear: they demand sustainable practices, transparency in carbon accounting, and demonstrable progress toward emissions reduction. This has led to a growing emphasis on carbon reporting, lifecycle assessments, and the integration of sustainability metrics into project delivery frameworks. Supply chains are being re-evaluated, with preference given to partners who can demonstrate low-carbon credentials and a commitment to continuous improvement. The construction industry is being reshaped by these demands, and those who fail to adapt to this risk being left behind.

FIGURE 1

Carbon and wider sustainability as core project values

At the same time, AtkinsRéalis has its own sustainability ambitions. The company's vision to "*engineer a better future for our planet and its people*" reflects a deep commitment to environmental stewardship, social responsibility, and technical excellence. The challenges of climate change require bold action, and AtkinsRéalis is determined to be part of the solution. This means embedding sustainability into core business strategy, investing in research and innovation, and fostering a culture where environmental performance is valued as highly as time, cost, quality, and safety.

The approach to decarbonisation is multifaceted. It involves reducing emissions from internal operations, supporting clients in meeting sustainability goals, and advocating for systemic change across the industry. Efforts are underway to explore low-carbon materials, promote circular economy principles, and leverage digital tools to optimise design and construction processes. Engagement with policymakers, academic institutions, and industry bodies is also a key strategy to drive progress and share best practices.

Decarbonisation is not a one-size-fits-all endeavour. Each project presents unique challenges and opportunities, shaped by its location, scale, function, and stakeholder priorities. AtkinsRéalis plays a strategic role in navigating this complexity, providing tailored solutions that balance environmental performance with economic and social value. This requires a deep understanding of carbon accounting methodologies, regulatory frameworks, and emerging technologies, as well as the ability to communicate effectively with diverse audiences.

Looking ahead, the construction industry must embrace a new paradigm, one where sustainability is not an add-on, but a fundamental driver of decision-making. This will require a shift in mindset, skills, and systems. It will demand collaboration across the value chain. And it will necessitate a commitment to transparency, accountability, and continuous learning.

This paper presents a solution to this challenge by proposing to "*demystify carbon*" and provide a practical, inclusive approach that embeds carbon thinking into every project and enables transparent reporting of progress.

2. Methodology

2.1 MARKET RESEARCH

A crowded arena for specialist quantification tools

A comprehensive market assessment was conducted to identify whether there was an existing digital solution that could meet the organisation's needs. The objective was to find a scalable, flexible, and adaptable tool that could support qualitative carbon assessments across our diverse range of services, sectors, and markets. The research revealed a crowded landscape of carbon quantification tools, many of which are well-established within their respective disciplines. However, a significant gap emerged in their applicability to the unique context and needs of the organisation.

Most tools were designed with a narrow focus; developed by experts in specific disciplines for specific application within that discipline, tailored to the technical workflows of particular professions. For example, RIB CostX Carbon Estimating Software (RIB, 2025) has been produced using a cost management software and is geared towards quantity surveyors. OneClick LCA Carbon Designer (Ramachandran, 2024) is optimised for architectural applications, and the IStructE embodied carbon calculator (Wood, 2025) is intended for structural engineers.

These tools often require specialised technical skillsets, coupled with detailed and time-consuming quantitative methodologies, both of which are a blocker to applying the approaches at scale.

A need for qualitative guidance and an overarching framework

That "***you don't need to measure carbon to reduce it***" is commonly understood. In our day to day lives, everyone can take measures to reduce carbon, e.g. using sustainable transport, conserving energy in our homes and workplaces, reducing food miles, etc. A common framework was sought that could be applied across projects: a qualitative approach that could enable meaningful carbon reduction through informed decision-making, even in the absence of detailed quantification. Encouraging qualitative input was identified as a way to unlock valuable opportunities for low-carbon design that might otherwise be overlooked.

While existing solutions offered robust quantification capabilities, they were not suitable for high-level, qualitative assessments that can be used by non-specialists across multidisciplinary teams. Their complexity and specificity limit their accessibility and usability for non-specialists, posing a challenge for organisations operating across diverse sectors and disciplines. Furthermore, many tools were not designed to facilitate transformational change at scale, unlike mature systems developed for health and safety or cost management.

None of the existing solutions provided a unified, organisation-wide approach to carbon management that could be embedded into everyday decision-making processes. A digital solution was required to serve as a common language across teams, enabling consistent carbon thinking without requiring deep technical expertise. It had to be intuitive enough for general use, yet rigorous enough to support meaningful insights and drive change.

The absence of such a solution from the marketplace, or among competitors, highlighted a critical opportunity for innovation. Findings underscored the need for a tool that could bridge the gap between technical precision and strategic applicability. To meet carbon management objectives, it became necessary to either develop a bespoke solution or significantly adapt existing tools to suit the organisation's specific requirements.

This market research phase was instrumental in shaping our understanding of the digital carbon landscape and clarifying the limitations of current offerings. It also reinforced the importance of designing a solution that aligns with organisational values: multidisciplinary collaboration, scalability, and transformational impact. The insights gained here laid the foundation for the next phase: exploring the development of a custom digital framework that could support consistent, qualitative carbon management across all areas of the business.

2.2 DEVELOPMENT OF A CUSTOM SOLUTION

A comprehensive market review revealed that no existing digital solution adequately addressed the specific carbon management needs of a multidisciplinary organisation. In response, an internal development programme was launched to create a bespoke qualitative carbon management framework. This methodology outlines the collaborative process undertaken to design, build, and operationalise the framework.

2.2.1 Project Initiation

The project was commissioned as a global initiative under the Engineering Net Zero programme, with sponsorship from the Chief Operating Officer's office. A detailed business case, outlining the problem statement, the market research and the proposed solution was developed to obtain funding. Funding was secured through contributions from global regional business units, reflecting the strategic importance and cross-regional applicability of the solution. A dedicated task group was formed from specialists from across the business to lead the development. There were three core workstreams that were operationalised to support the project.

- The technical development team were responsible for defining the carbon management framework and ensuring alignment with international standards, particularly PAS 2080:2023.
- The digital team were responsible for building a user-friendly digital platform to host the framework and ensure that it was accessible to all.
- The roll out and adoption workflow focused on stakeholder engagement, market analysis, and operationalisation across sectors and regions.

The task group was made up from individuals representing sectors and business units from across the organisation, ensuring that the approach was balanced and addressed our diverse needs. The task group was supported by a wide network of stakeholders, which included carbon and sector-specific subject matter experts from transportation, civil infrastructure, buildings, masterplanning, and environmental disciplines. These individuals provided critical input into the framework's technical rigor and contextual relevance. It also included market stakeholders who were fundamental in understanding sector-specific needs and ensured relevance and usability in different contexts. Market stakeholders and key account managers, with their deep understanding of client needs, played a critical role in ensuring that the ambitious nature of client carbon targets was effectively addressed. This collaborative structure ensured that the framework was both technically robust and operationally viable.

2.2.2 Proof of Concept and Iterative Development

Once the concept had been developed and the core team mobilised, initial workshops were conducted across global markets and regions to start defining the landscape and requirements for the framework. These sessions informed the development of user 'journeys', which were essentially narratives that mapped typical carbon management workflows based on real-world carbon management experience. Using Mural, a collaborative digital whiteboarding tool, the core team translated these stories into decision flows. These flows captured key considerations, input requirements, and expected outputs, forming the basis for early proof of concepts. Example projects were used to validate assumptions and ensure sectoral relevance.

An initial proof of concept was developed in Microsoft Excel to test the functionality and logic of the framework that was starting to take shape. These mock-ups included decision trees and structured input/output formats. Input from the digital team to provide visual mock-ups was critical to this stage, as this progressed the development of the user interface and interaction pathways, helping stakeholders visualise the product. These prototypes were tested with diverse groups across the business with a particular focus in ensuring that the terminology, lifecycle stage descriptions, and user expectations were aligned across disciplines.

2.2.3 Technical Development

After extensive engagement with specialist and non-specialist stakeholders from the business, it became clear that there was a lot of technical and industry knowledge and best practice available that could be integrated into the framework to unlock value for all users. The technical development team worked closely with carbon subject matter experts to gather carbon resources into one central location and make it available to the rest of the business. This involved a number of critical developments.

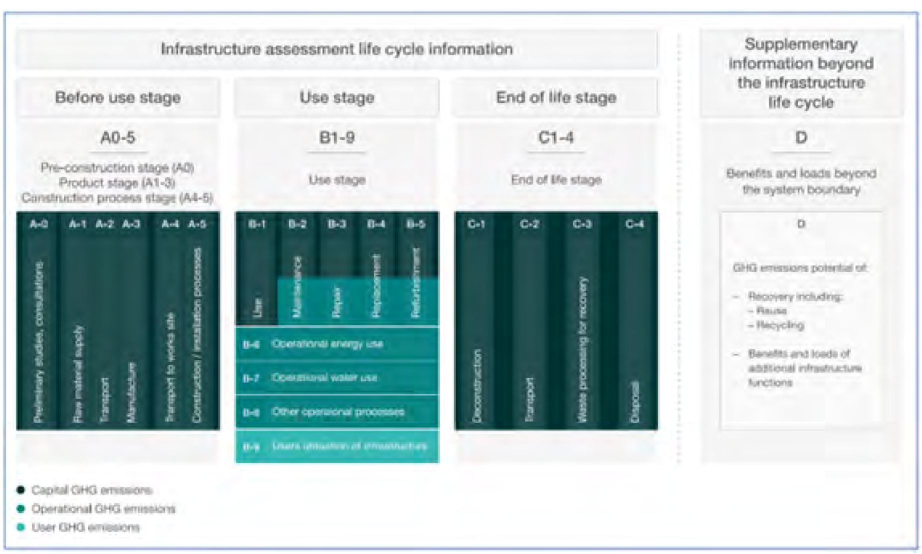
Standard Carbon Benchmarks

A key component in the development of the framework was the identification, collection, and structuring of benchmark data related to carbon hotspots of different asset types in different regions and sectors. Many subject matter experts had identified or developed valuable benchmark datasets which were available at relatively granular levels. Despite the data being spread across different regions, sectors and disciplines, we were able to identify common threads which allowed us to collect and catalogue it in a consistent and usable way. We found that these datasets provided insight into typical carbon hotspots across multiple different dimensions of an asset:

- **Lifecycle Hotspots:** Identify which stages within the asset lifecycle (as defined in EN 15978:2011) where carbon emissions are typically concentrated (Figure 2.1).

FIGURE 2.1

PAS2080 lifecycle stages as defined in EN 15978:2011



- **Elemental Hotspots:** Identify specific components or systems within an asset where carbon emissions are typically concentrated. See Figure 2.2 for an example of the elemental hotspots for a typical rail enhancement project.

FIGURE 2.2

Elemental hotpots for a typical rail enhancement project

- **Material Hotspots:** Identify particular materials (e.g., concrete, steel, asphalt) that are regularly used within specific asset types which have a significant contribution to the carbon emissions of that asset.

This granular understanding of carbon distribution is essential for enabling targeted interventions. By identifying where carbon is most likely to be concentrated, project teams can prioritise efforts and resources toward areas with the greatest potential for impact. Moreover, this approach supports early-stage decision-making, even in the absence of full carbon quantification, by providing a qualitative basis for assessing risk and opportunity.

The utility of this benchmark data is contingent on its consistency and accessibility. To ensure that the data could be effectively integrated into the framework and used across the organisation, a structured methodology was developed for its collection and storage. This involved:

- **Standardisation of Data Formats:** All benchmark data was reformatted to conform to a uniform schema, enabling consistent interpretation and application across sectors and regions.
- **Centralised Database Architecture:** The data was stored in a centralised digital repository, ensuring accessibility for all users and facilitating integration with other framework components.
- **Metadata and Provenance Tracking:** Each benchmark entry was tagged with relevant metadata (e.g., sector, region, asset type, source) to maintain traceability and support future-proofing of the data.

The inclusion of benchmark data plays a pivotal role in aligning the framework with PAS 2080:2023. By supporting evidence-based identification of carbon hotspots and enabling structured application of the carbon reduction hierarchy, the benchmarks serve as a foundational element in the overall methodology. They bridge the gap between qualitative reasoning and quantitative analysis, making carbon management more accessible without compromising on rigour.

Carbon Reduction Interventions Library

The 'Carbon Reduction Interventions Library' was developed as a central component of the framework, designed to support the sharing of best practice carbon reduction and lessons learned to scale up carbon reduction opportunities to encourage cross-sector and cross-region collaboration and the dissemination of technical knowledge.

The origin of the library lies in a carbon reduction tracker initially implemented on a best-practice PAS2080 compliant project within the business. This tracker served as a real-world example of how carbon interventions can be identified, recorded and tracked to facilitate their implementation. The initial tracker provided qualitative insights into the types of interventions that were most effective in reducing carbon emissions and highlighted important supporting information that was necessary to ensure their implementation into the project. The initial tracker also provided valuable information on the carbon reduction potential of the interventions when compared to standard business as usual approaches. This information could be used as a guide to demonstrate the relative scale of certain interventions and their potential to influence carbon reduction.

Building on this foundation, a series of structured workshops were held with subject matter experts from across the organisation to define the ideal architecture of a scalable interventions library. These workshops focused on identifying the key attributes of effective interventions, the types of metadata required for their contextual application, and the filtering mechanisms necessary to support usability across diverse project contexts. One of the most important outcomes of the session was alignment in how interventions should be catalogued to enable users to filter and identify relevant interventions based on the nature of their project, their technical requirements, and their strategic priorities. Importantly, the library supports both technical specialists and generalist users, facilitating broader engagement with carbon management across the organisation.

During stakeholder engagement, it became clear that the feasibility and reduction potential of certain interventions varied significantly by geography due to differences in market conditions, supply chain maturity, regulatory environments, and baseline practices. For example, in the UK, the default specification for cement replacement in standard ready-mix concrete is approximately 25% (Royal Institute of Chartered Surveyors, 2023), whereas in the United States, baseline practices may differ substantially due to variations in material availability, standards, and client expectations. To account for these differences, regional annotations were added to the interventions library as supporting information. These annotations provide guidance on local applicability, baseline assumptions, and considerations for implementation, ensuring that users can make informed decisions based on their specific project context. This regionalisation of the library enhances its technical robustness and supports alignment with PAS 2080:2023, which emphasises the importance of context-specific carbon management.

Technical experts from across the global business were engaged to populate the library. Contributions were solicited through targeted engagement with discipline-based communities of practice (Global Technical Networks) and sector-specific working groups. Each submission was reviewed for technical accuracy, relevance, and completeness before being incorporated into the central database. As of the current reporting period, the Carbon Reduction Interventions Library contains over 250 curated interventions, spanning multiple sectors, including transportation, water, energy, and buildings and applicable in many regions.

Quantification and Reporting

Quantification represents a critical dimension of carbon management, providing the empirical foundation necessary for tracking performance, validating interventions, and supporting transparent reporting. While our framework was designed to prioritise accessibility through a qualitative-first approach, it was essential to ensure that quantitative carbon data could be incorporated in a technically robust and consistent manner if available.

Market research made it clear that the development of a bespoke carbon quantification tool was not necessary. Numerous tools already exist across the industry; each tailored to specific disciplines and technical workflows, actively maintained and regularly updated to reflect market developments. Given the diversity of specialisms within the organisation, it was determined that different teams would naturally adopt the tools most appropriate to their project and client requirements. To support this, a 'Carbon Tools Library' was developed which outlines the strengths, limitations, and applicability of various quantification tools to enable people to select a quantification tool that is right for them within their respective disciplines.

The intent was to support informed tool selection while maintaining consistency in how quantification outputs are integrated into our broader carbon management framework. People are encouraged to carry out quantification using the most suitable external tool or software for their project context, with results subsequently captured back in a central platform in a structured and standardised format. This approach ensures that all carbon data, regardless of origin, is captured in a centralised location, enabling consistent reporting, comparability across projects, and alignment with PAS 2080:2023.

To achieve this, the framework was designed to accommodate quantification inputs in a way that ensures comparability across projects, sectors, and regions. One of the primary challenges in carbon quantification is the variability in scope definitions, methodological assumptions, and data sources. Without a standardised approach, the risk of misinterpretation or misrepresentation increases, particularly when aggregating data at portfolio level or comparing performance across different contexts.

To mitigate these risks, the framework includes a structured set of input fields that capture the essential parameters of any quantification data submitted. These fields were developed to elicit information about the physical scope of the assessment, the temporal boundaries over which emissions are considered, and the lifecycle stages included in the analysis. For example, users are asked to specify whether the quantification pertains to the entire asset or a subset of components, such as structural elements or building services. They are also required to define the time horizon of the assessment, distinguishing between upfront embodied carbon associated with construction and whole life carbon over the asset's design life, including its operation. Furthermore, the framework prompts users to clarify which lifecycle stages have been included, such as product and construction stages (A1-A5), use stage (B1–B7), end-of-life (C1–C4), and beyond lifecycle benefits (D), in alignment with international standard, EN 15978, as outlined in PAS 2080:2023.

In addition to scope definition, the framework incorporates a series of questions designed to assess the review and verification process associated with the quantification data. These questions aim to establish the credibility and reliability of the reported figures by capturing whether the data has undergone validation or verification by suitably qualified or competent carbon specialists. Users are also asked to indicate the level of confidence or uncertainty associated with the data, providing further context for interpretation and use.

This structured approach ensures that quantitative data entered into the framework is not only technically sound but also interoperable across different project contexts. It supports benchmarking by enabling comparison of carbon performance across similar asset types and project typologies. It facilitates tracking of carbon reductions over time, allowing teams to monitor progress relative to baseline conditions. It also enhances reporting capabilities, enabling the generation of auditable carbon metrics for internal performance monitoring and external stakeholder communication.

Importantly, the integration of quantification does not compromise the accessibility of the framework. Users who do not have access to detailed carbon data can still engage meaningfully through qualitative assessments, while those with technical expertise can input and analyse quantitative data in a structured and transparent manner. This dual functionality reinforces the framework's versatility and ensures that it remains applicable across a wide range of project scales, disciplines, and data maturity levels.

2.2.4 Digital Platform Development

The technology stack that was to be used to enable the framework to be rolled out across a global business, was selected following a comprehensive evaluation against the functional and non-functional requirements specified by the technical development team. A strategic decision was made to implement a web application architecture, utilising React for the front-end interface, .NET Core for the backend API, and Microsoft SQL Server for data storage, all hosted within the Azure Cloud environment.

A user interface prototype was developed, informed by the original Excel-based proof of concept and stakeholder input. This facilitated rapid design iteration and enabled early-stage user testing to assess the platform's visual design and usability. Feedback from these sessions was incorporated prior to commencing digital development.

The backend database was structured around the required user inputs and datasets developed by the technical team. This included benchmark tables for the Baseline section and an interventions library for the Routemap section. Data tables were designed to minimise duplication, with key columns indexed to optimise performance. Each table serves a distinct function, whether for users, settings, or activity, ensuring clarity, scalability, and ease of management. Stored procedures were implemented to support consistent and secure data operations.

Front-end development followed an iterative cycle of build and review between the technical and digital development teams, ensuring accurate interpretation of technical requirements. All development activities were initially conducted in a dedicated development environment, with functional and user testing completed prior to deployment to the live production environment.

Prior to launch, the application underwent rigorous penetration testing to proactively identify and mitigate potential vulnerabilities. Access control is managed via Azure Active Directory (AAD), ensuring that only authorised AtkinsRéalis users can access the system, with user permissions strictly enforced.

2.2.5 Testing, Feedback, and Endorsement

The framework underwent multiple rounds of testing with internal users across a range of markets, disciplines, and regions. Feedback was gathered through structured workshops, informal discussions, and a dedicated Microsoft Form, allowing for both qualitative and quantitative input. This feedback informed iterative refinements to both the technical content and the user interface, ensuring the framework was responsive to the needs of its intended users.

Following the release of Version 1, a formal feedback cycle was initiated to assess user engagement and identify areas for improvement. Insights from this process, particularly around how users interacted with the tool and which features supported their workflows most effectively, were used to inform the development of Version 2. The updated version reflects these findings, with enhancements focused on improving usability, aligning functionality more closely with design processes, and addressing specific technical feedback.

Ongoing engagement with technical stakeholders was maintained throughout the development lifecycle. This ensured that all updates were subject to expert review and endorsement, preserving the framework's credibility and securing buy-in across the business. The iterative approach adopted throughout the testing phase has been instrumental in refining the tool's performance and ensuring its alignment with both user expectations and organisational standards.

3. Results

As a result of the steps taken above, a *Carbon Insights* was produced - a qualitative carbon management framework to "demystify carbon". The framework is a structured, repeatable, and standards-aligned approach to carbon management, developed in accordance with PAS 2080:2023. The structure of the framework is outlined in three core steps; Baseline, Routemap and Deliver. Each step is designed to support systematic carbon management throughout the project lifecycle. While the interface and prompts are tailored to suit different project contexts, the underlying structure of the framework remains consistent, ensuring methodological integrity and comparability across applications.

BASELINE

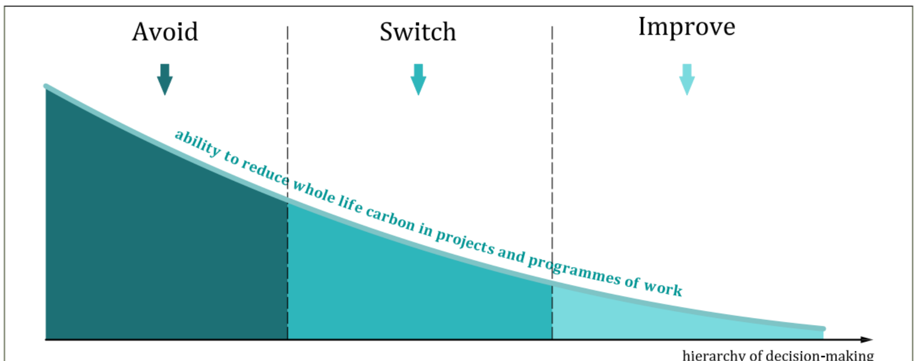
The Baseline stage facilitates the identification of carbon hotspots using industry benchmarks and qualitative indicators. This approach enables early-stage carbon assessment without requiring full quantification, which is often unavailable or impractical at project inception. Users are guided to determine which aspects of the project fall within their control and influence, allowing for a flexible and context-sensitive carbon strategy. Where quantitative data is available, it can be incorporated to establish a formal baseline. This dual capability ensures that the framework is accessible to non-specialists while remaining sufficiently rigorous for technical practitioners.

ROUTEMAP

The Routemap stage encourages the use of the PAS 2080:2023 carbon reduction hierarchy (see Figure 3.1) to identify opportunities to reduce the carbon impact of the identified hotspots. Users can explore the Carbon Reduction Interventions Library to see the interventions that have been used by colleagues on similar projects. While users are supported in exploring potential interventions through access to the Carbon Reduction Interventions Library, the transition from general guidance to project-specific implementation is facilitated through the use of the Carbon Tracker. The Carbon Tracker is a structured tool designed to monitor the application of carbon reduction strategies at the project level. This functionality allows teams to systematically record all carbon reduction opportunities being considered, track their status, and document outcomes throughout the project lifecycle. The tracker encourages the consideration of broader risks, such as cost implications, programme impacts, and potential effects on quality, to ensure that reduced carbon does not compromise other drivers and supports balanced decision-making. The tracker also facilitates the identification of co-benefits, such as improvements in biodiversity, resource efficiency, or social value, helping teams to evaluate interventions holistically.

FIGURE 3.1

PAS 2080:2023 Carbon reduction hierarchy



***NOTE** This figure represents a simplified and streamlined version of the carbon reduction hierarchy presented in PAS 2080:2016 and the* Infrastructure carbon review *[1]. It has been updated to clarify its applicability and relevance to a wider range of projects and programmes within the built environment (i.e. to clarify that the carbon reduction hierarchy is not solely about new builds).*

DELIVER

The Deliver stage supports the implementation of interventions and tracking of project outcomes. Where applicable, updated carbon quantification data can be entered to demonstrate reductions achieved relative to the baseline. This comparison supports transparent reporting and enables teams to demonstrate progress toward client and organisational carbon reduction targets. Qualitative insights are also collected, lessons learned are identified, including what worked well, challenges encountered, and any adjustments made to accommodate project-specific constraints. Furthermore, the Deliver stage provides an opportunity to identify and report any outstanding risks or unresolved challenges related to carbon performance that could be picked up in a later stage. This iterative process supports continuous improvement and enables aggregation of data across projects, facilitating portfolio-level analysis and reporting.

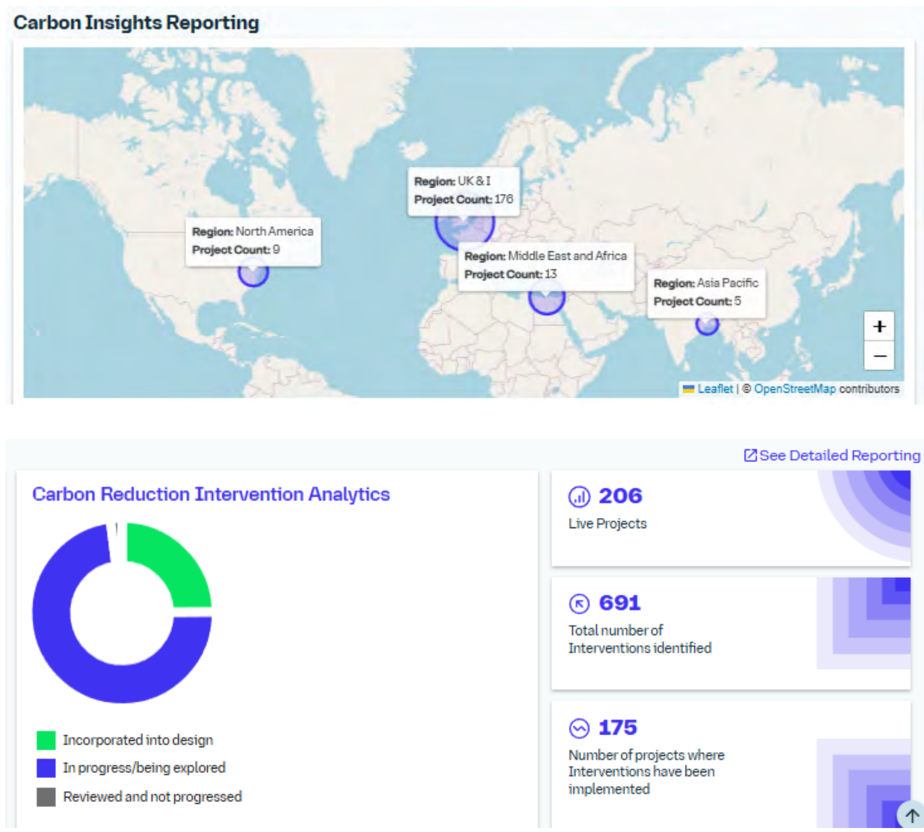
ROLL OUT

As of the latest reporting period, over 200 projects have utilised the framework, providing carbon management support to over 100 clients spanning across the Transportation, Water, Energy, and Buildings sectors. This demonstrates the scalability of a framework which was created to enable transformation change. Not only has the platform started to be adopted on live projects, but it is also enabling the integration of carbon management into project governance such as project controls, decision logs, and delivery workflows.

Additionally, with a power BI dashboard to collate project data at framework, programme, sector and regional levels, *Carbon Insights* is supporting scalable reporting and regional and global performance monitoring and resulting in industry recognition for its transformational capacity. The framework was shortlisted for the UK's National Sustainability Awards.

FIGURE 3.2

Carbon Insights reporting and performance monitoring



4. Conclusion

In *Carbon Insights*, AtkinsRéalis has developed a qualitative framework which provides a robust and scalable methodology for carbon management available to be used across the global business. Its alignment with PAS 2080:2023 ensures technical credibility, while its qualitative-first design 'demystifies' carbon and promotes accessibility and widespread adoption.

By offering a high-level, qualitative approach, Carbon Insights makes carbon management accessible to all project teams. Since launch, over 3,250 people have been engaged via regional webinars, project-specific workshops and client tech labs. The platform has supported over 200 projects and 100 clients across Transport, Water, Energy and Buildings sectors; identifying over 600 carbon reduction opportunities which can inform future projects, enabling continuous improvement.

The platform also enables consistent reporting of quantified data, where available. For example, a masterplanning project using a combination of *Carbon Insights, BIM Analytics and OneClick LCA* presented 17% embodied carbon and 10% operational emissions savings. Another infrastructure project reported savings of over 100 tons of embodied carbon through optimising the design in line with the PAS2080 carbon reduction hierarchy. Reducing embodied carbon often results in lower material costs, creating win-wins for clients.

Carbon Insights also promotes broader sustainability outcomes, including climate resilience, nature-based solutions and circular economy. It aligns to sustainability frameworks, such as ENVISION and the RICS Whole life carbon standards which are already being adopted across the industry. The platform simultaneously assesses the long-term risks and co-benefits of carbon reduction opportunities, ensuring that carbon reduction does not compromise broader sustainability or project outcomes, such as quality, programme or cost and creates optimized solutions for projects and clients.

The platform supports AtkinsRéalis' corporate Environmental, Social, and Governance (ESG) goals and was central to the UK business' PAS2080 verification in 2024. Independent auditors, LRQA had not seen anything comparable in other companies, stating that AtkinsRéalis had "*an excellent standard of implementation…strongly supported by the carbon management system framework provided and embedded within the organization.*"

In summary, *Carbon Insights* is scalable, user-friendly and transformative. It empowers teams to make informed, carbon-conscious decisions, helping the company meet its own ESG goals and deliver meaningful sustainability outcomes for its clients. The framework serves as a foundational tool in the transition to net zero and in supporting client ambitions while enabling sustainable outcomes across projects.

Acknowledgements

We would like to acknowledge all those who have contributed, and continue to contribute, to the development and implementation of this framework. This includes members of the core task group, whose leadership and coordination were instrumental throughout the project. We extend our thanks to the technical carbon and sector-specific subject matter experts who provided critical input, ensuring the framework's technical rigour and relevance across disciplines. We also recognise the Carbon Champions who played a key role in promoting adoption across the business, and the Global Technical Networks whose contributions have supported the ongoing development and refinement of the Carbon Reduction Interventions Library. Together, this collective expertise and commitment have been essential to the success of this initiative.

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05: Aligning Geotechnics and Hydrogeology to Design an Efficient Bored Pile Underpass in Complex Ground and Groundwater Conditions – A Project Example

Significance Statement

A deep understanding of soil and groundwater can lead to smarter, safer infrastructure. Faced with challenging conditions—including a geological fault and pressurized groundwater—detailed site investigations and advanced modelling were used to rethink the design of a major underpass. By applying sound engineering principles, a conservative, high-carbon solution was replaced with a more efficient one, reducing concrete use and environmental impact – all while protecting nearby infrastructure and managing complex groundwater pressures. The work exemplifies technical excellence and collaboration, offering a blueprint for how thoughtful and holistic design can deliver better outcomes for clients, communities, and the planet.

Énoncé d'importance

Une compréhension approfondie des sols et de l'hydrologie peut mener à la conception d'une infrastructure plus intelligente et plus sécuritaire. Dans un contexte environnemental complexe, notamment la présence d'une faille géologique et d'eaux souterraines sous pression, le recours à des études détaillées du site et à une modélisation avancée a permis de repenser la conception d'un passage souterrain névralgique. En appliquant des principes éprouvés d'ingénierie, une solution conservatrice et à haute intensité carbonique a pu être remplacée par une solution plus efficiente, utilisant moins de béton et plus respectueuse de l'environnement – tout en protégeant une infrastructure adjacente et en gérant des pressions hydriques complexes. Ce projet est un parfait exemple d'excellence technique et de collaboration, offrant un modèle à suivre en matière de conception réfléchie et holistique produisant de meilleurs résultats pour les clients, les collectivités et la planète.

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Abstract

The A57 upgrade is a project of national importance, designed to relieve traffic congestion in the village of Mottram in Longdendale, Manchester and involves bypassing the village with a dual carriageway. The largest structure in the scheme is the Mottram Underpass, a 130m long, 10m deep underpass which is to be constructed in complex geotechnical and hydrogeological conditions, comprising a geological fault and artesian groundwater. The structure is adjacent to a large rock cutting. Outline design proposed secant piles and a thick concrete base to ensure a watertight structure. However, preliminary reviews suggested the effects of the adjacent cutting on the groundwater regime were not fully captured, leading to potentially conservative design assumptions. Additional investigation was undertaken to characterise the complicated ground conditions, and a hydrogeological model was constructed to understand the structural impact on nearby infrastructure and the local groundwater profile. The findings indicate that the use of contiguous piles presents a cost-effective and environmentally preferable solution, while also ensuring effective management of groundwater effects.

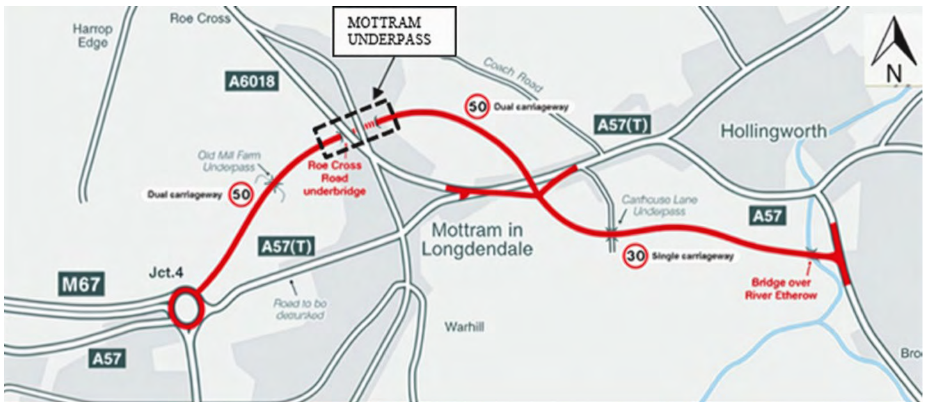
KEYWORDS
Carbon reduction; Project case study; Geological fault; Hydrogeology

1. Introduction

The A57 Trans-Pennine upgrade project is a National Highways nationally significant infrastructure project that involves the creation of a 3km bypass of the existing A57 road through Mottram in Longdendale (Figure 1), on the eastern edge of Greater Manchester, UK. Balfour Beatty Atkins (BBA) Alliance took on the detailed design and construction.

FIGURE 1

Indicative layout of proposed bypass
© National Highways



The project involves the bypass of Mottram in Longdendale village with a new dual carriageway connecting the M67 to the existing A57 at Mottram Moor. From Mottram Moor junction a new single carriageway will connect to the existing A57 south of Woolley Bridge (see Figure 1).

The dual carriageway portion bypasses Mottram in Longdendale village by way of a new bridge along Roe Cross Road and an underpass spanning between Old Road and Old Hall Lane. The underpass is approximately 130m in length and at its maximum, the road is 11m below existing ground level (m bgl). To the east of the underpass is Mottram cutting, up to 14m deep and 400m in length. An underpass was selected as the preferred way of bypassing the village in order to maintain connectivity at existing ground level across the village and reduce the impact on the village. A community public space and park is proposed on top of the underpass once completed.

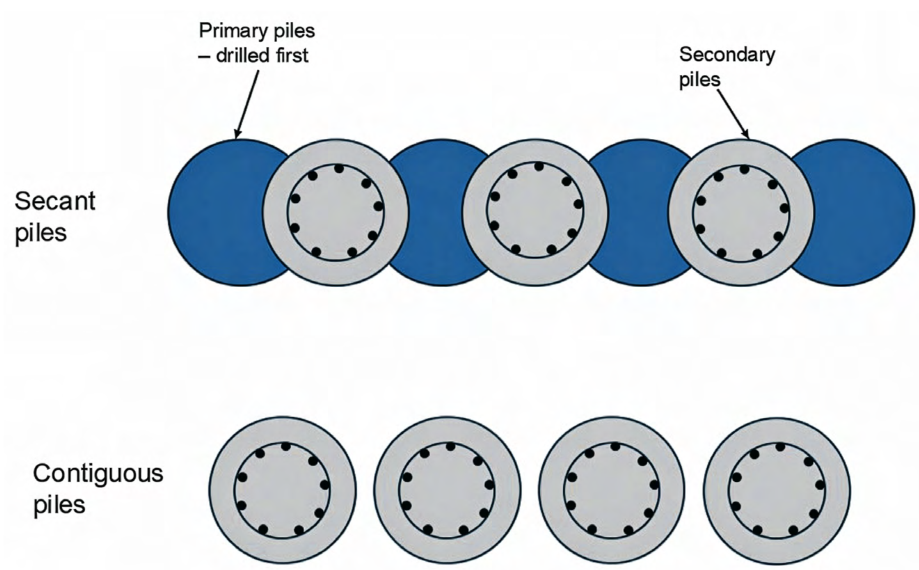
1.1 DESIGN DEVELOPMENT

The preliminary design showed the underpass and wingwalls to be secant (overlapping) piles (see Figure 2), with a base slab able to resist uplift pressure from a design groundwater level at existing ground level. The design had also considered the requirement for anchor piles to resist uplift pressures from the groundwater and aimed to create a watertight box solution.

A value engineering exercise was undertaken at the beginning of the detailed design stage, involving optioneering to seek out opportunities for cost, carbon and programme savings by a mult-iplinary team of AtkinsRéalis designers, Balfour Beatty 'Method Led' team and National Highways experts. During this phase, the geotechnical and hydrogeological teams advised that the preliminary design may have inadequately accounted for the influence of the adjacent deep cutting and the underpass structure on the broader groundwater regime. A detailed modelling of the geological formations and characteristics and the groundwater extents could result in a more realistic representation of the localised conditions and potentially in a more cost-effective design with a reduced carbon footprint. In light of this, the ground investigation was strategically directed to acquire further detailed information. This data subsequently fed detailed hydrogeological modelling and design which confirmed that a less carbon intensive design may be possible by changing the design from secant piles to contiguous piles (see Figure 2).

FIGURE 2

Schematic of secant and contiguous piles in plan



This paper presents an overview of the investigation findings and describes the design strategies implemented to achieve an efficient underpass solution within complex geological and groundwater conditions. This design approach led to significant savings in both cost and carbon in the process. The paper also demonstrates best practice in geotechnical design by showcasing a first-principles approach, including the coordination of a robust ground investigation, consideration of realistic modelling of geological and hydrogeological conditions and the impact on surrounding infrastructure. In sum, the work exemplifies technical excellence in infrastructure design through disciplined application of engineering fundamentals, cross-disciplinary collaboration, and evidence-based decision-making. The ground investigation required to complete the design is presented in Section 2, and the hydrogeological and geotechnical design phases are presented in Sections 3 and 4 respectively.

2. Ground Investigation

2.1 INTRODUCTION

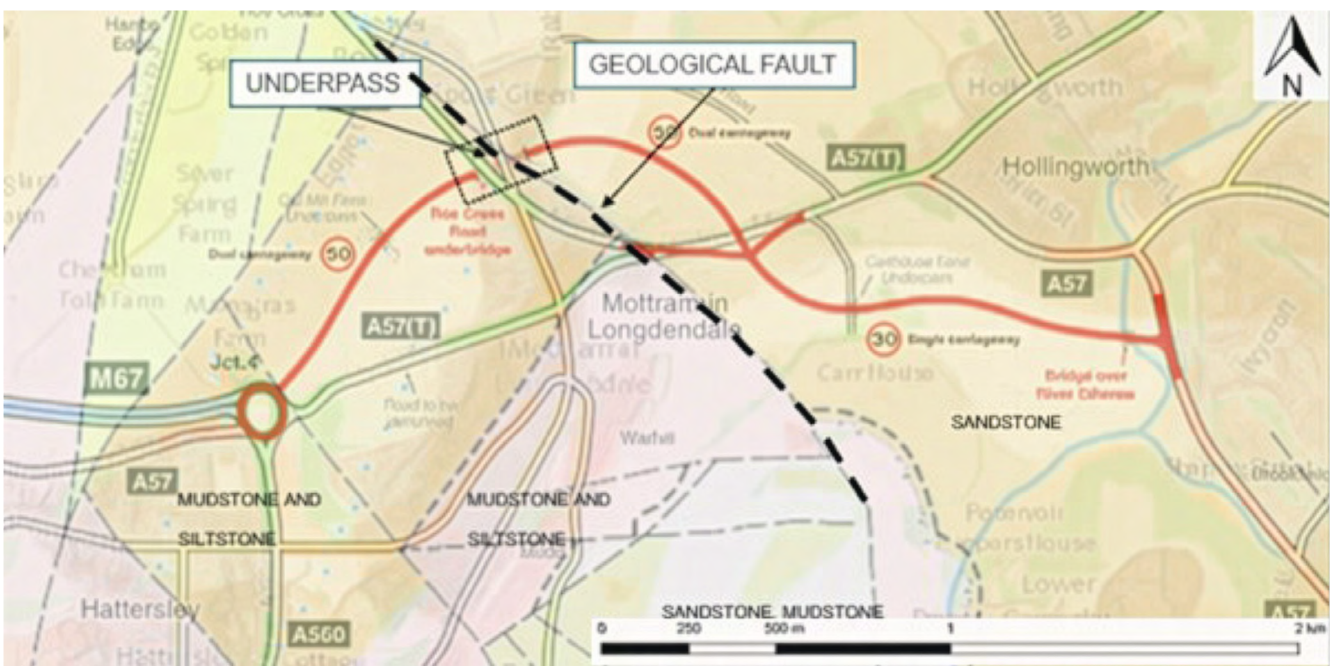
A series of historical ground investigations, some undertaken over 50 years ago, were inherited from the preliminary design and the data was evaluated. Due to significant changes in the scheme proposal and the complexity of the ground conditions, an additional investigation was proposed to inform the detailed design of the scheme.

2.2 GROUND CONDITIONS

In the vicinity of the proposed underpass, ground conditions comprise cohesive glacial till with sand bands, overlying Millstone Grit bedrock (interbedded mudstone, siltstone and sandstone). A key feature is a geological fault that intersects the proposed underpass (Figure 3). Unlike previous ground investigations, the recent investigation confirmed the location and its possible extents, indicating a faulted zone rather than a discreet fault feature.

FIGURE 3

Solid geology and geological features in the proposed underpass area



The recovered rock core samples identified the different nature and reduced engineering strength parameters of the faulted material compared to the adjacent rock outside of the fault zone. Figure 4 shows two typical rock samples for the non-faulted and faulted material extracted from similar depths, approximately at 20m bgl from two boreholes within 20m horizontal distance. Borehole BH514 shows that the rock has been weathered completely to a clay-like soil, whereas the typical non-faulted material in BH512 appears to be fractured rock.

FIGURE 4

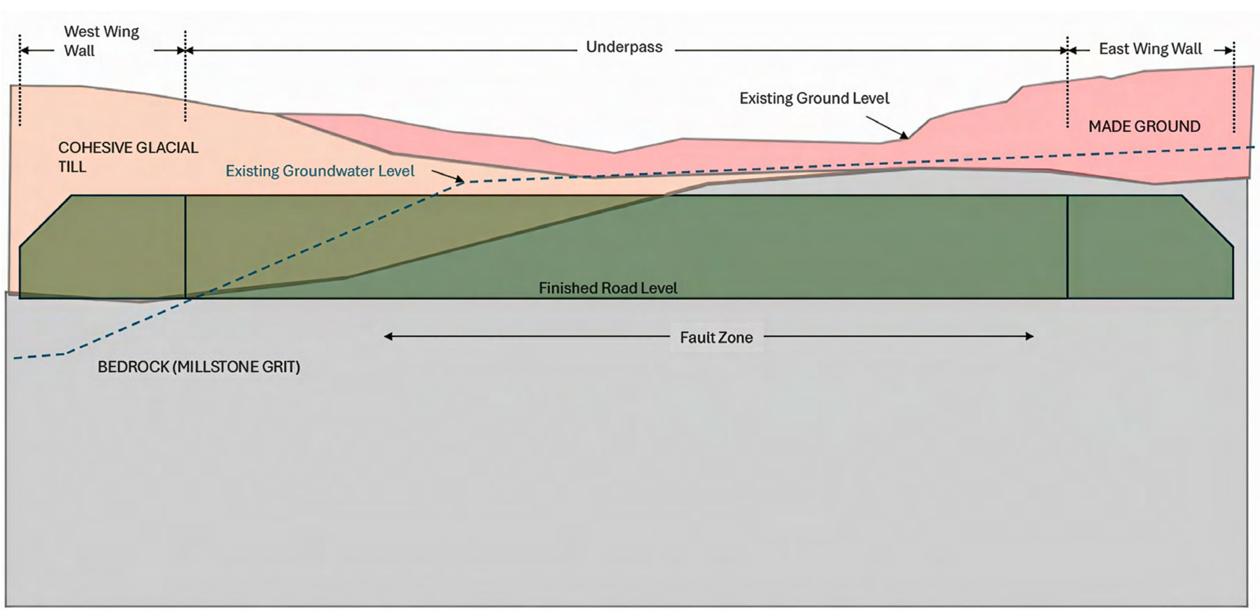
Obtained core samples of competent rock (BH512 – top) and faulted rock (BH514 – bottom)

2.3 GROUND MODEL AND GEOTECHNICAL PARAMETERS

Due to the high variability of the ground conditions and the presence of the geological fault, three ground models were derived for the underpass and its wing walls. Figure 5 presents an illustrative ground model along the length of the underpass, highlighting how the ground conditions change along its length. For the main underpass located within the fault zone the characteristic parameters of the faulted rock were considered. The ground conditions at the western wing walls comprise superficial glacial tills overlying weak Millstone Grit bedrock. At the eastern wing walls, the thickness of the glacial till drastically reduces, with rockhead approaching surface. The characteristic geotechnical parameters were derived in accordance with the recognised UK standards and guidance (CIRIA C143 (CIRIA, 1995), BS8004:2015 (British Standards Institution, 2015)). As the design bedrock properties were critical to the design, different characteristic strength values were adopted for each ground model, depending on the degree of weathering and nature of the material. A number of in-situ and laboratory tests were also conducted to validate the determined parameters.

FIGURE 5

Schematic of ground model considered in the underpass design - not to scale

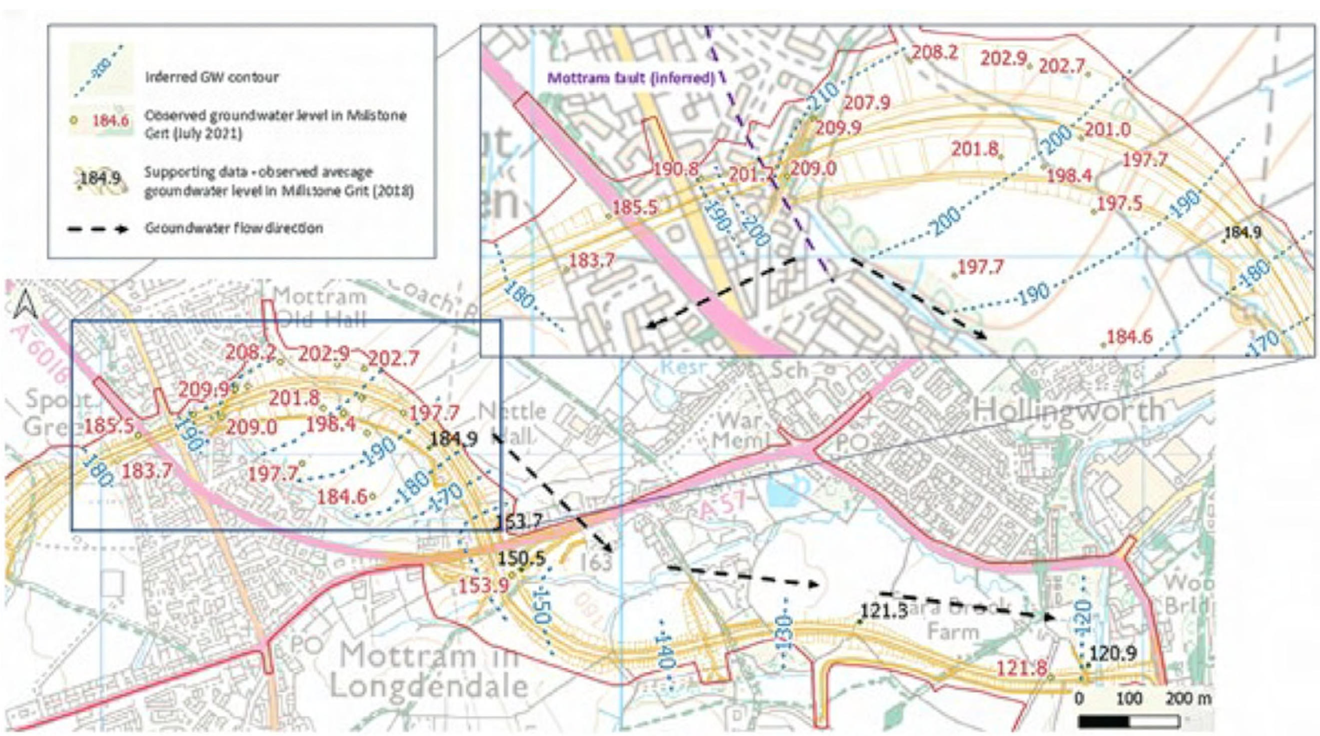


2.4 HYDROGEOLOGICAL INVESTIGATION AND OBSERVATIONS

Hydrogeological conditions at the site were not fully investigated during previous phases of ground investigation. Therefore, the most recent phase of investigation, designed by AtkinsRéalis, included significant groundwater monitoring and testing. Groundwater at the site was found to flow from the hills in the northwest of the site to the southeast towards the River Etherow (Figure 6).

FIGURE 6

Groundwater flow direction



During groundwater monitoring carried out within the vicinity of the underpass it was identified that artesian groundwater conditions were present within the bedrock to the east of the fault zone. Groundwater levels to the east of the fault zone were also found to be significantly higher than to the west. The data suggested (as seen in Figure 6) that the fault zone was acting as a barrier to groundwater flow.

Although a pumping test had been carried out in this area as part of a previous ground investigation in 2018, AtkinsRéalis felt it was necessary to carry out further testing to better understand the complex groundwater regime and the extent of the impacts that any future dewatering would have on the surrounding environment. Further pumping tests were carried in 2022 and 2024 lasting for up to 21 days, to obtain high quality representative information.

The ground investigation and pumping tests confirmed that the impact of any dewatering is unlikely to extend west across the fault line. The pumping tests also confirmed low rock permeability on a macro scale, resulting in low volumes of groundwater flows.

3. Hydrogeological Design and Modelling

Due to the identification of artesian groundwater to the east of the fault zone, it was determined that active (pumped) dewatering would be required during construction to manage groundwater pressures. However, further modelling was required to demonstrate whether the inherited preliminary design of a 'watertight box' was required for the underpass to resist the groundwater pressures, or whether a more efficient design was possible. The AtkinsRéalis hydrogeology team undertook detailed 3D modelling, using high quality investigation data, across a wide area to understand the long-term impact of the underpass and cutting excavation on the groundwater levels.

3.1 3D GROUNDWATER MODEL

A 3D groundwater model was first developed to simulate the baseline groundwater conditions across the area using available ground investigation and monitoring data. To assess the difference in the predicted drawdown associated with the different underpass design options, long-term scenario models were then created for both the secant (water-tight) and contiguous pile options for the underpass. The model showed that the extent of groundwater drawdown for both options was similar. However, the secant option indicated some groundwater pressure build up behind the northern pile wall. Figure 7 and Figure 8 below show the difference. The model predicted that if the contiguous pile option was chosen there would be less groundwater pressure behind the wall but there would remain some upwards groundwater pressure beneath the road that could lead to uplift or groundwater flooding.

FIGURE 7

Modelled groundwater drawdown contours for secant pile scenario

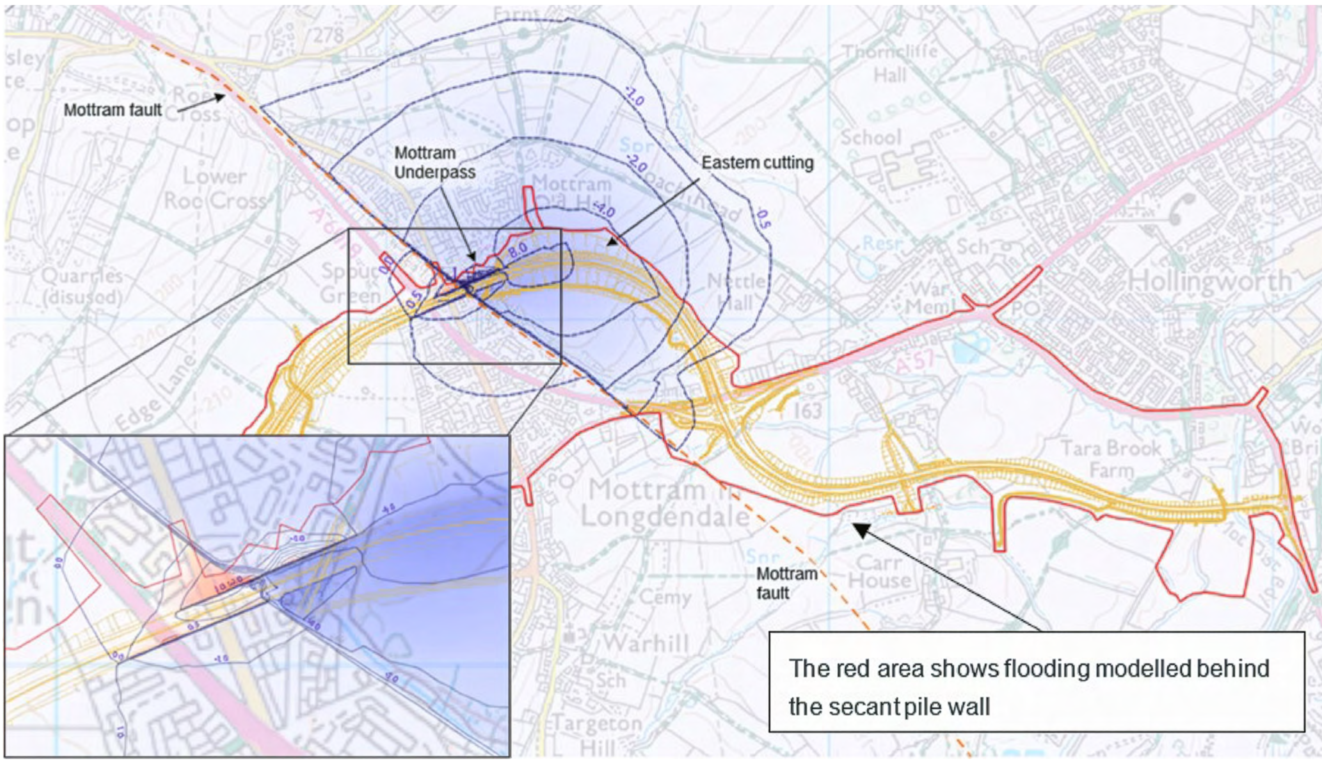
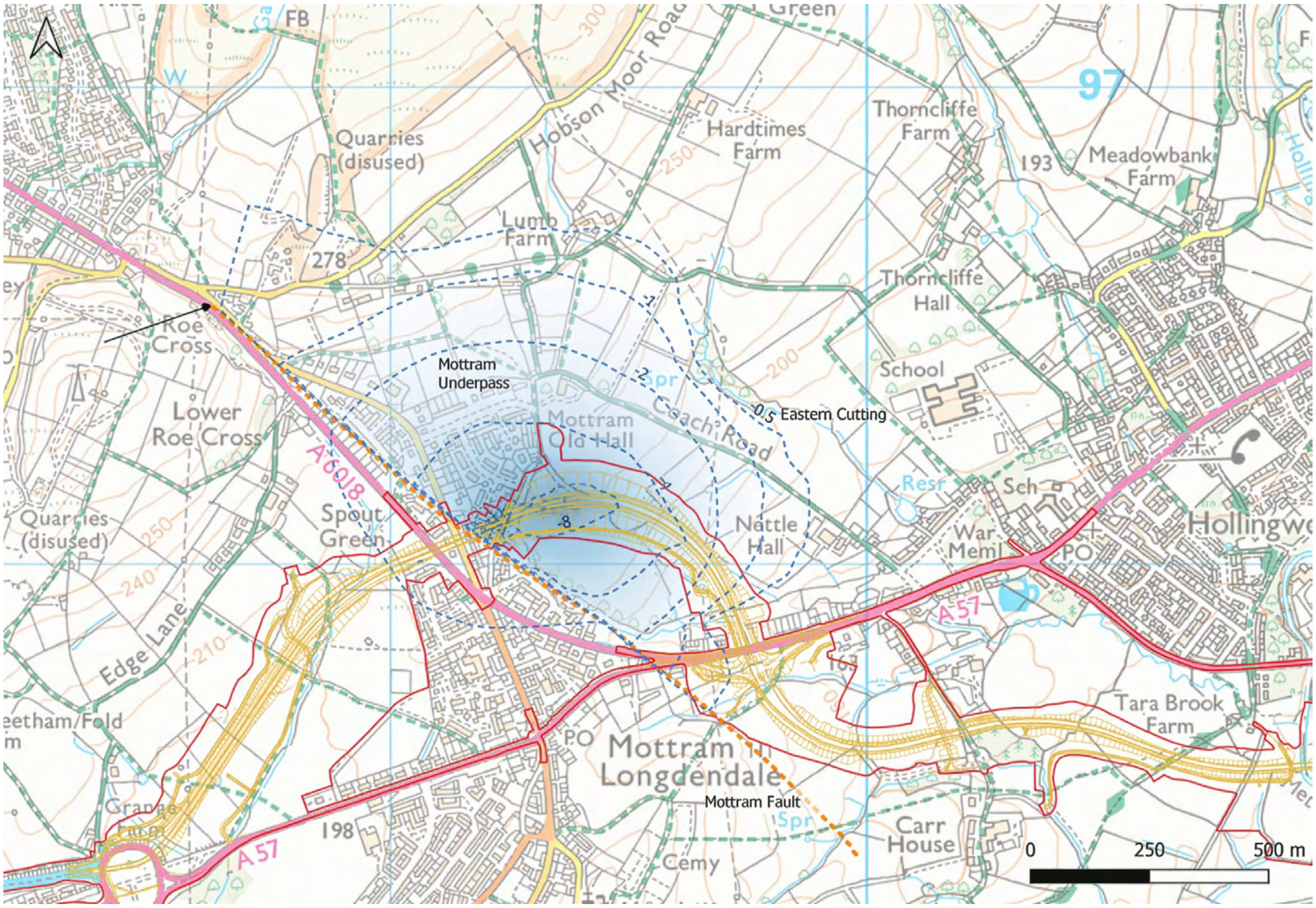


FIGURE 8

Modelled groundwater drawdown contours for contiguous pile scenario



3.2 PASSIVE DRAINAGE SYSTEM

AtkinsRéalis proposed using a passive dewatering system in the underpass and cutting where groundwater pressures were modelled to be higher than proposed road level. The purpose of the system was to prevent the potential for uplift beneath the carriageway and groundwater flooding, when considering the contiguous pile option. The use of this relatively novel technique in highways dewatering, enabled the change in pile design at the underpass and helped to facilitate substantial carbon and cost reduction on the project.

The passive dewatering system comprises long rows of groundwater wells drilled below proposed highway level deep into the rock. They are located in two rows, adjacent to the piles and in the central reserve, through the underpass and the cutting. These wells are designed to relieve any potential build- up of groundwater pressure beneath the highway and maintain the groundwater level to 1m below the road surface.

The 3D model was run to demonstrate the efficacy of the dewatering wells, and various spacing of wells (5m, 10m, 20m) were tested within the model. It was found that two rows of wells at 5m spacing to a depth of 10m below highway level would reduce the pressure to the required level within the underpass (see Figure 9 and Figure 10 comparing groundwater pressures at different well spacing). To ensure the design estimates were robust, sensitivity analysis was carried out for rainfall averages and hydraulic conductivity of the bedrock.

FIGURE 9

Modelled groundwater pressure with passive wells at 10m spacing

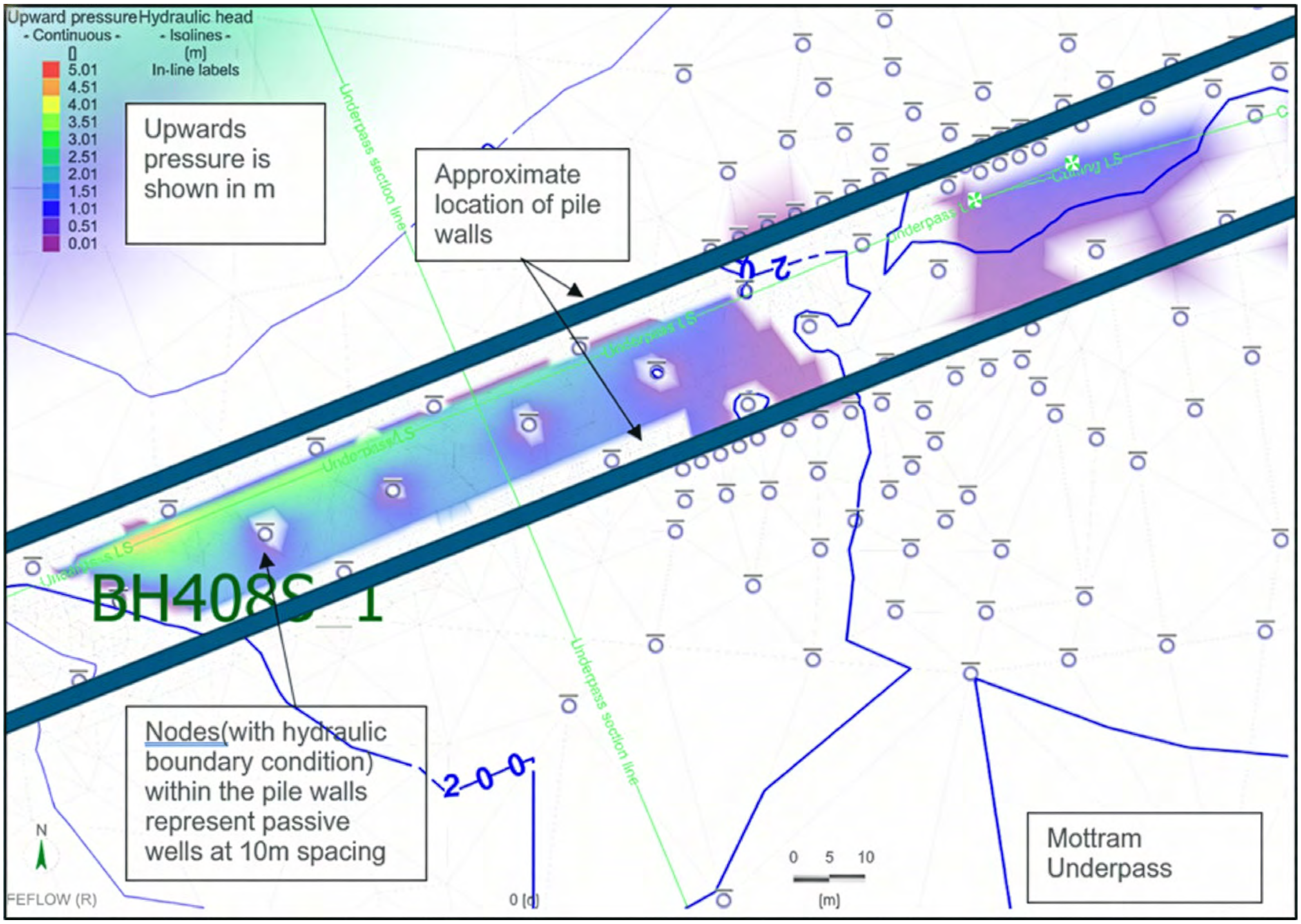
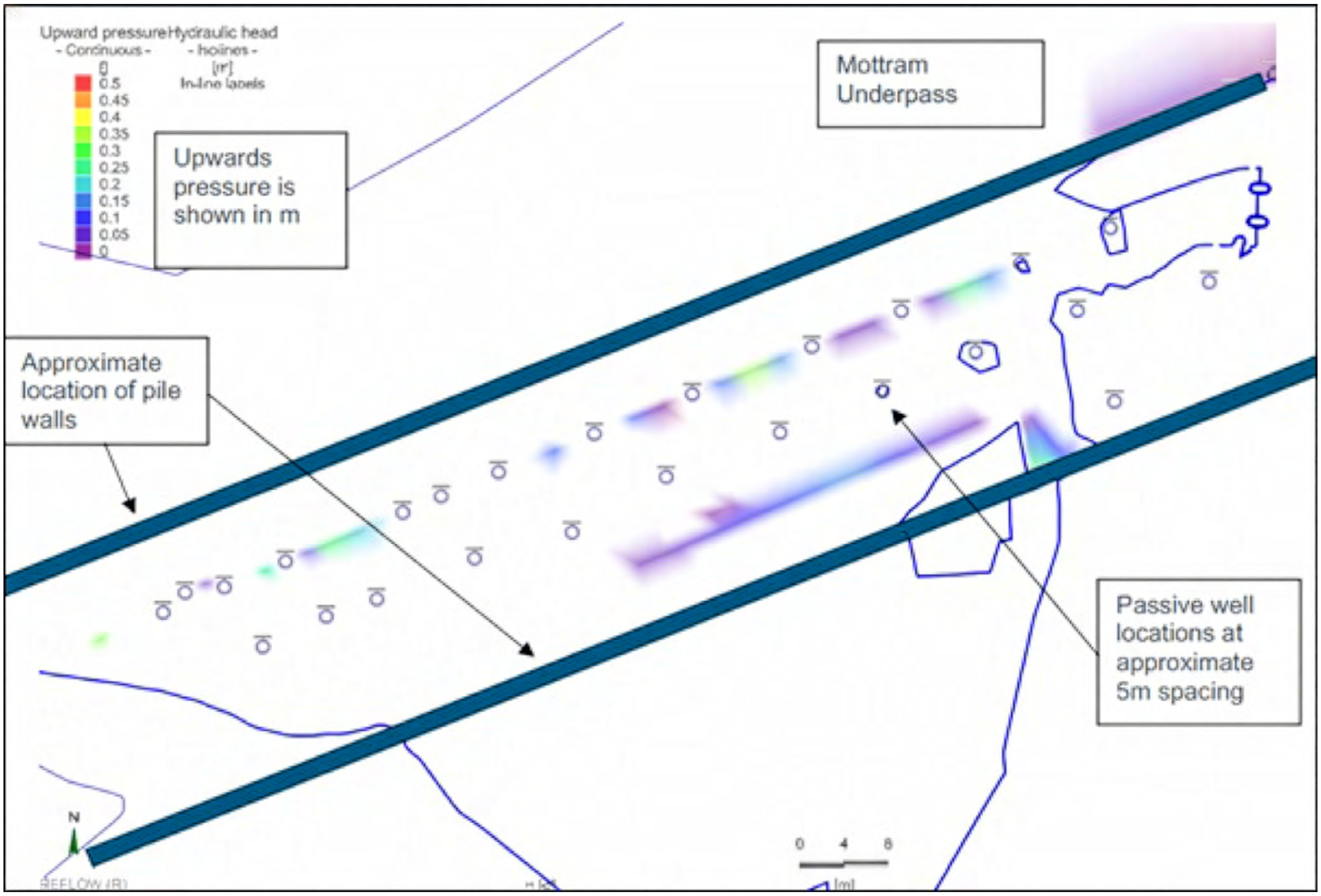


FIGURE 10

Modelled groundwater pressure with passive wells at 5m spacing



3.3 SEEP MODELLING

Two dimensional (2D) finite element numerical modelling was also undertaken using Seep/W software (Figure 11 and Figure 12) to understand if there would be pore-water pressure behind the underpass contiguous pile wall during operation for input into geotechnical design analyses. A conceptualisation of the underpass dewatering system was developed on the basis of geological cross sections, available site investigation data, and engineering designs of the road and drainage system.

FIGURE 11

Groundwater pressure behind pile wall without passive wells

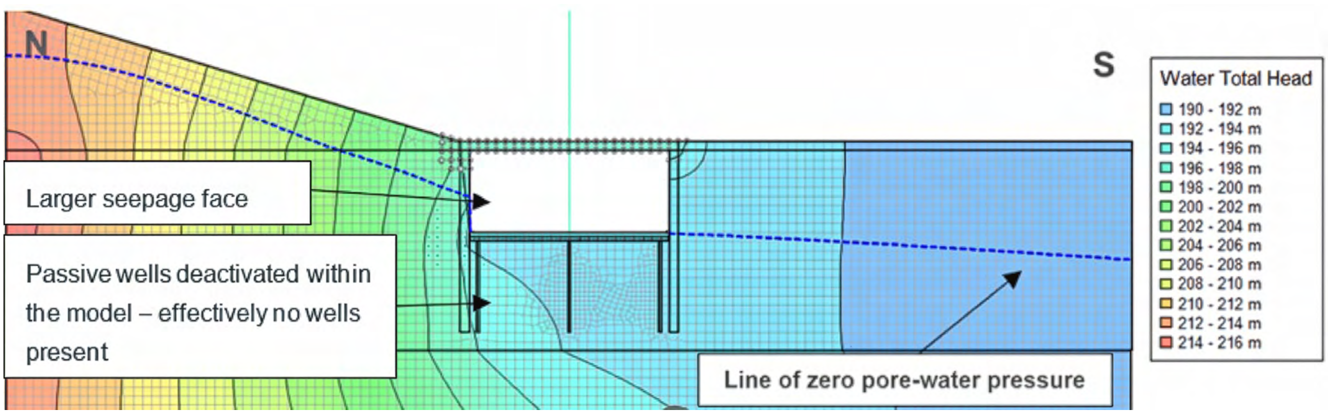
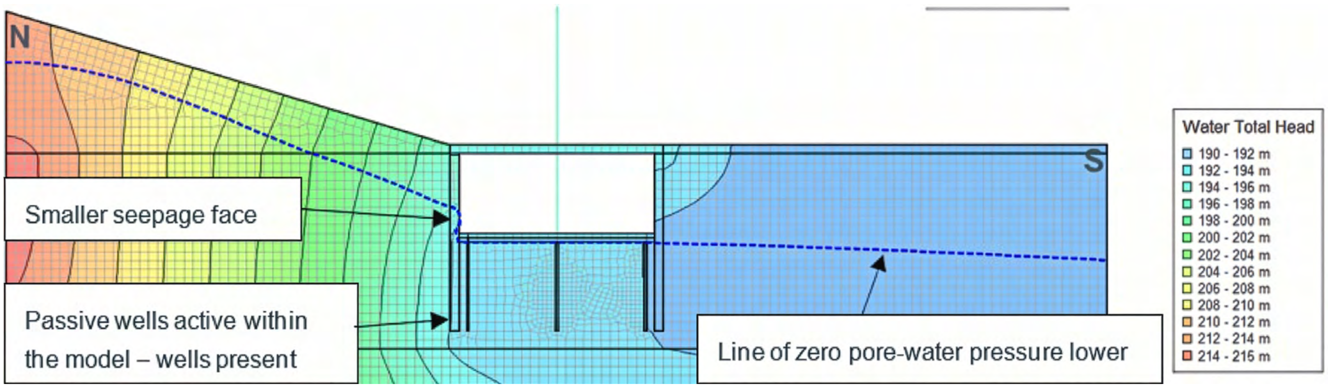


FIGURE 12

Groundwater pressure behind pile wall with passive wells



Using the PhD research of AtkinsRéalis geotechnical engineer Stan Qi (Qi, 2022), the pile wall was modelled in 2D as one continuous feature with an average hydraulic conductivity, equivalent to modelling the individual piles and gaps with varying hydraulic conductivity.

The results of the 2D modelling (Figure 11 and Figure 12) show that the presence of the passive dewatering wells reduces the pore water pressure behind the pile wall and the height of the seepage face on the northern pile wall is reduced.

4. Geotechnical Design of the Underpass

4.1 DESIGN DEVELOPMENT

As discussed above, the additional ground investigation gave the designers adequate data to be able to confidently model the impact of the hydrogeology on the geotechnical design of the underpass. The hydrogeology team and geotechnical team worked in parallel to complete the design of a contiguous bored pile underpass, moving away from the secant piled 'watertight box' solution. Section 3 discusses the hydrogeological modelling that was undertaken alongside the geotechnical design discussed in this section.

4.2 STRUCTURE

The structural design of the underpass comprised contiguous piles, a capping beam and a diaphragm with a fully integral connection with the underpass top slab. A top down construction sequence was preferred for ease of construction and identifying the construction sequence was key to ensuring all stages were appropriately modelled, and the worst-case design scenarios were identified and designed for. The sequence allowed for long-term concrete stiffnesses and strengths to be reached, in the case of delays between stages and possible re-programming of works.

The summary construction sequence was as follows:

1. Excavation to pile platform level.
2. Construct piles.
3. Excavate to underside of capping beam and construct capping beam and diaphragm.
4. Lift and tie in top slab beams.
5. Excavate to underside of highway construction and build passive drainage system.
6. Fill up to highway level and surface.

The integral connection between piles and top slab requires an iterative design process in line with the process outlined in PD6694-1:2011 (British Standard Institution, 2011). The geotechnical design was undertaken using Wallap software for a 2D design, iterated with a 2D portal structure designed in Lusas software. Coherence had to be achieved between the two models, ensuring output bending moments and deflections matched. Once the model outputs were coherent, the structural design was completed in Lusas 3D.

The design conservatively considered a water pressure of 1/3 retained height behind the piles. This was to account for the estimated water pressure behind the piles as discussed in the 2D seepage modelling (Section 3.3).

5. Settlement

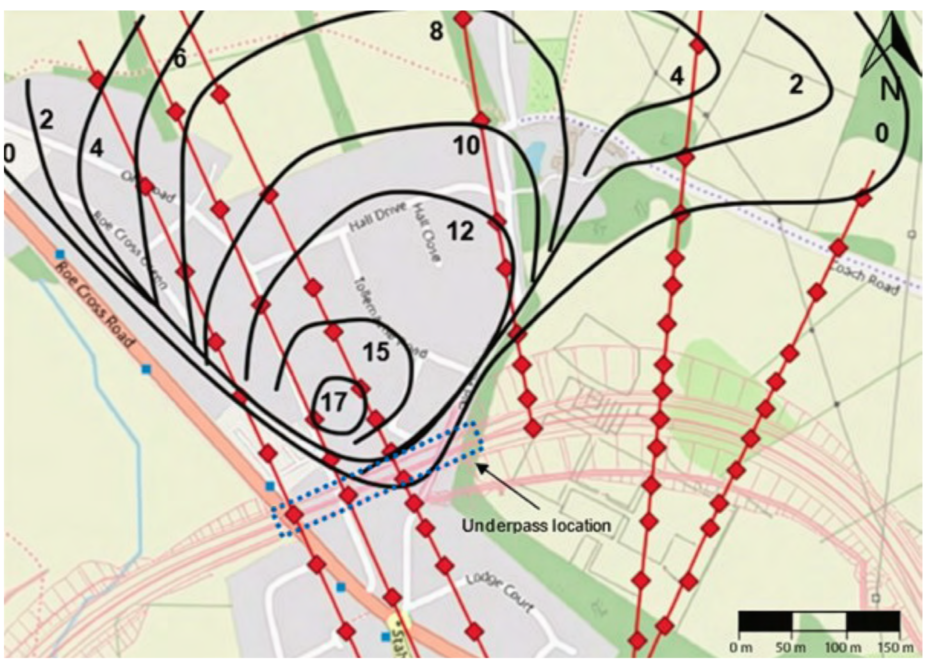
The long-term drop in groundwater level due to the proposed underpass and adjacent cutting can induce settlement and risks affecting the integrity of nearby structures. Settlement is associated with a drop in groundwater levels because the effective self-weight of the superficial material increases as the water level drops due to the loss of the effect of the buoyancy.

A simple settlement analysis was undertaken considering the change of groundwater level as a surcharge force on the superficial glacial till material. The modelling described in Section 3 provided the change in groundwater level for the assessment, which was undertaken on a grid of locations around the underpass. The results were then contoured and are presented in Figure 13.

The final stage of the assessment considered the largest differential settlement, to ensure that structural integrity of nearby buildings was not at risk. The maximum differential settlements were estimated to be 15 to 20mm over 40m (<1 in 2000), resulting in an angular distortion significantly lower than the minimum levels required to cause structural damage or cracking in walls in typical framed buildings and load bearing walls (Tomlinson, 2001). Therefore, the assessment concluded that the likelihood of damage was low.

FIGURE 13

Estimated soil settlement related to dewatering in the wider area of the proposed underpass (contours show settlement in millimetres)



6. Next Stages and Conclusions

Construction and associated earthworks commenced on site during the summer of 2025, with piling activities for the underpass scheduled to begin later in the year. The integrated work of hydrogeological and geotechnical design teams, supported by a robust ground investigation and detailed modelling, showed that a contiguous piled structure could be constructed, whilst managing the groundwater through supplementary control systems. The proposed solution comprised contiguous pile walls moving away from the secant piled 'watertight box' solution, along with a passive drainage system to ensure hydrostatic pressures are maintained below the road level and an active dewatering system during construction to manage groundwater pressures. The case study presented herein exemplifies best practices in addressing complex geological and hydrogeological challenges, achieving efficient geotechnical design, safeguarding the structural integrity of both new and existing infrastructure, and promoting strategies that contribute to carbon reduction.

Acknowledgements

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06: Innovative Approaches to Hazards Assessment in SMRs: Enhancing Safety and Efficiency

Significance Statement

AtkinsRéalis has developed a comprehensive hazard assessment methodology to enhance safety in Small Modular Reactors (SMRs) - a class of advanced nuclear technologies characterised by compact design and economic scalability. The spatial proximity of safety critical systems within SMRs presents distinct risks, particularly in relation to combined hazards. To address these, a targeted three-stage screening process was established to help identify and manage these risks, contributing to safer reactor design. Successfully applied to the Rolls-Royce SMR project, the methodology shows potential for broader use across the nuclear sector. This work illustrates how innovation is shaping the future of clean, reliable energy.

Énoncé d'importance

AtkinsRéalis a mis au point une méthodologie exhaustive d'évaluation des risques afin d'améliorer la sûreté des petits réacteurs modulaires (PRM), une catégorie de technologies nucléaires avancées caractérisées par leur conception compacte et leur évolutivité économique. La proximité spatiale des systèmes critiques de sécurité dans les PRM présente des risques distincts, notamment en ce qui concerne les risques combinés. Pour y remédier, un processus d'examen préalable ciblé en trois étapes a été établi pour aider à déterminer et à gérer ces risques, contribuant ainsi à la conception plus sécuritaire des réacteurs. Appliquée avec succès au projet de PRM de Rolls-Royce, cette méthodologie offre un potentiel d'application à plus grande échelle dans le secteur du nucléaire. Ce travail illustre comment l'innovation façonne l'avenir d'une énergie propre et fiable.

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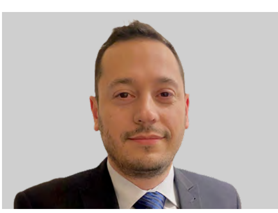

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Abstract

Small Modular Reactor (SMR) technology aims to reduce costs and simplify the building process for nuclear reactors by minimising civil structures and introducing innovative safety barriers.

For hazards assessment, the compact size of the SMR increases the likelihood of combined hazards affecting multiple safety-critical systems, with key targets often located closer to hazard sources. To address this challenge, a layered and comprehensive approach has been developed for External-Internal combined hazards (EH-IH). This strategy was implemented effectively by AtkinsRéalis, leveraging its extensive expertise in nuclear safety and hazard analysis.

Generic Screening eliminates obvious hazard combinations, based on the hazard characteristics, Area Specific Screening re-evaluates the generic screening output for specific plant areas and Layout Specific Screening assesses the impact of hazards on individual targets within an area, considering equipment layout and positioning.

AtkinsRéalis played a central role in conceptualising and implementing this structured, versatile, and scalable methodology. The approach not only supports the Rolls-Royce SMR Generic Design Assessment (GDA) but also offers broad applicability to other NPP designs, particularly SMRs. By integrating advanced hazard modelling techniques and layout-sensitive analysis, AtkinsRéalis has contributed significantly to enhancing the safety case and regulatory robustness of next-generation nuclear technologies.

KEYWORDS

Small Modular Reactors (SMRs); Hazards screening; Combined hazards; Design assessment; Pressure part failure hazards; Fire; Flooding

1. Combined Hazards Principles

1.1. EXTERNAL AND INTERNAL HAZARDS

As part of the development of this strategy, External Hazards (EHs) are defined as natural or man-made hazards that originate outside the boundaries of the site, and outside of the processes conducted on the site. Therefore, the licensee has limited or no control over the hazard. Internal Hazards (IHs) refer to hazards to the facility or its Structures, Systems and Components (SSCs) that originate within the site boundary and over which the licensee has control in some form.

1.2. CORRELATED AND CONSEQUENTIAL HAZARDS

To systematically identify potential hazard combinations, the concepts of Initiating Events (IEs), Consequential Hazards and Correlated Hazards are used. The definition of Correlated and Consequential Hazards are based on the principles outlined in the Office for Nuclear Regulation (ONR) Technical Assessment Guide (TAG) 13 [1] and TAG 14 [2].

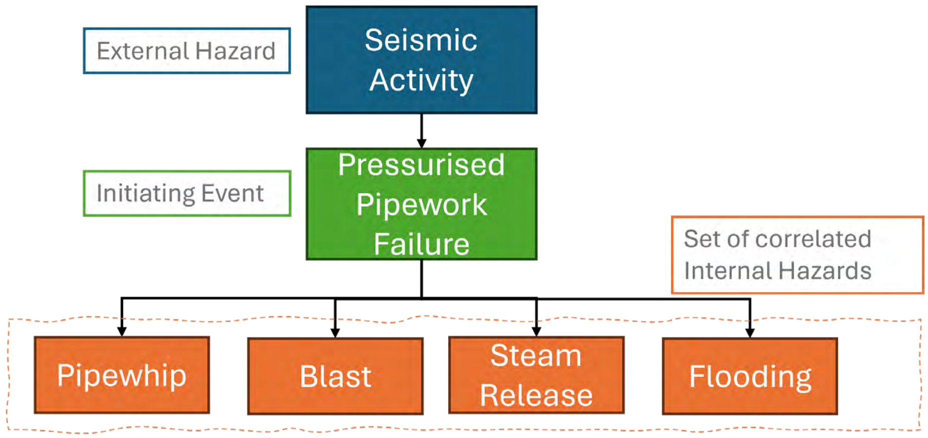
An IE is defined as the IH source, e.g. pipework failure (IE) may lead to blast (IH). Hazard combinations can be coincident, correlated, consequential, or both correlated and consequential. A consequential sequence occurs when a Primary Hazard directly causes a Secondary Hazard. On the other hand, several hazards originating from the same IE are defined as Correlated Hazards. Independent or coincident hazards originate from unrelated causes but may still occur within the same timeframe, they can be generally screened out from the combined hazards assessment due to low frequency.

The approach presented considers secondary consequential events but does not extend to tertiary and beyond. The inclusion of tertiary hazards may be overly conservative due to low conditional probability. Furthermore, the correlated hazards approach already considers multiple hazard loadings (e.g., pipework failure IE considers blast, steam release, flooding, missiles, and pipe whip). Thus, it is considered that a full analysis of all tertiary sequences would be disproportionate in effort compared to its value. However, the NPP designer may choose to assess specific tertiary hazards on a case-by-case basis and the strategy presented in this work would still be valid.

For example, in Figure 1, Seismic activity is the Primary Hazard. Pipewhip, Blast, Steam Release and Flooding are a set of correlated IHs arising for the same IE (pressurised pipework failure). Each one of the IHs are, at the same time, consequential to Seismic Activity.

FIGURE 1

Correlated and consequential hazards



1.3. NUCLEAR SAFETY TARGETS

A comprehensive assessment of EH-IH necessitates a thorough understanding of potential hazards and their effects on critical nuclear safety targets. Specific targets may vary between NPPs based on their design; however, the following target types are generally relevant for any NPP.

- Barriers providing segregation between SSCs supporting Fundamental Safety Functions (FSF).
- SSCs that are exceptions to segregation, i.e. where redundant trains of SSCs are not segregated by a barrier, relying on separation by distance instead.
- Very High Reliability (VHR) or High Reliability (HR) components.
- Any other SSCs requiring hazard protection to prevent or respond to hazard scenarios which are not bounded by the fault analysis, e.g. if the hazard damages multiple SSCs causing a demand on safety system performance that exceeds the fault analysis assumptions.

2. A Methodology to Assess Combined External- Internal Hazards

The key steps to develop, screen and assess the EH-IH combinations are described in this section.

2.1. BUILD THE EXTERNAL HAZARD AND INTERNAL HAZARD LIST

It is regular practice for NPPs to conduct separate assessments to define the specific EHs and IHs to be considered in the design process. The combined hazards assessment assumes that these individual evaluations have already been completed for the NPP, and that Design Basis EH and IH have already been defined prior to commencing the assessment.

Worked Example Scenario: Seismic Activity Impact on Nuclear Safety

Consider the case where a NPP licensee has developed comprehensive lists of EH and IH through separate assessments. Among the considered EH, seismic activity is identified as a potential threat to the NPP area. To illustrate the combined hazards approach, a simplified scenario with the following sequence of events is examined:

- Seismic Activity (EH): initiates the sequence,
- Failure of Pressurised Equipment (pipes/vessels) (IE)[1] : triggered by the seismic activity,
- Consequential IH (Flooding, Blasts, Missiles, Steam Release, Pipe Whip etc.): as a result of the IE.

1 It should be noted here that an EH can lead to various IE at the same time. However, for the sake of simplicity, we are considering only two IE as part of this example (pressurised pipework failure and pressurised vessel failure).

2.2. ESTABLISH SCREENING CRITERIA

A set of screening criteria is defined to eliminate potential combinations posing no feasible risk. Several sources of information are considered in deriving the criteria presented in Table 1 in line with best practice from [1], [3], [4], [5] and [6]. These criteria are sufficiently generic to be applicable for assessing any NPP. Nevertheless, individual NPP designers may modify the criteria to better align with their specific design requirements.

TABLE 1

Screening criteria

ID	Criteria
SC1	Hazard effects do not physically combine in a way that adversely affects the same hazard target
SC2	Hazard effects do not occur within a sufficiently close time or location to adversely affect hazard targets[2]
SC3	Primary hazard will not cause a foreseeable con-sequential hazard[3]
SC4	Frequency of combined hazards is sufficiently low
SC5	Combined hazard effects are bounded by another combination
SC6	The combination is bounded by the effects under the individual hazards assessment
SC7	The combination has a demonstrably low impact upon nuclear safety targets

2 This criterion, if used, is mainly done as part of Civil and Structural assessments as long as it can be proven that there is no residual damage on the target.

3 This screening criteria may also consider safety measures in place that eliminate the possibility of primary hazard leading to the IE (e.g. presence of flood defence walls as part of plant civil envelope will prevent water from external flooding to cause an IE which could lead to an IH).

2.3. GENERIC SCREENING

This initial screening step involves evaluating each EH-IH sequence against the Screening Criteria and eliminating the most obvious combinations based on the hazards' characteristics and safety measures available for External Hazards. Theoretically, the outcome of the Generic Screening exercise could apply to any nuclear site with similar EH safety measures.

2.3.1. Build an EH-IH Screening Table

At this point, a matrix type Screening Table should be built in order to perform a comprehensive screening exercise. This matrix pairs each EH to all the potential IEs, and therefore, all potential IHs. Depending on the number of External and Internal Hazards to be considered at the NPP under assessment, this matrix could contain hundreds of sequences of the type EH – IE – IH. Sequence IDs are developed for each one of the sequences (see Table 2), which are used to aid with the amount of data and manage it effectively.

Building on the worked example sequence, presented in Section A, the screening table matrix is presented in Table 2. Each of the EH-IE-IH is given a unique sequence ID (combination of letters to denote EH and IH, and numbers to denote IE).

TABLE 2

Worked example screening table

External Hazard	Initiating Event	Internal Hazard	Se-quence ID
Seismic Ac-tivity (x)	Pressurised pipework failure (1)	Flooding (F)	x1F
x	1	Blasts (B)	x1B
x	1	Missiles (M)	x1M
x	1	Pipe Whip (P)	x1P
x	1	Steam Release (S)	x1S
x	Pressurised vessel fail-ure (2)	Flooding (F)	x2F
x	2	Blasts (B)	x2B
x	2	Missiles (M)	x2M
x	2	Steam Release (S)	x2S

2.3.2. Perform Generic Screening

Generic screening using the Screening Criteria (Table 1) is performed on all sequences in the Screening Table. If any screening criterion is met, the EH-IH sequence will be screened out and the consequential IHs will not be assessed.

At this stage there may be key representative justifications used in the screening process that will be repeated for several sequences derived from the same EH, it is imperative to identify them and provide a clear case on the reason for screening a sequence out as this would optimise the process by reducing the number of combinations. For example, consider coastal or fluvial flooding. It is reasonable to assume that a pipe or vessel failure could occur due to the impact forces from a coastal flood. However, this may not be considered credible if the nuclear site employs safety measures to ensure that a Design Basis (DB) flood does not affect the site's SSCs relevant to nuclear safety. These measures might include installing sea or river defences, designing appropriate drainage and barriers around sensitive areas, and locating SSCs above flood levels. Therefore, any sequences with a primary hazard of 'coastal/fluvial flooding' may be excluded based on Screening Criteria SC3. The output of Generic Screening is a set of EH-IH combinations that needs to be considered in the NPP design, independently of the layout.

Progressing the previous worked example scenario, all sequences identified in Table 2 are reviewed for their credibility against the screening criteria (as per Table 1). It is found that all the mentioned sequences are credible and screened 'in' at generic screening level. This is because seismic activity has the potential to cause pressurised pipe/vessel failure such that it results in corresponding IH.

2.4. AREA SPECIFIC SCREENING

This screening stage involves assessing the results of the Generic Screening for specific plant areas and screening out any hazard combinations that are not feasible due to the absence of equipment capable of causing the hazard (IE).

2.4.1. Area Splitting and IE Type Count

It is expected that a NPP site would have defined and segregated reactor buildings/sectors. Each one of these buildings/sectors should be divided into appropriate Screening Areas based on its general layout and available hazard barriers. The nature and layout of each building influence how these areas are intuitively divided. For example, if a building is compartmentalised by civil[4] walls claimed as hazard protection barriers, each one of these compartments can be considered as a separate Area. The division process should assume that hazard effects in one Area do not impact or have minimal effects upon other Areas. In this way, the combined hazards assessment can be optimised by focusing on one area at a time. For buildings that are not compartmentalised, spatial separation (e.g. divisional zones separating safety system trains) can be used to define areas, appropriately justifying that hazards from one Area will not affect other Areas.

After defining the Areas, the IEs should be identified and counted within each area to determine the number of sources for each IH present. For the worked example, a sample area[5] with its IE count is shown in Table 3:

TABLE 3

Worked example IE count

	Pressurised pipe-work failure		Pressurised vessel failure	
	IE Count	**Seismic classifica-tion**	**IE Count**	**Seismic Classifica-tion**
Area - A	2	SPC1	3	SPC3

4 Often but not exclusively of reinforced concrete construction

5 Note that the considered area, its layout and IE count in each is just for this example and does not correspond to any particular area of the NPP.

2.4.2. Identification of Seismic Performance Class (SPC) Equipment

When screening out EH-IH sequences, it is important to consider the protection measures for Design Basis Seismic Activity. IAEA SSG-67 [7] outlines the functional criteria to be considered when defining Seismic Performance Classification. For Design Basis earthquakes it is considered that SSCs designated as Seismic Performance Classification 1 (SPC1) must remain fully functional during and after the earthquake, while those designated as SPC2 must retain limited functionality without negatively impacting SPC1 SSCs. Consequently, neither SPC1 nor SPC2 SSCs will cause consequential IHs following seismic activity, allowing associated EH-IH sequences to be screened out.

2.4.3. Perform Further Screening

For each Area identified, the Generic Screening outcome should be re-evaluated based on which IEs have been identified. All the sequences containing an IE that is not present in the area can be screened out with suitable justifications. At this point it is suggested that the process is automated where possible as the number of sequences to evaluate from the Generic Screening can be in the hundreds. Based on the IE count in the area, if the IE count is zero, the entire sequence can be easily screened out. The outcome of the Area Specific Screening is the set of EH-IH combinations to be considered in a specific site Area.

Extending the worked example, in Area - A, of the two types of IEs considered: pressurised pipework and pressurised vessels, the pressurised pipes are seismically qualified SPC1 and pressurised vessels are seismically qualified SPC3. In this case all the sequences involving pressurised pipework are screened out. However, since pressurised vessels are not seismically qualified, sequences where seismic activity leads to pressurised vessel failures as IEs are still retained in the Screening Table for Area - A. Thus, sequences screened 'in' following area specific screening: x2F, x2B, x2M and x2S.

2.4.4. Bounding Area Selection

For specific reactor buildings it can be useful to group similar areas and identify bounding areas that contain the most significant hazard sources. Selecting a bounding area should consider the number of IE along with IH and EH magnitude and effects on the target. Identifying bounding areas may minimise the number of combinations to consider. However, care must be taken not to exclude potentially significant hazard sequences.

2.5. LAYOUT SPECIFIC SCREENING

This screening stage builds on Area Specific Screening by considering the plant layout. It focuses on the relative locations of IH sources and targets, screening out combinations where the target is outside the IH 'zone of influence'[6]. The type and worst-case severity (in terms of loading and range) of a hazard should be considered when defining its zone of influence. Layout Specific Screening should be conducted based on the targets in each area, identifying unique credible hazard sequences for each target.

2.5.1. Target Selection

The objective of this step is to identify targets important to nuclear safety within each designated area and, if credible, to reduce the number of targets for consideration. A sequence can be screened out if the target is not at risk, i.e. it is proven that the loads from the primary (EH) and/or secondary hazard (IH) could not impact the target under consideration.

In areas with multiple targets, it may be possible to bound the assessment of one or more targets, provided it can be justified that the worst-case loads they could experience are bounded by those exerted on equivalent targets in the area. For example, if an area has multiple barriers as targets, the 'bounding target' should be based on the worst load affecting the weakest barrier as the conservative case.

6 Zone of influence is the zone / distance from the hazard source where the hazard is capable of damaging the target.

2.5.2. Development of Hazards Sources List

Once all targets within a specified area have been identified, a Hazard Sources List is created to summarise the targets under consideration, the hazard sources (IEs) and the associated hazards and resulting loads that may affect each target. Hazards and IEs that have been screened out during the area specific and generic screening stages are not included in the Hazard Sources List.

The feasibility of a load impacting the target is assessed based on the hazard source's zone of influence relative to the target. A viable hazard source is one where the specified target is within its zone of influence.

2.5.3. Perform Further Screening

Layout Specific screening is conducted for each area and target identified in previous steps. If the Primary Hazard (EH) does not lead to one or more IEs due to the area's layout, these sequences should be excluded. If the Secondary Hazard (IH) in a sequence does not impact the target (based on Hazards Sources List) this sequence can be excluded. For instance, for the IE 'water pressurised pipework failure', correlated IHs might include pipewhip, flooding, blast, and steam release. However, if the target under consideration is located outside the pipewhip zone of influence due to being outside the pipework whipping length or angle, that sequence can be screened out. The outcome of the Layout Specific Screening is the same matrix as Area and Generic Screening: a matrix type Screening Table with a reduced number of sequences due to the screening exercise.

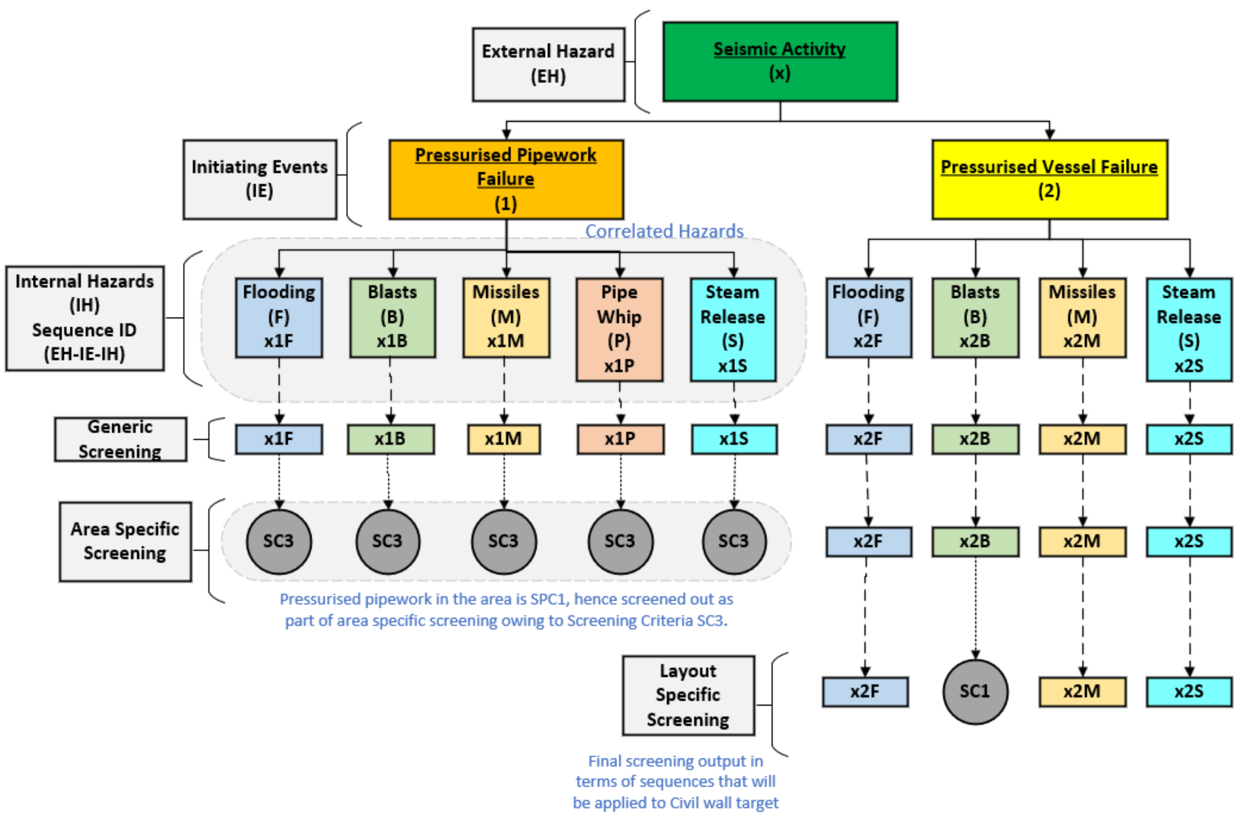
For the final screening stage of the worked example, the sequences from Area – A are assessed for their potential to impact a civil wall (identified as the target). The IE 'Pressurised vessel failure' correlated IHs are flooding, blast, missile and steam release.

Flooding and steam release affect the whole room volume, so they are screened in. For blast, the target is outside of the blast zone of influence (overpressure wave), hence x2B can be screened out. In case of missiles, it is often challenging to predict the range of resulting missiles in the event of vessel burst. Hence, conservatively, missiles are screened in. As a result, the sequences involving flooding, steam release and missiles are screened in: x2F, x2M and x2S, with blast sequence screened out.

In this example, the identified sequences (x2F, x2M and x2S) represent the final output of the layered screening process. The loads from these combined sequences should be applied to the safety target, in this case, the civil wall. Figure 2 presents the visual representation of the layered screening stages as applied for the worked example.

FIGURE 2

Visual representation of worked example screening



2.6. COMBINATION OF LOADS

This part of the combined hazards strategy focuses on the effects (i.e. loads) that hazards can have on specific targets, i.e. civil structures and/or SSCs, and how these loads are combined based on their immediacy, duration, and the required level of conservatism. Its purpose is to support the application of outputs from the layered screening process by other disciplines, such as civil and structural engineering.

The effects of each hazard are classified into short duration (e.g. missile impact) or long duration (e.g. internal flooding), immediate occurrence (e.g. blast) or gradual occurrence (e.g. increase in internal pressure due to steam release).

It is then proposed that the loads are combined depending on the desired conservatism level by the designer and based on design requirements and maturity. The most conservative option is combining loads assuming all loads act simultaneously at peak magnitude, which may be useful for a high-level analysis. A more realistic option is for the load combinations to be disaggregated into a set of sequential combination of loads, using formulas incorporating load-duration aspects. This is useful for more detailed analysis, e.g. for the analysis of a structural member with the purpose of reinforcement detailing. In all cases, the combinations of loads are established in a notation that is compatible with modern codes, such as ACI 349-13 [8] and AISC N690 [9].

3. Conclusion

To address the challenge of assessing combined hazards on NPPs, and particularly SMRs, key principles and a strategy to assess External – Internal Combined Hazards are presented. The strategy is based on linking feasible External Hazards to Internal Hazard sources (IE) and associated Internal Hazards, and performing a staged screening exercise — Generic, Area Specific, and Layout Specific Screening—progressing from broad, site-wide considerations to detailed, plant-specific characteristics of a NPP. The outcome is a set of credible EH-IH sequences for each nuclear safety-critical target, forming the basis for subsequent design assessments.

The strategy presented is designed to be broadly applicable across different plant designs, offering a systematic framework for assessing hazard combinations. It aims to minimise the risk of overlooking critical combinations while providing structured guidance on optimising the process. The approach ensures both rigour and flexibility, allowing alignment with specific safety requirements and design maturity.

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Nuclear Engineering

07: SafeMove: Multi-Model Navigation for Fail-Resistant Autonomous Nuclear Material Transport

Significance Statement

Radioactive waste must be moved every day. This work is essential but dangerous for people. As these movements grow, traditional manual methods are becoming too risky and inefficient. We set out to answer a simple question: can autonomous vehicles take on this challenge? Partnering with the University of Oxford, we created SafeMove, a breakthrough system that turns standard electric vehicles into self-driving carriers. Using sensors and AI, it maps surroundings, detects obstacles, and plans safe routes without GPS or costly site changes. Demonstrated in real-world conditions, SafeMove proved safer, faster, and more cost-effective, protecting people while transforming operations.

Énoncé d’importance

Les déchets radioactifs doivent être déplacés tous les jours. Ce travail est essentiel, mais aussi dangereux pour les personnes. Et plus ces déplacements se multiplient, plus les méthodes manuelles traditionnelles deviennent trop risquées et inefficaces. Nous avons alors voulu répondre à une question toute simple : des véhicules autonomes pourraient-ils relever ce défi? En partenariat avec l’Université d’Oxford, nous avons créé SafeMove, un système révolutionnaire qui transforme des véhicules électriques standard en véhicules autonomes. À l’aide de capteurs et de l’IA, le système cartographie l’environnement, détecte les obstacles et planifie des tracés sécuritaires, sans nécessiter de GPS ou de modifications coûteuses du site. Testé dans des conditions réelles, SafeMove s’est révélé plus sécuritaire, plus rapide et plus rentable, protégeant les personnes tout en transformant les activités.

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Abstract

The nuclear industry requires safe and efficient transportation of radioactive materials, especially in decommissioning and waste management. As waste package movements increase from monthly to daily frequencies, traditional manual methods have become unsustainable, exposing operators to hazardous environments and creating potential operational bottlenecks. This paper introduces SafeMove, an advanced autonomous transportation system developed by AtkinsRéalis and the Oxford Robotics Institute, designed to address these critical issues. This work builds on a close collaboration between AtkinsRéalis and the Oxford Robotics Institute, where AtkinsRéalis served as the systems integrator and nuclear-domain lead, coordinating the project and stakeholder engagement, translating operational and safety requirements into system constraints, and planning and delivering the operationally representative demonstration and analysis, while the Oxford Robotics Institute provided the vehicle-agnostic autonomy stack. Together, these results validated a practical, GPS-free, infrastructure-light approach to safe, scalable, vehicle-agnostic autonomous transport, aligned with the realities of nuclear sites.

SafeMove integrates a vehicle-agnostic hardware and software autonomy stack with a sophisticated multi-sensor fusion system that combines LiDAR, cameras, and inertial sensors. This fusion enables robust localization, detailed 3D mapping, and real-time mission planning, allowing the system to navigate without reliance on GPS or extensive infrastructure modifications. Key functionalities include dynamic obstacle detection, point-to-point mission execution, and risk-aware replanning, ensuring adaptability to complex and evolving conditions within nuclear facilities. Tested in environments analogous to nuclear sites, the system demonstrated exceptional reliability, safety, and operational efficiency. To ensure readiness for deployment in active nuclear facilities, a comprehensive risk assessment based on ISO 26262 standards was conducted.

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This paper details the development process, testing outcomes, and deployment considerations of SafeMove, highlighting its potential to revolutionize nuclear waste management. Its implementation offers transformative benefits for the nuclear sector, including significant reductions in human exposure to hazardous conditions, improved operational throughput, and enhanced cost efficiency. Additionally, the system's adaptability makes it suitable for a wide range of applications, from waste transportation to autonomous inspection and monitoring tasks. By addressing the industry's need for safe, sustainable, and technologically advanced solutions, SafeMove exemplifies the role of robotics and AI in shaping the future of nuclear waste management and decommissioning activities worldwide.

KEYWORDS

Autonomous vehicles; Mobile robots; Sensor fusion; Hazardous environment robotics; Nuclear facility automation

1. Introduction

Transporting radioactive materials safely and efficiently is a critical challenge for the nuclear industry, especially in decommissioning and waste management activities. Increasing demands for nuclear waste transportation, coupled with the hazardous nature of these environments, require innovative solutions that prioritise safety, operational efficiency, and scalability. Traditional manual handling methods are increasingly unsustainable, exposing operators to significant risks and creating operational bottlenecks. This urgency drives the need for autonomous systems capable of revolutionising operations in nuclear facilities. SafeMove addresses these challenges with a scalable and adaptable autonomous vehicle solution designed to enhance safety, reduce human exposure, and improve cost efficiency in nuclear waste transportation. By integrating advanced robotics and artificial intelligence, SafeMove offers capabilities that align with the nuclear industry's goals of safe, environmentally responsible, and innovative waste management practices.

Autonomous vehicles have emerged as a transformative technology with the potential to address these challenges. By reducing human involvement in hazardous environments, these systems enhance safety while increasing operational throughput and cost efficiency. However, the deployment of autonomous vehicles in nuclear facilities presents unique challenges, including:

- Navigating GPS-Denied Environments: Nuclear facilities often lack GPS coverage due to shielded structures and indoor settings.
- Infrastructure Compatibility: Autonomous systems must adapt to existing infrastructure without extensive modifications.
- Dynamic Conditions: The ability to detect and respond to moving objects, such as pedestrians and vehicles, is critical for safe operations.
- Regulatory and Safety Standards: Compliance with stringent safety protocols and regulations is paramount in nuclear environments.

The use of autonomous vehicles in nuclear facilities remains in its early stages, with applications primarily focused on inspection and monitoring. For instance, Boston Dynamics' Spot robot has been employed for remote inspections, leveraging cameras and sensors to collect real-time data in hazardous areas [1]. Similarly, autonomous drones are being used for mapping radiation levels in inaccessible zones [2]. While these technologies have demonstrated value, they are limited in scope and primarily focus on data collection rather than material handling or transportation. Existing autonomous transportation systems outside the nuclear sector, such as warehouse robots and autonomous forklifts, often rely on GPS or predefined markers for navigation [3]. These solutions are not directly transferable to nuclear facilities due to the lack of GPS coverage and the need for robust obstacle detection and dynamic planning. Additionally, many current systems require significant infrastructure modifications, such as the installation of fiducial markers or specialised pathways, which are impractical in nuclear sites. This gap highlights the need for a robust and adaptable system specifically designed to address the safety, operational, and scalability demands of nuclear environments.

SafeMove bridges this gap by integrating an advanced hardware and software autonomy stack capable of transforming any electrical vehicle into a fail-resistant autonomous platform. At the core of SafeMove's functionality is the ORI-AutoNav-System, which delivers robust localisation, mapping, and mission planning through a vehicle-agnostic approach. This includes GPS-free navigation, real-time graph-based optimisation, and topological mission planning that enables navigation along pre-planned routes, with real-time obstacle avoidance and risk-aware replanning. A scientific publication overviewing this work was published in a research robotics conference [4]. That publication focused more specifically on integration of the system on a walking robot operating in an indoor industrial inspection context – further demonstrating the versatility of the autonomy system.

A key feature of this work is the delivery model. SafeMove is the product of an industry-academia collaboration in which AtkinsRéalis serves as systems integrator and nuclear-domain lead, responsible for stakeholder engagement, requirements capture, safety and cybersecurity considerations, and the planning and delivery of demonstrations in representative facilities. ORI contributes the autonomy stack (mapping and localisation, perception, and mission planning/scheduling) and supports integration on the vehicle-agnostic platform. This division of responsibilities ensures that the technology is not only performant in technical trials but also aligned with site processes and ready for route-to-deployment.

The system uses a modular architecture that combines dynamic perception, adaptive planning, precise localisation, and real-time sensing, enabling seamless operation in nuclear environments. Its perception capabilities allow it to detect, track, and predict the movements of pedestrians, vehicles, and other dynamic objects, maintaining situational awareness for informed decision-making. The planning module dynamically manages mission execution, handling tasks such as driving and parking while adapting to changing environmental conditions. Localisation provides continuous feedback by integrating data from high-resolution sensors, including vision cameras, LiDAR, inertial measurement units (IMU), and digital data sharing (DDS) implementation, which supports precise positioning and robust navigation. Together, these capabilities enable SafeMove to operate without reliance on GPS or extensive infrastructure modifications. Additionally, SafeMove can be integrated into COTS (Commercial Off-The-Shelf) platforms based on operational requirements such as load capacity, speed, and terrain. This flexibility allows the system to adapt to diverse operational conditions, transforming standard electrical vehicles into autonomous agents capable of executing complex missions in hazardous environments. The system has been demonstrated across various scenarios, validating its ability to navigate large, dynamic sites efficiently while maintaining fail-resistant performance.

SafeMove's development directly addresses the critical challenges associated with deploying autonomous vehicles in nuclear facilities. These include:

- Dynamic Obstacle Management: Real-time perception and planning ensure the detection and avoidance of moving objects.
- GPS-Independent Navigation: Integration of LiDAR, graph-based mapping, and inertial sensors enable SafeMove to navigate effectively in GPS-denied environments.
- Risk-Aware Replanning: Adaptive algorithms manage battery performance, obstacles, and safety risks during mission execution.
- Infrastructure Compatibility: The modular design enables seamless integration with existing vehicles and site configurations.

This paper explores SafeMove's development and deployment, focusing on how its innovations overcome the challenges of autonomous vehicle integration in nuclear facilities. By addressing critical operational and safety needs, SafeMove represents a significant step forward in enhancing the efficiency, safety, and sustainability of nuclear waste management operations.

2. System Architecture

To achieve the goal of autonomous material transportation, SafeMove leverages a modular system architecture that integrates key functional components. These components include mapping, localisation, perception, planning, and sensing capabilities, which collectively enable robust autonomous operation in dynamic and complex environments. Figure 1 illustrates the overall system architecture, highlighting the modular design that facilitates seamless integration of SafeMove's components (shown in blue) with a wide range of control systems and vehicle interfaces. This architecture supports vehicle-agnostic deployment, ensuring compatibility with diverse platforms and operational conditions. The core modules handle mapping and localisation, object detection and tracking and mission planning, while interfacing with external vehicle-specific systems for trajectory execution and control.

3. SafeMove Payload – Hardware

The core hardware component of the SafeMove system is the Frontier device (Figure 2). The Frontier integrates a NUC mini-PC with an Intel i7-1165G7 processor running at 2.8 GHz and 32 GB of RAM, a Hesai XT-32 LiDAR, three time-synchronised Sevensense Alphasense fisheye cameras, and a Bosch BMI085 IMU. These components are housed in a lightweight, compact, 3D-printed enclosure with a total weight of 1.5 kg.

The Frontier is integral to SafeMove's functionality, as it runs the AutoNav system, the autonomous navigation software stack that powers SafeMove's perception, localisation, and mission execution capabilities. The sensors on the Frontier are precisely calibrated to ensure accuracy and consistency. Camera intrinsics and extrinsics are calibrated using Kalibr [5], and the camera-to-LiDAR extrinsics are calibrated following established methodologies [6]. Since all sensors are rigidly mounted, the device can be transferred between vehicles without requiring recalibration, providing flexibility for deployment across different platforms. The AutoNav system operates entirely on the Frontier, eliminating the need for continuous network connectivity except when receiving operator commands. Operators monitor the system remotely using an external computer, ensuring oversight and control during operations.

FIGURE 1

Autonomous Vehicle System Architecture. SafeMove's core modules (in blue), including mapping, localization, perception, and planning, integrate with control systems and interfaces, enabling vehicle-agnostic and adaptable deployment.

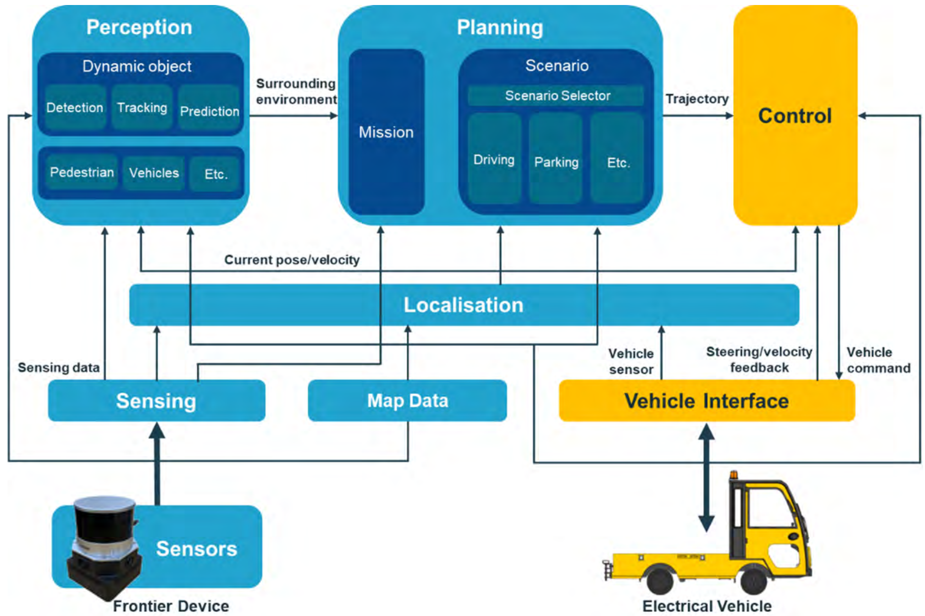
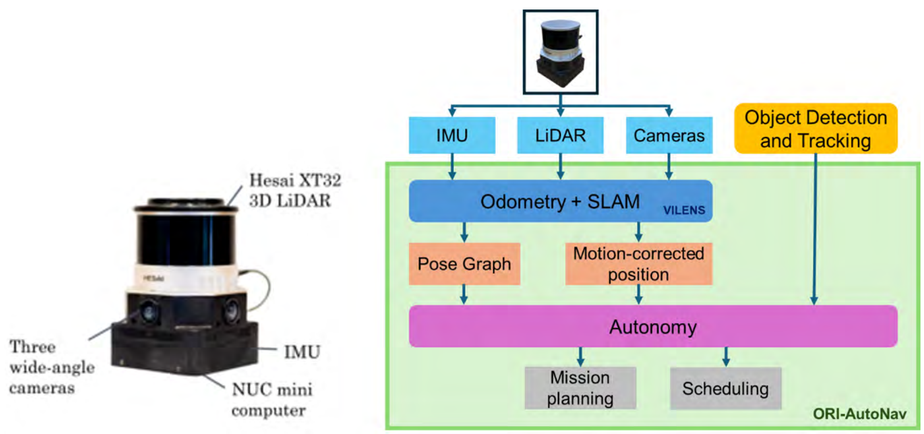


FIGURE 2

(Left) Frontier payload with Hesai LiDAR, three Sevensense Alphasense cameras, and an IMU. (Right) ORI AutoNav system using Frontier: VILENS fuses IMU, visual, and LiDAR data to produce continuous pose and SLAM graph for topological autonomy, mission planning, and scheduling.



4. Mapping and Localisation

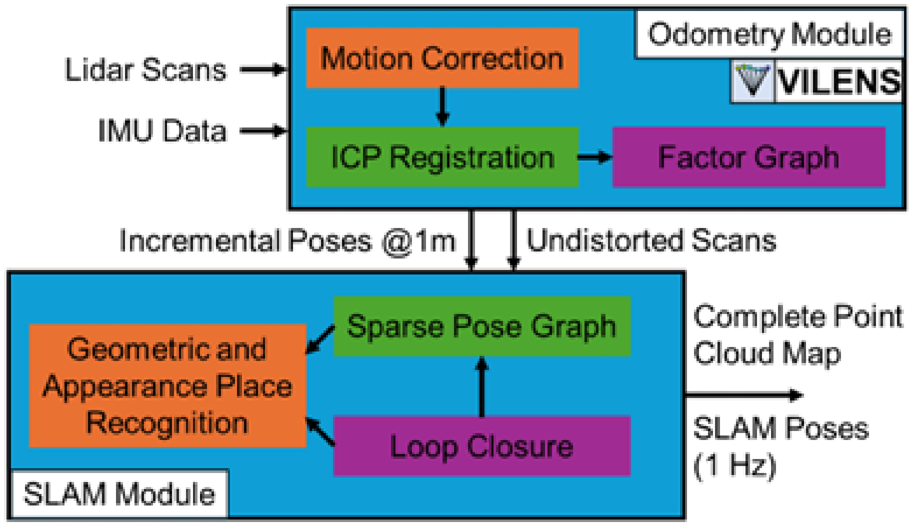
The mapping and localisation system uses the VILENS odometry [7] and SLAM systems [8], which fuse data from the IMU, and LiDAR to provide robust and accurate odometry. To ensure mapping fidelity, the system compensates for LiDAR motion during each scanning sweep. This correction is critical to counteract the effects of dynamic vehicle motion, enabling the generation of high-resolution, accurate maps required for safe and efficient autonomous operation. The VILENS system has been successfully demonstrated in various challenging environments, including construction [9], forestry [10], and aerial inspections with drones [11].

4.1. INITIAL SLAM MAPPING

To enable autonomous operation, the system localises within a pre-built map of the environment. This map can be generated from existing 3D LiDAR scans acquired with a terrestrial LiDAR scanner or created from scratch using our SLAM system. When generating a map from scratch, odometry is provided by VILENS [7], which can be configured to utilise various odometry sources, including IMU, visual feature tracking, LiDAR ICP (Iterative Closest Point) registration and produces motion-corrected LiDAR scans. The motion-corrected LiDAR scans are processed by VILENS SLAM [8], which employs the iSAM2 solver [12] to perform pose graph optimisation. Loop closure proposals are generated based on geometric constraints and place recognition. Place recognition utilises the ScanContext descriptor [13] to identify previously visited locations. An overview of the system is presented in Figure 3. The output of the mapping step is a pose graph with associated individual point clouds, as well as a global map in which all individual point clouds have been registered in a global reference frame.

FIGURE 3

Overview of the VILENS odometry and VILENS SLAM system



4.2. SUBSEQUENT LOCALISATION IN PRIOR MAP

To re-localise within a global prior map, the system utilises ICP alignment, which requires an accurate initial pose estimate. This estimate can be provided by the operator or achieved by initialising the robot in a known location. The pose estimate is then iteratively refined at a rate of 2Hz, aligning LiDAR data to the prior map through ICP. Alternatively, localisation can be performed using a prior map composed of individual pose-graph point clouds. In this approach, place recognition is employed to determine the initial pose estimate for each iteration. This method does not rely on an explicit initial pose and is particularly advantageous in large-scale environments when performing ICP directly on a single large point cloud would be computationally prohibitive.

5. Object Detection and Tracking

Dynamic or moving objects within the operational environment of an autonomous vehicle pose significant hazards. While the 3D mapping and localisation subsystem ensures accurate positioning to prevent collisions, it does not classify objects or track their movements. To address this limitation, SafeMove integrates an object detection and tracking system designed to identify, classify, and monitor objects in real time.

5.1. OBJECT DETECTION

Several object detection methods were evaluated during the development of SafeMove, including both 2D and 3D detection approaches. A 2D object detection framework was selected for its optimal balance between computational efficiency, detection accuracy, and real-time performance. The D-FINE network was chosen due to its superior latency and reliability. Tested on standard PC hardware, the system achieved detection latencies as low as 30 milliseconds, making it suitable for real-time deployment. The framework is also compatible with edge computing platforms, providing versatility for a wide range of hardware configurations. While 3D object detection offers the potential for richer spatial information, it remains a relatively nascent methodology with less mature solutions than 2D detection. As 3D technologies advance, they are expected to surpass 2D methods in terms of convenience and performance, presenting opportunities for future enhancements.

5.2. OBJECT TRACKING

The system employs the ByteTracker algorithm to track objects across sequential frames. This algorithm effectively links detections over time, assigning unique identifiers to individual objects and monitoring their trajectories. ByteTracker was selected for its ability to balance computational speed and tracking accuracy, ensuring reliable performance in dynamic environments.

5.3. 3D PROJECTION

To enhance situational awareness, 2D object detections are re-projected into 3D space using data from SafeMove's multi-sensor array. This capability allows for precise localisation of objects in the global environment, facilitating more informed decision-making and safer navigation in complex scenarios.

6. Autonomy

A key component of the SafeMove system is its autonomy subsystem, which integrates topological mapping, topological navigation, mission planning and scheduling, and a user interface, forming the foundation for autonomous navigation and task execution (Figure 4).

At the core of the autonomy subsystem is a topological map representation, which provides a modular and efficient system for navigation and mission execution. Combined with the mapping and localisation subsystem, this representation enables the vehicle to operate in its environment without the need for continuous monitoring or input from operators. Topological maps are particularly effective for representing large physical spaces [14] and have been extensively used as a navigation abstraction for mobile robots since their introduction by Brooks [15]. These maps are well-suited for incorporating domain knowledge during deployments and adapting the system's behaviour based on specific operational needs. Additionally, they support advanced planning and resource allocation algorithms, which are critical for mission scheduling and optimisation. Topological maps have demonstrated their utility in both field deployments, such as in office environments [16] and agricultural applications [17], and in theoretical research [18].

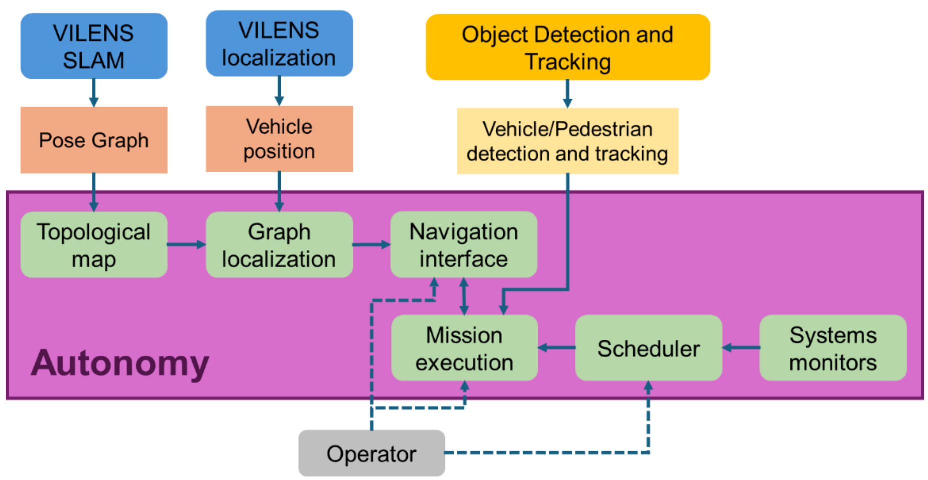
Beyond their technical advantages, topological maps offer significant usability benefits. They provide an intuitive visual representation of the vehicle operational area, allowing end users to easily understand and interact with the system. Features such as naming locations within the map enhance communication about missions, facilitating efficient coordination. Topological maps can be constructed using various methods, including aerial imagery [19] and 2D or 3D maps [20]. SafeMove employs a hybrid approach, automatically generating an initial map from the SLAM pose graph during global map construction and then tailoring it manually using graphical user interface (GUI) tools.

Integrating a new platform with the autonomy subsystem involves implementing a localiser for the graph and an edge traversal interface. This modular structure supports the core tasks of mission planning and scheduling while accommodating different localisation and navigation methods. This adaptability ensures that the system can integrate with COTS platforms, transforming standard electric vehicles into autonomous platforms capable of operating in complex environments.

Figure 4 illustrates the autonomy subsystem. The topological map is created using data from the VILENS SLAM pose graph, and the vehicle determines its position on this map using 3D pose data from the localisation system. Navigation is handled through the navigation interface. Mission execution performs tasks based on mission specifications. The scheduler organises and runs missions on a set schedule, allowing interruptions from system monitors. Operators typically interact with the system by scheduling or initiating missions directly.

FIGURE 4

Overview of the autonomy subsystem



6.1. TOPOLOGICAL MAP

The topological map forms the core of the autonomy subsystem, serving as a structured representation of the environment. An example of this map is illustrated in Figure 5. The map is represented as a graph consisting of nodes and edges, where an edge connecting two nodes indicates a navigable path between those locations. This representation is both simple and versatile, enabling annotations of nodes and edges with domain-specific information relevant to deployment scenarios. Additionally, it provides a structured abstraction of the environment, facilitating input to advanced planning algorithms.

The topological map primarily captures spatial relationships implicitly through the connections between nodes and edges. For most deployments, nodes are augmented with 3D positions that specify their location within the global reference frame, enhancing spatial precision and compatibility with localisation systems. A key feature of the topological map is its adaptability; the user interface allows real-time editing of the map without interrupting the system's autonomous operation. This flexibility ensures that the autonomy subsystem can accommodate dynamic changes in the environment while maintaining consistent performance.

FIGURE 5

Top-down view of point cloud with overlaid topological map

6.2. TOPOLOGICAL NAVIGATION

The topological map serves as the foundation for navigation within the autonomy subsystem. To direct the vehicle to a specific node within the graph, the system computes the shortest path by evaluating the costs associated with each edge. The vehicle follows this path by traversing each edge sequentially. If an edge cannot be traversed—for example, due to an obstacle—the system autonomously reroutes by temporarily deactivating the obstructed edge and recalculating the shortest path. This ensures that the vehicle can adapt to dynamic changes in the environment without requiring operator intervention. The navigation subsystem interfaces with the vehicle's navigation system to execute edge traversal. These interfaces translate the planned edge transitions into precise commands for the vehicle, enabling execution of the navigation plan.

6.3. MISSION EXECUTION AND SCHEDULING

The mission execution subsystem integrates topological navigation with task execution, enabling the autonomous vehicle to complete transportation missions. A task is defined as performing a specific action, such as transporting material from Point A to Point B. A mission consists of one or more tasks, which are typically specified by human operators but can also be generated programmatically. Missions are executed sequentially, with the vehicle navigating to the location of each task, performing the associated action, and proceeding to the next task until all tasks are successfully completed. Minimising travel distance when manually constructing missions can be challenging for operators. To address this, the system can optimise the order of tasks by solving a standard traveling salesperson problem, reducing overall path costs and enhancing efficiency. Task execution may fail due to an inability to reach the task location or an error during the action itself. When such failures occur, the system can be configured to either continue executing the remaining tasks in the mission or abort the mission entirely, depending on the operational requirements.

The final layer of the autonomy subsystem is the scheduler, which extends mission execution by enabling missions to be repeated on predefined schedules. Missions can be scheduled to run periodically (e.g., hourly, daily at 09:00, or weekly on Tuesdays at 16:00) or as one-time executions at a specific time. The scheduler also incorporates system monitors that can conditionally trigger or prevent mission execution. For example, a battery monitor prevents the initiation of scheduled or user-requested missions when the vehicle's battery level is low and instead triggers a mission directing the vehicle to the nearest charging station.

7. Results

7.1. DEMONSTRATION

The SafeMove system was demonstrated at Oxford's Begbroke Business Park, a controlled environment selected for its suitability to replicate conditions found in nuclear facilities. The demonstration involved equipping an electric vehicle with the SafeMove Payload and testing its core capabilities, including mapping, localisation, mission planning, and real-time obstacle detection. The vehicle was manually driven during the entire demonstration to collect data and validate these functionalities.

The demonstration route consisted of an 800-metre loop (approximately 2 kilometres in total), as shown in Figure 6. The area featured a mix of normal roads (red), car parks (orange), and pedestrian paths (green). The route included waypoints labelled A through to L to simulate a series of point-to-point transportation missions. These waypoints represented key locations connected by the system's graph-based map, enabling the planning and demonstration of point-to-point missions, mimicking material transport in nuclear facilities. The route was specifically chosen to include varied environments accessible to small vehicles while adhering to a speed limit of 5–10 mph. These conditions closely resembled operational constraints in nuclear facilities, such as limited space, diverse terrain, and strict safety requirements.

FIGURE 6

(Left) SafeMove payload on an electric vehicle with a standard roof rack. (Right) Begbroke Business Park map showing roads (red), car parks (orange), and pedestrian paths (green). Waypoints AL define point-to-point missions over an 800 m loop, totalling about 2 km.

7.2. MAPPING AND LOCALISATION

The first stage of the demonstration involved using the SafeMove Payload to generate a detailed 3D map of the campus while the vehicle was manually driven along the designated route. This 3D map formed the basis for the system's topological navigation and mission planning by creating a graph network that connected key physical locations. The mapping process was entirely independent of GPS, leveraging LiDAR-based place recognition to localise the vehicle within the generated map. This capability demonstrated SafeMove's suitability for GPS-denied environments, a critical requirement for nuclear facilities.

The mapping process supports progressive updates to extend operational areas by merging data from multiple mapping sessions. As shown in Figure 7, the mapping system progressively integrates new sessions, with the single-session map expanding to include data from three and six sessions, resulting in a comprehensive and detailed representation of the environment.

FIGURE 7

Multi-sensor mapping results: single-session (left), three-session (center), and six-session (right) maps showing progressive expansion and accurate integration across sessions.

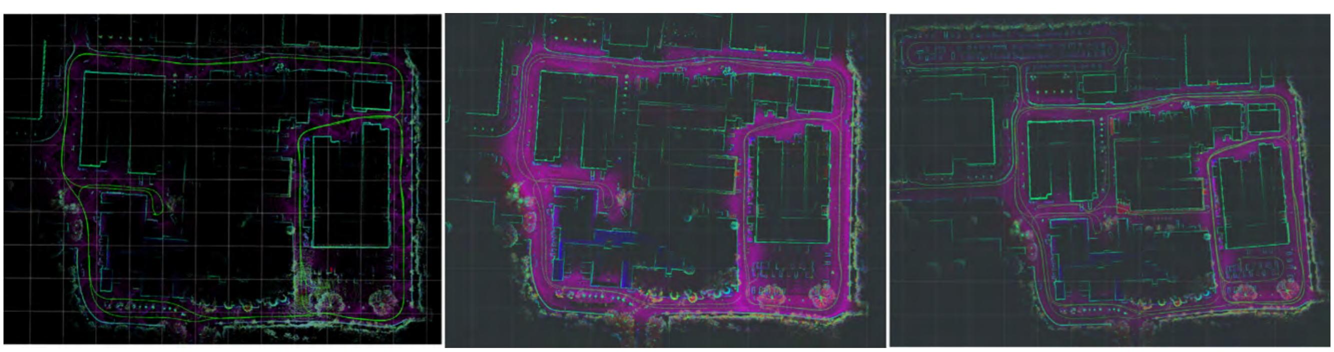


Figure 8 illustrates the LiDAR place recognition system, which operates in two distinct phases: map building and online operation. During the map-building phase, a 3D map of the test site is constructed, consisting of nodes spaced 1–2 metres apart. The connectivity between these nodes forms the autonomy "highway," where travelling along the nodes is assumed to be safe unless obstructed. Additionally, a database of descriptors is created for each node to support future localisation. During the online operation phase, the system identifies matching nodes from the map to estimate the vehicle's position within the local point cloud. Once multiple matches are accumulated, the vehicle is declared "locked into the map," ensuring robust and precise localisation. A video demonstrating these results is available at https://youtu.be/zSbx-vCsm2Q.

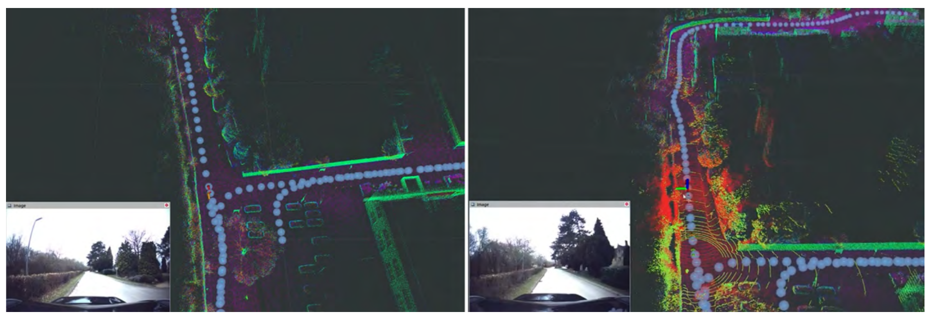


FIGURE 8

LiDAR place recognition: (Left) 3D map node connectivity during mapping. (Right) Real-time localization using matching nodes for precise vehicle positioning.

7.3. POINT-TO-POINT MISSION PLANNING

The demonstration showcased point-to-point mission planning using the constructed topological map. With the map as a foundation, the system was able to plan efficient routes between waypoints, simulating material transport missions such as moving from a home base at Point A to destinations including Points B, C, D, E, and others. Although navigation was not autonomous during this demonstration, the system successfully computed routes, optimised path planning, and demonstrated the process of mission creation and execution within the mapped environment.

As illustrated in Figure 9, the topological map serves as a navigation graph, representing a structured "highway" for the vehicle to follow. Nodes signify key waypoints, and edges represent traversable paths connecting these waypoints. The left image shows the navigation graph overlaid on the 3D map, with the green dot indicating the starting point of the mission and the yellow dot representing the endpoint. The right image highlights the system's local path planning, where the yellow line depicts the specific edges to be traversed based on the mission planning policy. The point-to-point mission planning workflow transitions from the 3D map to the autonomy graph. The system dynamically generates a mission planning policy to ensure safe and efficient navigation, specifying which edges should be traversed when the vehicle reaches a node. This capability validates the robustness of the SafeMove system in mission creation and execution. A video demonstrating these results is available at https://youtu.be/iXn4U9DBWtQ.

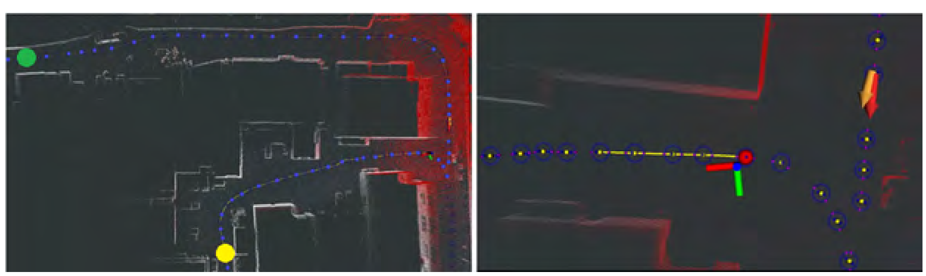


FIGURE 9

Point-to-point mission planning: (Left) Navigation graph on 3D map with start (green) and end (yellow) points. (Right) Local path (yellow) showing graph edges for precise autonomous routing.

7.4. OBJECT DETECTION AND TRACKING

The final stage of the demonstration focused on validating the real-time object detection and tracking capabilities of the SafeMove system. The system effectively identified and tracked dynamic objects, including pedestrians and vehicles, providing the necessary situational awareness for safe navigation in complex environments. These capabilities are critical for ensuring safety in operational deployments at nuclear facilities.

7.4.1. Object Detection

As illustrated in Figure 10, the system demonstrates its object detection capabilities. The left image shows vehicles being detected, while the right image highlights the detection of pedestrians. Each detected object is assigned a classification label and confidence score, showcasing the system's ability to accurately identify different object types in real time. This detection functionality serves as the foundation for subsequent tracking processes, enabling precise monitoring of object trajectories during navigation.

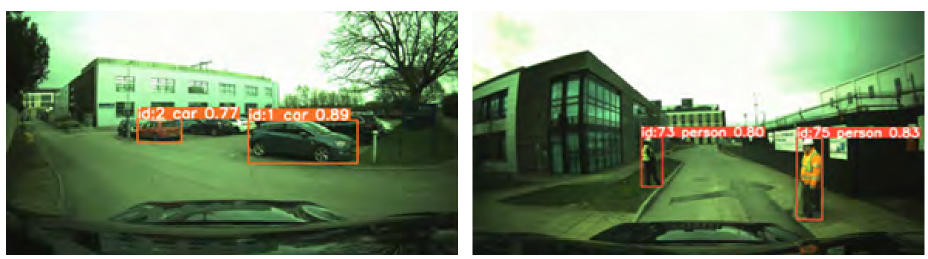


FIGURE 10

Results of object detection. (Left) Detection of vehicles, including classification labels and confidence scores. (Right) Detection of pedestrians.

The object detection process is powered by the D-FINE network, which, at the time of this work, achieved the highest mean Average Precision (mAP) on the COCO dataset. The network delivers high detection performance with a mean latency of less than 30 milliseconds on a standard laptop PC, enabling real-time operation without compromising classification accuracy. Comparisons with other detection models, such as SSDLite + MobileNet and FasterRCNN, confirmed D-FINE's superior balance of speed and reliability. The performance metrics for these models are summarised in Table 1.

TABLE 1

Performance comparison of object detection models in terms of accuracy and latency

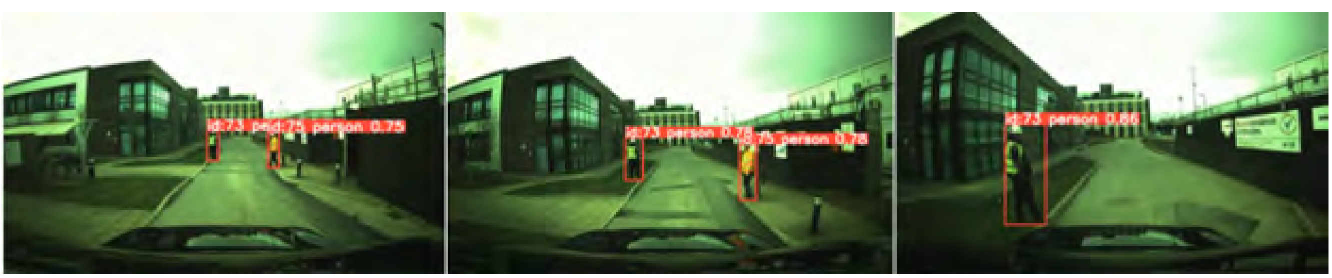
Model	Mean Accuracy (COCO)	Latency (laptop GPU)
SSDLite + MobileNet V3	21.30%	14ms
FasterRCNN + MobileNet v3	22.8% / 32.8%	25ms / 31ms
D-FINE Nano	42.80%	27ms

7.4.2. Object Tracking

The ByteTracker algorithm consistently tracked objects across frames, assigning unique IDs and generating reliable object trajectories. Testing in environments representative of nuclear facilities confirmed its effectiveness in detecting and tracking dynamic obstacles, such as vehicles and pedestrians, with high accuracy and efficiency. As illustrated in Figures 10 and 11, ID 73 is assigned to a person and consistently maintained throughout the sequence. Additionally, another person is identified as ID 75 for part of the sequence, demonstrating the algorithm's capability to manage multiple objects simultaneously. These results highlight the robustness of the tracking system, which is crucial for ensuring safe navigation in dynamic and complex environments. A video demonstrating these results is available at https://youtu.be/r9t8vxUKLP0.

FIGURE 11

Object tracking results demonstrating robust performance, with ID 73 consistently assigned to one person and ID 75 partially assigned to another.



7.5. RISK ASSESSMENT FOR DEPLOYING AUTONOMOUS VEHICLES IN NUCLEAR FACILITIES

The deployment of autonomous vehicles in nuclear facilities requires a detailed hazard analysis to ensure safety, compliance, and reliability. Guided by ISO 26262 standards, a Hazard Analysis and Risk Assessment (HARA) was conducted to identify and mitigate potential risks. This process evaluated hazards based on severity, exposure, and controllability, producing actionable mitigation strategies summarised in Table 2. This structured risk assessment serves as a framework for deploying autonomous vehicles (including systems like SafeMove) in nuclear facilities, addressing complex operational challenges and ensuring safe, reliable integration.

TABLE 2

Hazards, and mitigation strategies for deploying autonomous vehicles in nuclear facilities

ID	Hazard Description	Hazardous Event	Severity	Exposure	Controllability	Mitigation Strategy
H001	Software glitch/bug in autonomous system	Autonomous vehicle fails to respond correctly	High	High	Low	▪ Rigorous testing and validation of autonomous systems. ▪ Implement fail-safe mechanisms (e.g., emergency braking, manual override). ▪ Regular maintenance and updates.
H002	Malfunction and technical/ hardware issues	Autonomous vehicle malfunctions	High	Medium	Medium	▪ Real-time monitoring and adaptive responses to unexpected scenarios ▪ Backup transportation methods (e.g., manual drivers). ▪ Plan for extreme weather conditions and road closures.

ID	Hazard Description	Hazardous Event	Severity	Exposure	Controllability	Mitigation Strategy
H003	Cybersecurity vulnerabilities	Unauthorised access to vehicle systems	High	High	Low	▪ Robust cybersecurity protocols (encryption, intrusion detection). ▪ Isolation of critical vehicle systems. ▪ Regular security audits. ▪ Secure communication channels
H004	Non-compliance with safety regulations	Violation of safety regulations	High	Medium	High	▪ Collaborate with regulatory bodies during the system design. ▪ Obtain necessary permits and approvals. ▪ Maintain accurate records
H005	Accidental spills or leaks during transportation	Environmental contamination	Critical	Medium	Low	▪ Secure packaging and containment of waste packages. ▪ Emergency response protocols for spills or leaks.
H006	Data privacy concerns	Unauthorised access to sensitive data	High	High	Medium	▪ Implement strict data access controls. ▪ Anonymise or pseudonymise sensitive data. ▪ Comply with privacy regulations.
H007	Cost overruns during development and deployment	Project exceeds budget	Low	Medium	High	▪ Detailed cost analysis during development and deployment.
H008	Ethical dilemmas	Ethical guidelines are not followed	Medium	Low	High	▪ Establish clear ethical guidelines for AV behaviour. ▪ Consider societal impact in decision-making.
H009	Interoperability and standards	Non-compliance with industry standards	Medium	Medium	High	▪ Align with industry standards (e.g., communication protocols, safety requirements). ▪ Collaborate with other techno providers and AV manufacturers.
H010	Infrastructure readiness	Infrastructure is not compatible with AVs	High	Medium	Medium	▪ Assess road infrastructure (e.g., signage, lane markings) for AV compatibility. ▪ Invest in necessary infrastructure upgrades.

8. Conclusions

SafeMove addresses critical challenges in nuclear waste transportation by demonstrating capabilities in mapping and localisation, point-to-point mission planning, and object detection and tracking. Its modular architecture integrates GPS-independent navigation, advanced planning, and real-time situational awareness, ensuring reliable operation in complex and hazardous environments. Field demonstrations validated the system's ability to construct detailed 3D maps, plan and simulate efficient point-to-point missions, and detect and track dynamic objects, establishing its readiness for deployment in nuclear facilities. The system’s modular design facilitates integration with a wide range of vehicle platforms, while its advanced mapping and localisation capabilities ensure precision without requiring extensive infrastructure modifications. Object detection and tracking features enhance safety and compliance with nuclear industry standards, supporting robust operations in challenging environments.

A key outcome of this work is the deployment pathway developed through the industry-academia collaboration. AtkinsRéalis, acting as systems integrator and nuclear-domain lead, translated nuclear-site needs into system requirements, structured safety activities, and coordinated an operationally representative on-site demonstration and evaluation. Combined with ORI’s autonomy stack, this provides a practical route to pilot deployments and scale-up across nuclear facilities. As lead commercialisation partner, AtkinsRéalis will carry forward platform integration, site acceptance, and stakeholder governance.

Future work will focus on transitioning SafeMove from manual demonstrations to fully autonomous deployment, including the integration of control systems and vehicle interfaces. Additionally, its modular architecture supports further applications, such as autonomous inspection and monitoring in other large-scale industrial settings, ensuring its continued relevance in advancing operational safety and efficiency.

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Capability Focus

08: Data Governance - The Evolution of an AtkinsRéalis Service Offering

Significance Statement

Organizations are swimming in data—but without structure, that data can't drive smarter decisions. Over six years and ten major projects, AtkinsRéalis has developed a scalable, operationally grounded data governance service that ensures data accuracy, consistency, and completeness through coordination and accessibility of information. Born from real-world challenges, this robust framework aligns data with business needs helping organizations realize a return on investment by eliminating technical debt while supporting the adoption of technologies like enterprise asset management, AI and digital twins/BIM. With clearly defined roles, integrated processes, and strategic oversight, organizations move beyond theory, accommodating smarter decisions at every level.

Énoncé d'importance

Les organisations croulent sous les données; mais sans structure, ces données ne peuvent mener à des prises de décisions intelligentes. En six ans et à travers dix projets majeurs, AtkinsRéalis a mis au point un service de gouvernance des données évolutif et basé sur le fonctionnement opérationnel, qui assure l'exactitude, la cohérence et l'exhaustivité des données grâce à la coordination et à l'accessibilité de l'information. Fruit de l'expérience récoltée en relevant des défis concrets d'infrastructure, ce cadre rigoureux aligne les données sur les besoins d'entreprise, aidant les organisations à obtenir un retour sur investissement en éliminant la dette technologique et soutient l'adoption de technologies telles que la gestion des actifs d'entreprise, l'IA et les jumeaux numériques/BIM. En combinant des fonctions clairement définies, des processus intégrés et une supervision stratégique, les organisations peuvent aller au-delà de la théorie et prendre des décisions plus éclairées à tous les niveaux.

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Abstract

AtkinsRéalis has developed a comprehensive data governance service offering to address the growing need for structured, scalable data management across infrastructure-focused organizations. Originating from a statewide engagement with a U.S. Department of Transportation, the program was designed to integrate disparate data systems, improve data quality, and support regulatory compliance. The framework includes strategic, tactical, operational, and support-level tools that align data lifecycles with business processes.

Key outcomes include the establishment of enterprise-wide data standards, a dedicated Office of Data Governance, and a successful proof of concept demonstrating the feasibility of automating data workflows using commercial technologies. The initiative revealed that effective data governance requires more than policy—it demands clearly defined roles, organizational change management, and practical tools that support daily operations.

Importantly, the program bridges the gap between theoretical governance models and real-world application, enabling organizations to adopt emerging technologies such as AI, digital twins, and enterprise asset management systems with confidence. Lessons learned across ten projects underscore the importance of flexibility, scalability, and business alignment in governance design. Data governance is positioned not only as a support function but as a strategic enabler of innovation, operational efficiency, and informed decision-making.

KEYWORDS

Data governance; Asset management; Data governance framework; Emerging technologies; Data strategy.

1. Introduction

Data and information (data) permeate everything AtkinsRéalis, and our clients do professionally. Data is used in the daily execution of tasks and in the creation of deliverables. Data informs decisions, documents facts, stores knowledge, and provides insights. Combined with experience, data provides wisdom that supports likely impacts from options from which we must choose when planning. Unfortunately, most organizations struggle with being data rich and information poor. Figure 1 demonstrates the struggles many organizations have with evolving their large investments in data into predictable impacts when using data to make informed decisions.

FIGURE 1

Without Data Governance

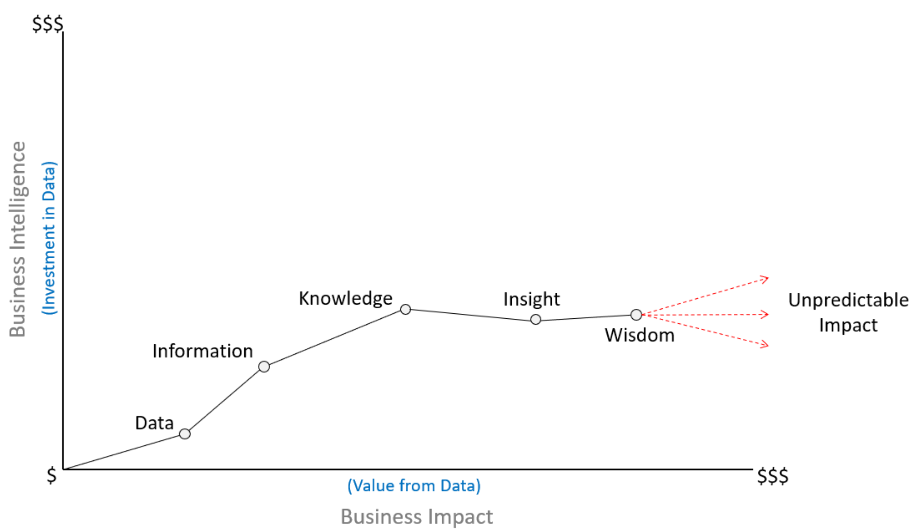
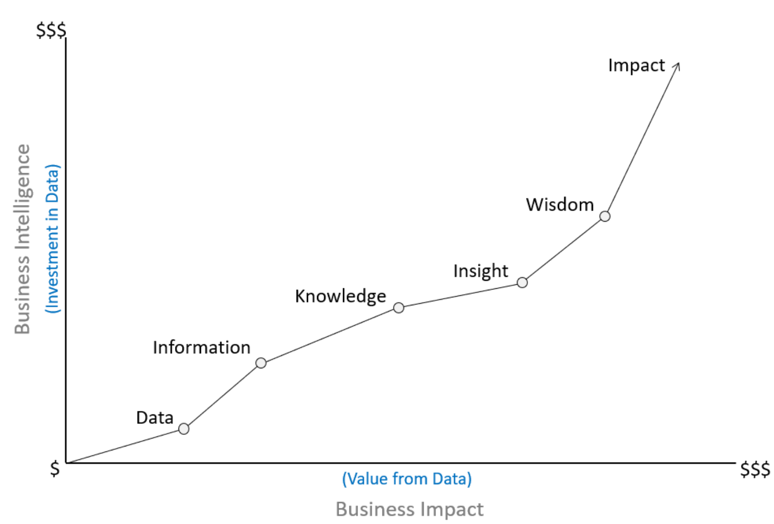


FIGURE 2

With Data Governance



Structured data (data that is stored in a fixed-format database) and unstructured data (data that lacks a fixed format that would make it easier to organize, query, filter, sort, or analyze its content) require a meaningful data governance program that addresses business data needs and processes related to creating, maintaining, and using data in performing daily work. Figure 2 demonstrates the progression from data to predictable impact a structured data governance program can have on an organization's return on investment in data and information.

AtkinsRéalis' development of formal enterprise data governance services was driven by the operational needs of infrastructure management clients tasked with maintaining public infrastructure networks and assets in a state of good repair. Struggles with aligning asset inventory data with asset condition and performance data, current project information and cost data stored in disparate systems creates time and resource strains on efforts to effectively plan for current and future infrastructure needs.

Facing these struggles while preparing to comply with the first reporting period of a new federal U.S. law requiring the creation of a Transportation Asset Management Plan (TAMP), a large U.S. Department of Transportation's (DOT) Office of Technical Services engaged AtkinsRéalis to assist. AtkinsRéalis was asked to evaluate, develop and help implement a statewide data governance framework to address the growing need to regularly assimilate and combine data from disparate systems into datasets, applications, dashboards, reports, or planning documents.

This initiative led to the establishment of a formal data governance service offering within AtkinsRéalis, based in the United States and designed to support clients through strategic consulting and advisory capabilities.

2. Genesis of AtkinsRéalis Data Governance Services

Most AtkinsRéalis client engagements include some consideration for the development or handling of project data and information, but few AtkinsRéalis projects were specific to the creation of enterprise data governance frameworks, programs, and tools. In January of 2019, AtkinsRéalis, doing business as Data Transfer Solutions LLC, began a service engagement for the development of statewide data governance. The scope of work consisted of 14 primary project goals related to people, process, and information technologies that resulted in 15 major deliverables that collectively defined the new statewide data governance program, including a proof of concept for automating data standardization and normalization procedures between disparate systems.

The following highlights the project milestones that led to DOT's data governance program:

- Evaluate existing data governance frameworks, whitepapers, and primers to determine what should be included in a data governance program
- Conduct an online statewide **Data Governance Maturity Survey** assessing 14 data management related categories coupled with key staff interviews
- Establish a definition for **Data Governance**
- Establish a **Data Governance Framework** that included consideration for business data drivers and data source lifecycles
- Establish a **Data Governance Committee** to oversee and guide the data governance program
- Establish an **Office of Data Governance** with recommendations for staffing, including a **Chief Data Officer**
- Define **Roles and Responsibilities** for all data creators, data stewards, and data consumers
- Develop a **Data Business Glossary** to standardize enterprise nomenclature
- Establish a **Data Governance Policy**

- Create **Business Data Plan** templates for each division managing transportation infrastructure
- Create a **Data Quality Assessment** process and scorecard to assess existing data
- Define and identify **Enterprise Data Elements** across disparate systems for **Data Standardization**
- Create an **Organizational Change Management** Plan with a tailored **Communication and Engagement Plan**
- Conduct a **Technical Proof of Concept** to see if technology exists to manage and control data workflows and system integrations while monitoring data quality against the standardized Enterprise Data Elements as part of data extract, transform, and load (ETL) procedures into a standardized enterprise data warehouse from which data for “canned” reports and ad hoc analysis can be accessed (Hint: It does!)

At the end of the two-year engagement, AtkinsRéalis provided a robust data governance program which included an Office of Data Governance staffed with a Chief Data Officer and Business Analyst, and a data governance framework with the tools to allow for the adoption and expansion of data governance throughout the organization.

3. Results

The DOT project yielded successful outcomes for both the client and AtkinsRéalis. The initiative was completed on schedule and within budget, with all contractual milestones and deliverables exceeding client expectations. Furthermore, the project's operational efficiency enabled the execution of a technology proof of concept, demonstrating the feasibility of leveraging commercial software to automate and enforce a data governance program at the client's data lifecycle level.

3.1 CLIENT SUCCESS

The implementation of a structured data governance program yielded immediate benefits for the client.

Key outcomes included:

1. Adoption of a first-of-its-kind enterprise data governance policy that included a defined data governance framework tailored to the client. A comprehensive Organizational Change Management Plan was developed and executed, facilitating agency-wide awareness and engagement.
2. Establishment of a dedicated Office of Data Governance, with key roles filled including Chief Data Officer, project manager, and data analyst.
3. Implementation of a data quality assessment and standards-setting process, resulting in the adoption of enterprise-wide data standards for commonly used fields across systems and databases. This effort involved the analysis of multiple enterprise databases.
4. Execution of a technical proof of concept (POC), which informed the client's evaluation of commercial software solutions capable of automating data workflows and applying governance standards across enterprise systems, including the integration and sharing of data between disparate platforms.

The POC utilized a test environment hosted by AtkinsRéalis mirroring the client's technology stack. A specific client use case was identified for the POC. The use case scenario centered around one staff member who produced four critical bridge structure reports for the federal government annually that a large percentage of the state DOT's federal bridge funding depended on.

Each report relied on data from the same four key systems that tracked bridge inventory, condition, project, and performance data. It was estimated by the DOT that the individual spent upwards of 1,000 hours per year managing, assessing, validating, and consolidating data before it could be formatted into one of the four critical report formats, which was its own undertaking once you had the consolidated data.

AtkinsRéalis evaluated the market for commercial enterprise data catalogs and data governance and management solutions to use in the POC. Upon selecting the leading candidates for data catalogs, virtual data warehouses, and enterprise ad hoc data queries and reporting, AtkinsRéalis configured the technology with the developed data governance program, data standards, and documented workflows.

The POC demonstrated the technology does exist to automate data exchanges that will control data extraction, transformation, and loading processes (ETL) and monitor them for data quality issues, providing the user with a variety of options on handling red flag issues along the data exchange workflow.

Lessons learned from the POC were used by the client to create an RFP for an enterprise data catalog solution and interview vendors. Unfortunately, upon selection of a preferred vendor, the DOT was informed a procurement would be indefinitely put on hold until a change in state leadership occurred. These types of scenarios are not uncommon to AtkinsRéalis clients. Fortunately for the client, they now had a structured data governance program they could rely upon moving forward.

5. Ongoing expansion of the data governance footprint, with the client continuing to build upon the foundational framework established during the engagement to further institutionalize data governance practices across the organization.

3.2 LESSONS LEARNED

Over the past six years, beginning with the development of the Department of Transportation's data governance program, numerous insights have been gained through project experience. These key lessons learned include:

- **The alignment of data governance with business needs has proven essential.** Effective governance is not merely a technical exercise; it requires a deep understanding of how data supports operational objectives and decision-making. When data lifecycles are mapped to business processes, improvements in data quality and system integration naturally follow.
- **Governance structures must be clearly defined.** Experience has shown that a successful implementation depends on establishing oversight mechanisms and delineating roles and responsibilities. Without these, governance efforts risk fragmentation and limited adoption.
- **Flexibility is critical in framework design.** Organizations benefit from recognizing that data governance does not require a fully mature or comprehensive framework at inception. Instead, incremental adoption—based on immediate priorities and existing capabilities—can be both practical and effective.
- **Scalability enhances sustainability.** A well-designed governance framework can be extended from individual applications or work programs to departmental and enterprise-wide levels. This scalability allows organizations to grow their governance footprint organically, adapting to evolving needs.

- **Enterprise standards are built progressively.** Rather than imposing top-down mandates, meaningful data governance often emerges from localized efforts—one program, one application, one department at a time—culminating in coherent enterprise-wide practices.
- **Data governance serves as a foundational integrator.** It functions as the central mechanism that connects content, document, and information management systems, ultimately enabling the development of robust organizational knowledge management capabilities.
- **Data visibility remains a persistent challenge.** Beyond data quality, organizations frequently struggle with understanding what data they possess, how to access it, and how it is used across functions. Addressing these gaps is essential for effective governance.
- **Technological advancement depends on strong governance foundations.** Realizing the full potential of existing systems—such as asset management and GIS—and emerging technologies like artificial intelligence, machine learning, digital twins, and operational technologies, depends on a mature and well-structured data governance program.

4. AtkinsRéalis Data Governance Service Offering

The success of the DOT project propelled AtkinsRéalis into nine additional data governance-specific projects between 2021 and 2025. During that time, AtkinsRéalis has turned data governance into a formal service line in the U.S. Technical Professional Organization (TPO) Asset Management consultancy group.

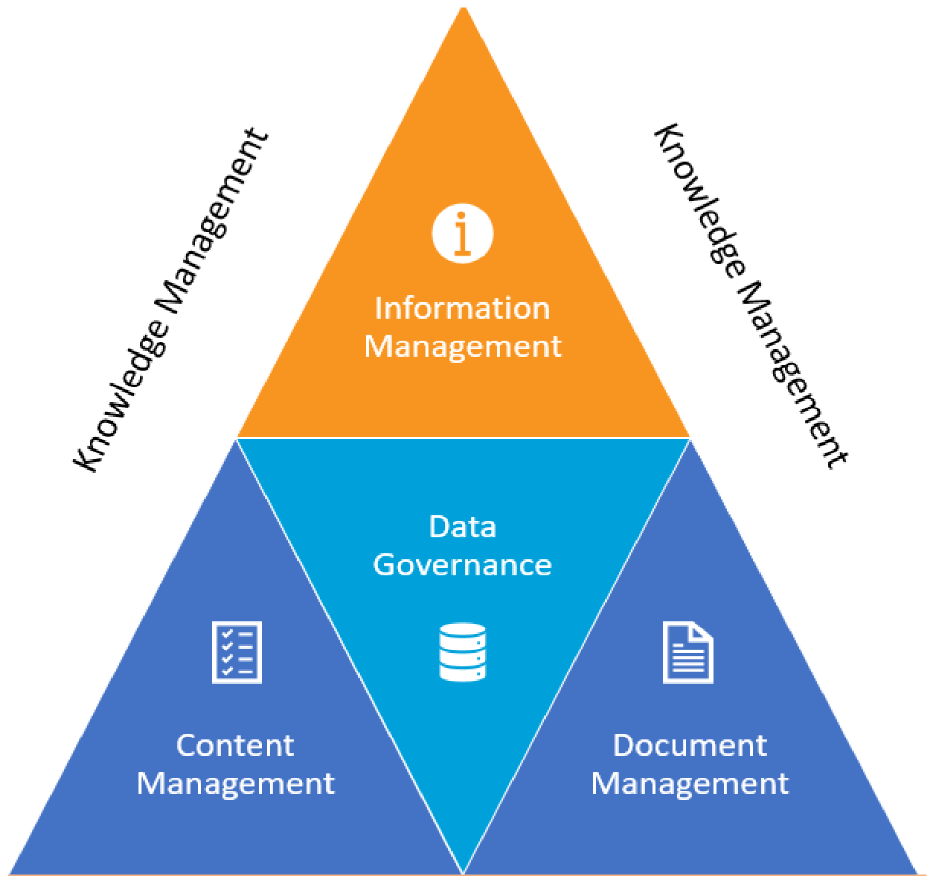
Members of the data governance services team also provide industry thought leadership related to asset management, data governance, and treating data and information as an asset through active participation with the Institute of Asset Management (IAM), International Organization for Standardization (ISO), and the U.S. National Academies of Science, Engineering, and Medicine's Transportation Research Board (TRB).

With the advent of emerging technologies such as digital twins, BIM, digital delivery in the office and operational technologies (OT) in the field, and the soon-to-be ubiquitous presence of artificial intelligence (AI), data governance has rapidly become the missing link to moving ahead with confidence with these technologies. Data governance can set the policy for adoption of emerging technologies and acts as the central processor for capturing, analyzing, and sharing data between technologies following strict organizational standards that meet the business data needs of the organization and the requirements of the technology.

The data governance services offered by AtkinsRéalis have evolved to incorporate components of content management, document management, and information management with data governance, which collectively make up the foundation of an organization's knowledge management system as it relates to its operations. Figure 3 shows the knowledge management pyramid developed by AtkinsRéalis to show the relationship and central role data governance plays in knowledge management.

FIGURE 3

AtkinsRéalis Knowledge Management Pyramid



AtkinsRéalis defines data governance as "a set of overarching program processes and information technologies to maximize the availability, integration, usability, quality, and security of data assets. It is a business competency that engages an organization's workforce at strategic, tactical, operational, and support levels to create, implement, and maintain data standards that promote data quality in support of better decisions making."

The AtkinsRéalis data governance service offering is designed to allow clients the flexibility to start developing a program at the macro or micro level and phasing the program's implementation over time to help manage organizational change as well as to protect against any unintended consequences from changes to existing data and information systems. The focus of a data governance program can be:

- At a specific business process level like environmental compliance reporting
- For a specific work program like a pavement management program
- For a specific department, division, or business unit
- For an enterprise software application like an asset management system or a data warehouse
- At the enterprise level for an entire organization and its key enterprise information management systems

Services focus on the building blocks of an effective data governance framework and program at the strategic, tactical, operational, and support levels. The following briefly describes the data governance program building blocks and program tools that can make up a data governance program. AtkinsRéalis provides defined services to help clients establish or manage their program.

4.1 STRATEGIC PROGRAM TOOLS

Strategic program tools include Data Governance Maturity Assessments, a Data Governance Strategy, and Organizational Change Management Planning. Data governance strategy is traditionally guided by key stakeholders and executive leadership.

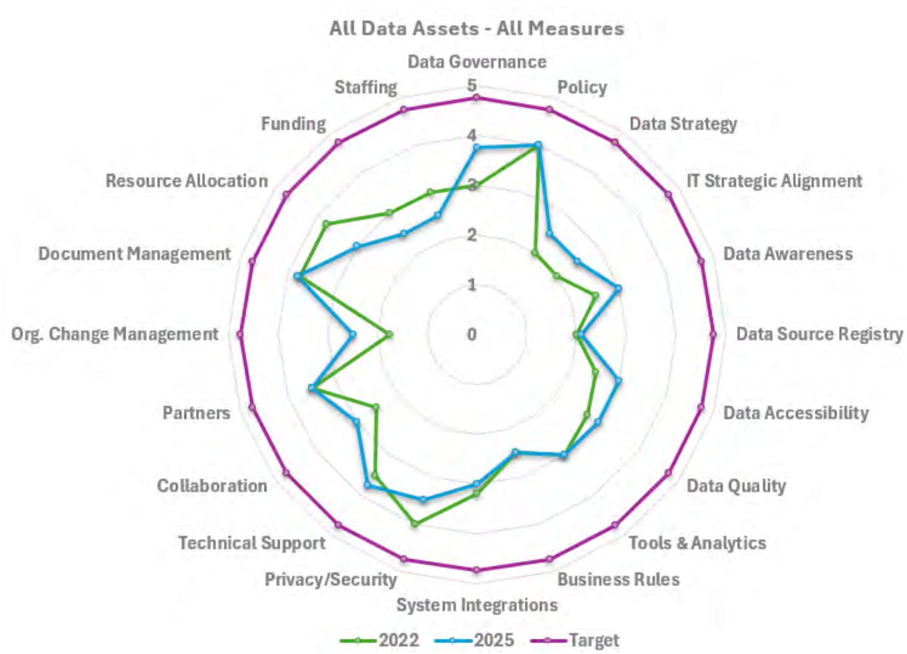
4.1.1 Data Governance Maturity Assessment

An online data governance maturity survey and key staff interviews are a critical first step in assessing an organization's need for data governance and an objective way to prioritize need. A maturity survey helps gather information throughout an organization from those individuals who create and enter data, to those who manage and are the data stewards of specific systems or datasets, to those who consume or use data on a regular basis in the performance of their jobs.

Periodically administrating a maturity survey allows an organization to monitor progress or regress in each area assessed as organizational data needs and information systems evolve along with their data governance program. Figure 4 is a sample comparison of two maturity survey results conducted three years apart showing areas of progress and regress that can now be addressed through a targeted data strategy.

FIGURE 4

Sample Comparison of 2022 Maturity Survey Scores to 2025



4.1.2 Data Governance Strategy

Upon reaching a clear understanding of an organization's data governance maturity and needs, a data strategy can be developed. There are two types of data governance strategies that can be developed:

- High-level strategic roadmap
- Detailed strategic plan

A high-level strategic roadmap outlines the tasks or phases in developing a data governance program, typically spread out over three years. A strategic roadmap addresses specific data governance needs, solutions, levels of effort, and resulting data governance building blocks.

A detailed strategic plan is a long-term plan that memorializes an organization's data governance program, approach, roles and responsibilities, process and procedures, and acceptable data management technologies. A data governance strategic plan is like an IT strategic plan with both plans being complementary to one another.

4.1.3 Organizational Change Management Planning

An Organizational Change Management Plan (OCMP) defines the essential components for achieving successful change adoption. Given the complexity and organizational impact of data governance initiatives, integrating change management throughout the development and implementation process is critical.

A Communication and Engagement Plan (CEP), a core element of the OCMP, addresses the human dimension of change. It outlines objectives, stakeholders, key messages, and engagement strategies, aligned with major milestones in the data governance program.

4.2 TACTICAL PROGRAM TOOLS

Tactical program tools include a Data Governance Charter, Data Governance Framework, Roles and Responsibilities, Data Governance Policy, Data Governance Oversight Committee, Data Business Glossary, Data Source Catalog, Data Use Mapping, Enterprise Data Dictionary, and a Data Quality Management Plan. Data governance tactical management is traditionally guided by chief information officers, chief technology officers and/or chief data officers, and members of a data governance committee.

4.2.1 Data Governance Charter

A data governance charter empowers a data governance program within an organization providing a program framework with defined roles and responsibilities and program oversight. A data governance charter includes a:

- Data Governance Policy
- Data Governance Framework
- Roles and Responsibilities
- Data Governance Oversight Committee
- Data Governance Change Request Process

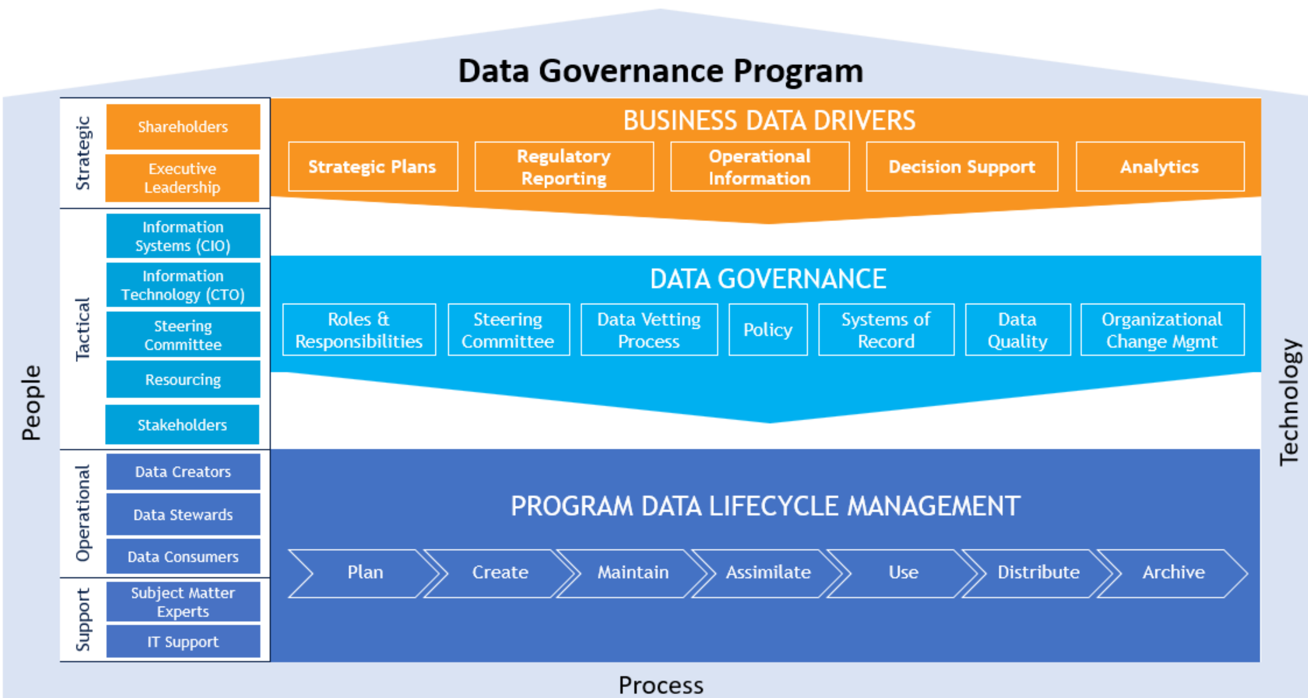
4.2.1.1 Data Governance Framework

A data governance framework is generally defined in the data governance policy and is a system and structure that defines the relationship between organizational resources (people, processes, and technologies) employed towards common business data needs and the key building blocks that make up a data governance program.

There are two noticeable components missing in most data governance frameworks. First, clearly defined and understood business data drivers, and second, their association with the data lifecycle of existing information management systems, software applications, and databases used to manage business data. Figure 5 is the AtkinsRéalis data governance framework that has evolved over the past six years and ten data governance projects.

FIGURE 5

AtkinsRéalis Data Governance Framework



The conspicuous absence of business data drivers that define the specific data and information needed to perform tasks and make decisions and an understanding of the respective program data lifecycles of the data used to satisfy those needs goes a long way to explain why organizations traditionally struggle with implementing their data governance programs and achieving the efficiency, data quality, and process improvements they seek.

4.2.1.2 Program Roles and Responsibilities

Clear roles and responsibilities (R&Rs) are essential for effective data governance. Defined by title/position or data user persona, R&Rs ensure accountability across all organizational levels. Data governance is a shared business competency involving everyone—data creators, managers, and consumers. Specific roles include analysts, stewards, technicians, and support staff, each with tailored responsibilities.

4.2.1.3 Data Governance Policy

The data governance policy commits an organization to a formal data governance program. Policies can be a statement of general goals for a data governance program or more specific, spelling out the data governance framework, oversight of the policy and program, and defining roles and responsibilities as it relates to the program. Policies may include policy guideline statements that focus on policies to address a specific topic within the realm of data management and data governance.

Examples of policy guidelines may relate to:

- Data quality
- Data architecture
- Data sharing
- Emerging technologies (ex: AI, digital delivery)
- Vendor-contractor service level agreements
- Document management
- Data classification and security

4.2.1.4 Data Governance Oversight Committee

A data governance oversight committee (DGC) is a working oversight committee that makes decisions and provides guidance related to data governance and data management of critical data and source systems of data.

The primary role of the DGC is to act as champions and help establish, implement, and grow the data governance program in their respective business areas and throughout an organization. A DGC's primary goal is to vet decisions to protect against unintended consequences impacting existing data, systems, and reporting tools.

A data change request process is the most important tool of a DGC. The DGC's intent is not to approve or reject a request, but rather to consider it from an organizational risk and consequence perspective. A defined process can help avoid scenarios like a data source manager unilaterally deciding to stop tracking a data field that is unknowingly being used in a critical managerial dashboard used for decision making.

4.2.2 Data Business Glossary

A data governance glossary standardizes terminology across departments, vendors, assets, and systems. It defines terms, acronyms, and aliases to ensure consistent language organization-wide. This tool supports enterprise governance, improves communication, and aids employee training by clarifying roles and data-related concepts based on usage and context.

4.2.3 Data Source Catalog

A data source catalog documents, in one central location, a list of all the official data and information source systems of record and the data it contains. Data source catalogs are created by mapping where and how data is used to its source and vice versa.

Data source catalog content can serve multiple purposes and is used in the development of Business Data Plans and Business Data Guidebooks.

4.2.3.1 Data Use Mapping

Data source mapping is the only way to document specific information about how, where, when, and what data is needed for decision support throughout an organization aligned with where that data is maintained. There are two approaches to documenting data sources and where data is used:

- Document content mapping
- Data source uses mapping

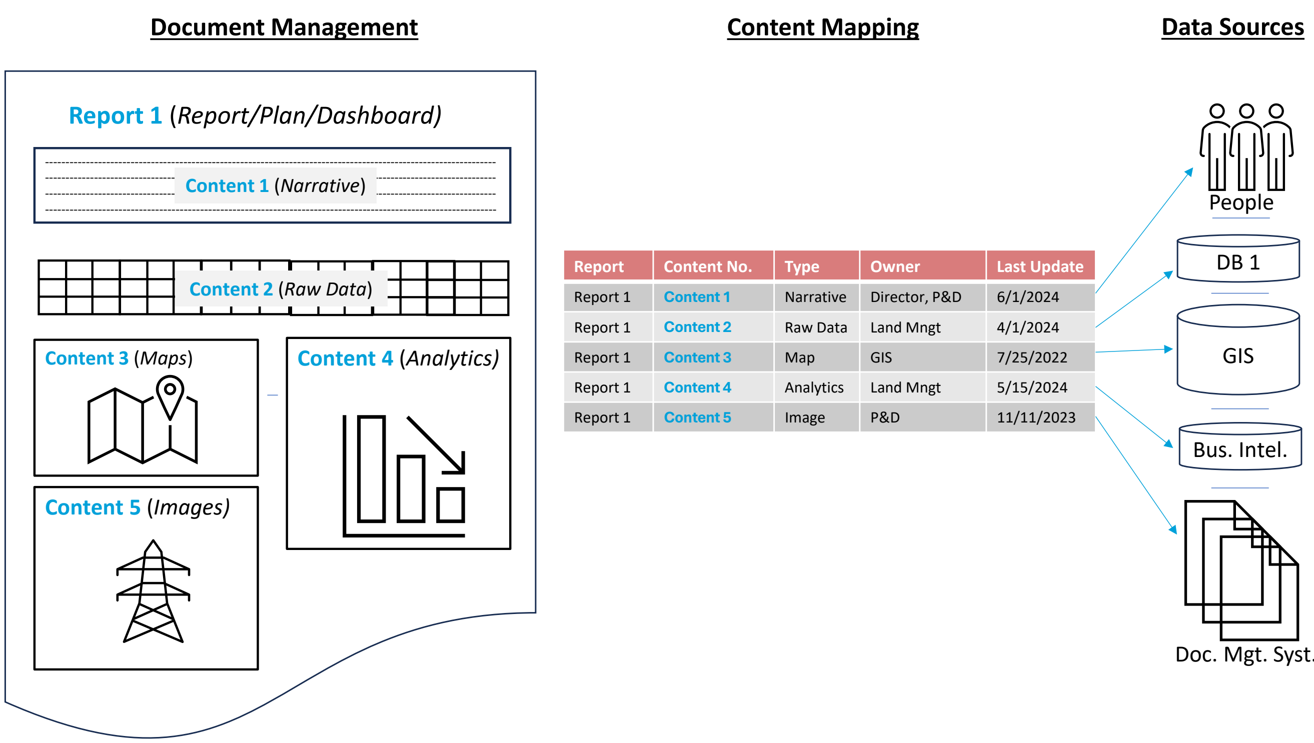
Document content mapping identifies the source(s) that provides data and information to a document. A document in this instance may include reports, documents, plans, or dashboards that contain structured and/or unstructured data from other sources. Figure 6 represents the content mapping process.

A critical business document (ex.: annual report, proposed budget, project plan) may include sections where the content comes from different sources. A single document may include a narrative that comes from an individual like a director; a section with raw data from a structured database; information visualized on a GIS map; data analyzed to show statistical trends; and images stored in a document management system. Each one of the sources may have a different age to its content and different frequency in its data update lifecycle that should be documented in the data source catalog.

For example, a physical asset in the official asset register may have been inventoried with identification, location, feature, and condition information captured at the time of its installation 10 years ago. If the asset is not rehabilitated, relocated, or replaced in those 10 years, it may not need to have its identification, location, and feature information updated. However, it is important to know the last time the condition of the asset was updated in those 10 years and what the standard frequency for updating asset condition information should be. Although identification, features, and location data may remain static, condition data is always changing as assets are always in a state of deterioration.

FIGURE 6

Document Content Mapping

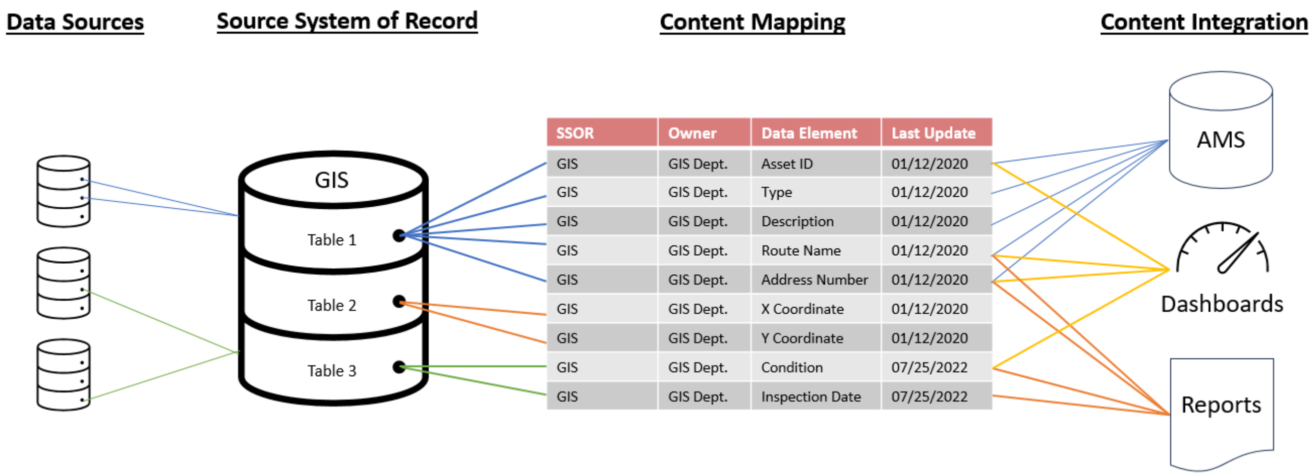


Report	Content No.	Type	Owner	Last Update
Report 1	Content 1	Narrative	Director, P&D	6/1/2024
Report 1	Content 2	Raw Data	Land Mngt	4/1/2024
Report 1	Content 3	Map	GIS	7/25/2022
Report 1	Content 4	Analytics	Land Mngt	5/15/2024
Report 1	Content 5	Image	P&D	11/11/2023

Data source use mapping is similar to document content mapping, but instead of beginning with a document, it starts with a key system of record as the foundation (See Figure 7). It starts with documenting the data tables and individual data elements and mapping their use to internal and external applications such as reports, performance and decision-making dashboards, and integrations with other data sources like GIS integration with an asset management system.

FIGURE 7

Data Source Use Mapping



Content derived from the data use mapping efforts are used in the development of Business Data Plans and Business Data Guidebooks and can aid in identifying areas for integration or process improvements to bring greater efficiency and consistency to data management efforts.

4.2.4 Data Dictionaries

A data dictionary documents essential data attribution to be tracked to meet an organization's reporting and decision-making needs. The dictionary contains additional metadata about each data attribute including field format, precision, use case, data source, data field values, data field requirements, etc.

Data dictionaries are used to document data standards for a report, performance metric, work program, software application, or other data assimilation processes requiring standardized data.

4.2.5 Data Quality Management Plan

Data quality is the ultimate goal of a data governance program. Consistency in quality data is indictive of an effective data governance program. Data quality indicates the extent to which data is fit for its intended purpose and use.

A data quality assessment score card is a tool developed to assess multiple dimensions of data quality. The Institute of Asset Management (IAM) defines six data quality dimensions: Accuracy, Completeness, Consistency, Timeliness, Validity, and Uniqueness. Six Sigma, a data-driven approach to quality, adds two additional dimensions to IAM's six, they are: Integrity and Reliability. AtkinsRéalis assesses two additional dimensions: Usability and Lineage.

Data quality assessments can help identify quality issues and influence data collection plans, data standards development, and resource allocation. Improving data quality will ultimately increase data management efficiency and improve timely and more predictable decision making.

4.3 OPERATIONAL PROGRAM TOOLS

Operational program tools include Business Data Plans (BDP) containing Data Use Cases, Data Management Best Management Practices and Standard Operating Procedures, Content Mapping, Data Dictionary, Data Sources, and Data Workflows. Data governance at the daily operational level focuses on program data lifecycle management and impacts data creators, data stewards, and data consumers.

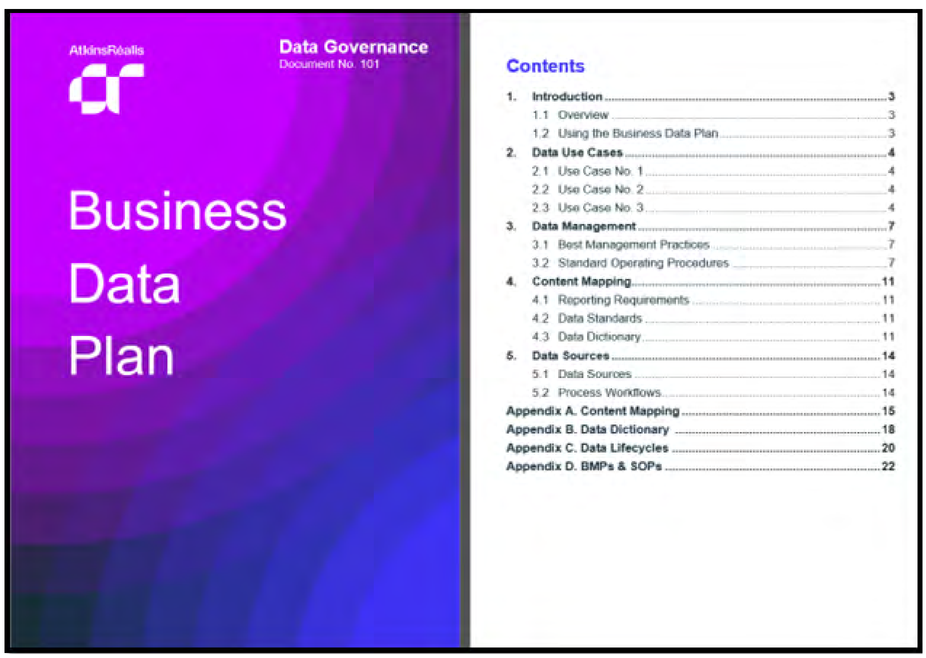
4.3.1 Business Data Plans

A BDP is used to document the data needs for reporting and decision making at a business operational level. Figure 8 contains sample content that may be included in a BDP. A BDP can be created to memorialize a:

- Business process
- Work program
- Business unit / division / department / organization
- Business system / software application

FIGURE 8

Sample Business Data Plan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Data Governance
Document No. 101

Business Data Plan

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4.4 SUPPORT PROGRAM TOOLS

Support program tools include Business Data Guidebooks (BDG) containing required Data Attribution, Data Workflows, Data Transformation Standards (ETL), and Data Source Mapping. Data governance at the support level engages business subject matter experts, data stewards, and IT support professionals.

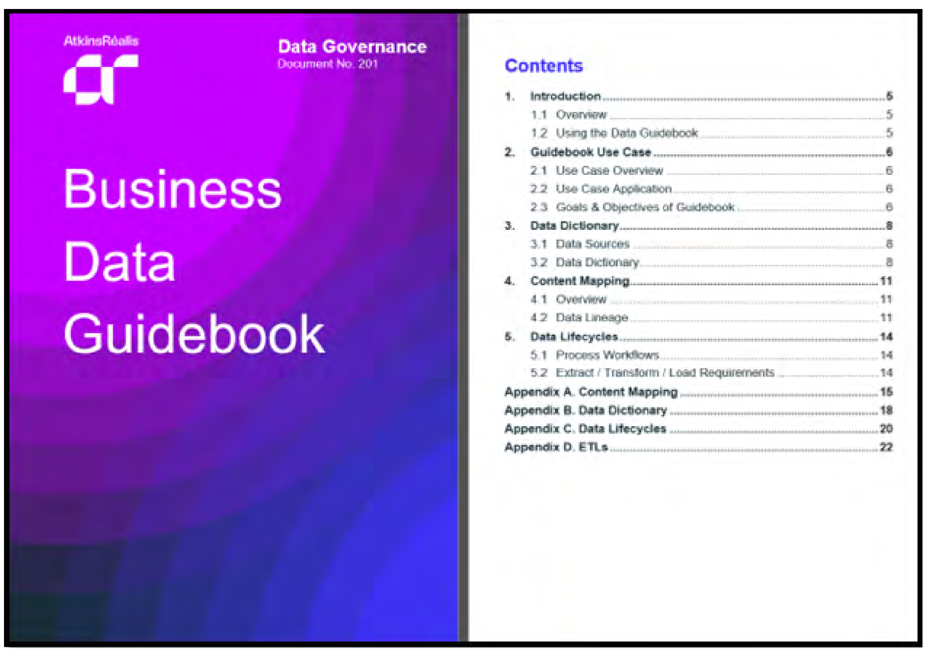
4.4.1 Business Data Guidebooks

A BDG is used to document the data needs for supporting business processes, data workflows, and information technology integrations. Figure 9 contains sample content that may be included in a BDG. A BDG can be created to memorialize:

- Performance metric calculations
- Document (report, plan, document, dashboard) creation
- Data collection or preparation workflows
- Software integrations

FIGURE 9

Sample Business Data Guidebook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Data Governance
Document No. 201

Business Data Guidebook

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Sidebar: Artificial Intelligence and Data Governance Data governance plays a critical role in the design, implementation, and ongoing support of Artificial Intelligence (AI) systems. As organizations increasingly rely on AI to automate tasks and make data-driven decisions, the need for consistent, high-quality, and well-managed data becomes essential.

A structured enterprise data governance program enables AI success by providing:

- **Defined Use Case Scenarios**
  Clearly articulated use cases help identify the specific data and information requirements, workflows, and decision logic (e.g., if-then scenarios) needed to train AI agents. These scenarios ensure alignment with organizational standards and objectives.
- **Data Quality and Integrity**
  AI models are only as good as the data they are trained on. Governance ensures that data used in training and reasoning is accurate, complete, and consistent—minimizing errors and improving model reliability.
- **Compliance, Risk Management, and Ethical Standards**
  Data governance enforces conformity with regulatory requirements and ethical guidelines. It ensures sensitive data—such as personal or proprietary information—is handled appropriately, reducing legal and reputational risks.
- **Access Controls and Data Stewardship**
  Governance frameworks define who can access what data, under what conditions. This protects data from misuse and ensures that AI systems are trained and operated using authorized, relevant datasets.

- **Operational Efficiency and Standardization**
  By automating tasks such as plan reviews or document classification, AI can enhance productivity. Governance ensures that these automations reference the correct standards, codes, and data sources—leading to consistent outcomes.
- **Trust and Transparency in AI Adoption**
  A well-governed data environment fosters trust among stakeholders. Decision-makers and end-users are more likely to adopt AI solutions when they understand how data is managed, validated, and used responsibly.

5. Conclusion

AtkinsRéalis integrates strategic, tactical, operational, and support-level tools to deliver a complete data governance framework. This comprehensive approach drives data management efficiency and strengthens decision-making across the organization.

AtkinsRéalis has learned numerous lessons over the past six years and ten data governance projects working with DOTs, tolling agencies, a utility district, and large municipalities and has evolved our service offering to meet the growing sophistication and needs of our clients and the sectors we serve.

As organizations increasingly rely on formal data governance programs to align business data needs with data source lifecycles, ensuring data quality for reporting and decision-making becomes critical. It is essential to promote awareness of the full scope of data governance services and expertise available. For inquiries regarding potential data governance service options or further information, contact the Data Governance Service Team within the U.S. Technical Professional Organization's Asset Management (US71) business unit.

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