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$$F = \frac{1}{\Sigma W \sin \alpha} \Sigma \left[\frac{c' B + (W - uB) \tan \phi'}{\cos \alpha + (\sin \alpha \tan \phi' / F)} \right]$$

- Effect of aspect ratio and load location on the performance of catenary arches under concentrated loading
- Revised simplex method: An alternative solver to the out-of-kilter method for water balance model decision support system
- Implication of reliability categories on the structural design of higher-risk buildings
- A socio-technical systems (STS) analysis of road fatalities in Gauteng province (2015–2019)
- A meta-synthesis of the strategic advantages of AI–BIM integration in AEC projects

$k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2} = 0$



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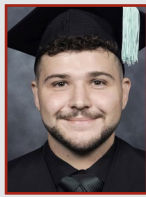
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Effect of aspect ratio and load location on the performance of catenary arches under concentrated loading

D L Teixeira, J E van der Merwe

Catenary arches represent an efficient structural form under self-weight, as they can develop pure compression with minimal bending. In practice, however, arches are often subjected to pattern loading and/or concentrated loads, which alter the theoretical thrust-line geometry and introduce bending moments.

This study investigates the influence of arch span-to-depth ratio and load position on the structural response of catenary arches subjected to concentrated loading. Two arch geometries with aspect ratios of 0.35 and 0.60 were tested experimentally under both central and eccentric point loads. Observed hinge formation and ultimate load-carrying capacities were compared with theoretical thrust-line calculations and results from simple linear elastic numerical analyses. The results show that arches can sustain higher loads when the concentrated load is applied at the apex rather than eccentrically. This influence of load position was found to be more pronounced for shallower arches.

The study compares experimental observations of hinge locations with locations estimated from theoretical thrust-line geometries and maximum bending moments from simplified linear elastic numerical models. It is shown that such simplified methods are adequate for estimating hinge locations even beyond the initial elastic response range.

Keywords: catenary arch, thrust line, optimised structural form, eccentric loading, hinge formation.

INTRODUCTION

Catenary arch structures are the optimal structural forms for ensuring pure axial force without induced moments over a span under self-weight (Allen & Zalewski 2009; Hawkins *et al* 2019). This is especially favourable for concrete arches, which are well-suited to form compression elements. As such, this form is often used in bridge construction (e.g. Figure 1) and has also been proposed for floor construction to reduce the amount of concrete material and, as such, embodied carbon (e.g. Figure 2). Vaulted structures designed by Heinz Isler highlight the extent to which concrete volume can be reduced when roof structures are built to follow catenary forms (e.g. Figure 3).

Robert Hooke described the optimal form of a structure spanning a horizontal distance under its own weight as that of a hanging chain – a structure in pure tension. Inverting this hanging form yields

the shape of a catenary arch, which is in constant compression under its own weight. Such lines, which define the shape of constant compression, are called thrust lines (also known as the funicular form). It is, however, Rene Descartes who is credited for establishing a connection between such a curve's construction and its algebraic equation in 1637 (Cvetković *et al* 2021). The geometry of this hanging chain catenary can be described according to Equation 1 (Block *et al* 2006).

$$y = a \cdot \cosh\left(\frac{x}{a}\right) \quad (1)$$

Where:

y = vertical height of the catenary
 x = horizontal distance from the centre of the catenary apex
 a = scaling factor that dictates the proportional shape (span/height) of the catenary.



Figure 1 The Salginatobel bridge in Switzerland was designed by Robert Maillart, who formed the arch according to thrust line patterns (Rama 2008)



Figure 2 Vaulted slab designed to minimise material use (Oval *et al* 2023)



Figure 3 Heinz Isler is renowned for the design of several thin vaulted structures, such as this garden centre in France (Boller *et al* 2024)

This concept has not only been used as the reference for some arch structures, but also for the analysis of domes (Figure 4) and vaulted structures (Figure 5) over centuries. It has also been shown that catenary theory can be used for the analysis and design of ordinary reinforced concrete beams (Gohnert & Bradley 2023).

Therefore, as long as the geometry of an arch centreline follows theoretical thrust lines, the arch can be expected to be in pure compression. Deviation of structural form from this thrust line geometry will, however, result in eccentric loading and, in turn, bending moments. If the flexural capacity of the arch cross-section is not capable of resisting such resulting bending moments, hinges will form. This is especially critical, for example, for stone masonry arches. Gáspár *et al* (2023) illustrate how the location and number of hinges that form in such masonry arches depend on the extent of arch geometry deviation from theoretical thrust lines (Figure 6).

The funicular form of a structure (i.e. the theoretical thrust line geometry) under loading that differs from uniform self-weight loading differs from the classical catenary form. Following Simon Stevin's description of masses suspended from a hanging chain in 1586, and Pierre Varignon's description of force polygons in 1725, Karl Culmann is credited as the first to formalise the method of graphic statics to analyse funicular structures under applied concentrated loads (Block *et al* 2006). While a hanging chain model

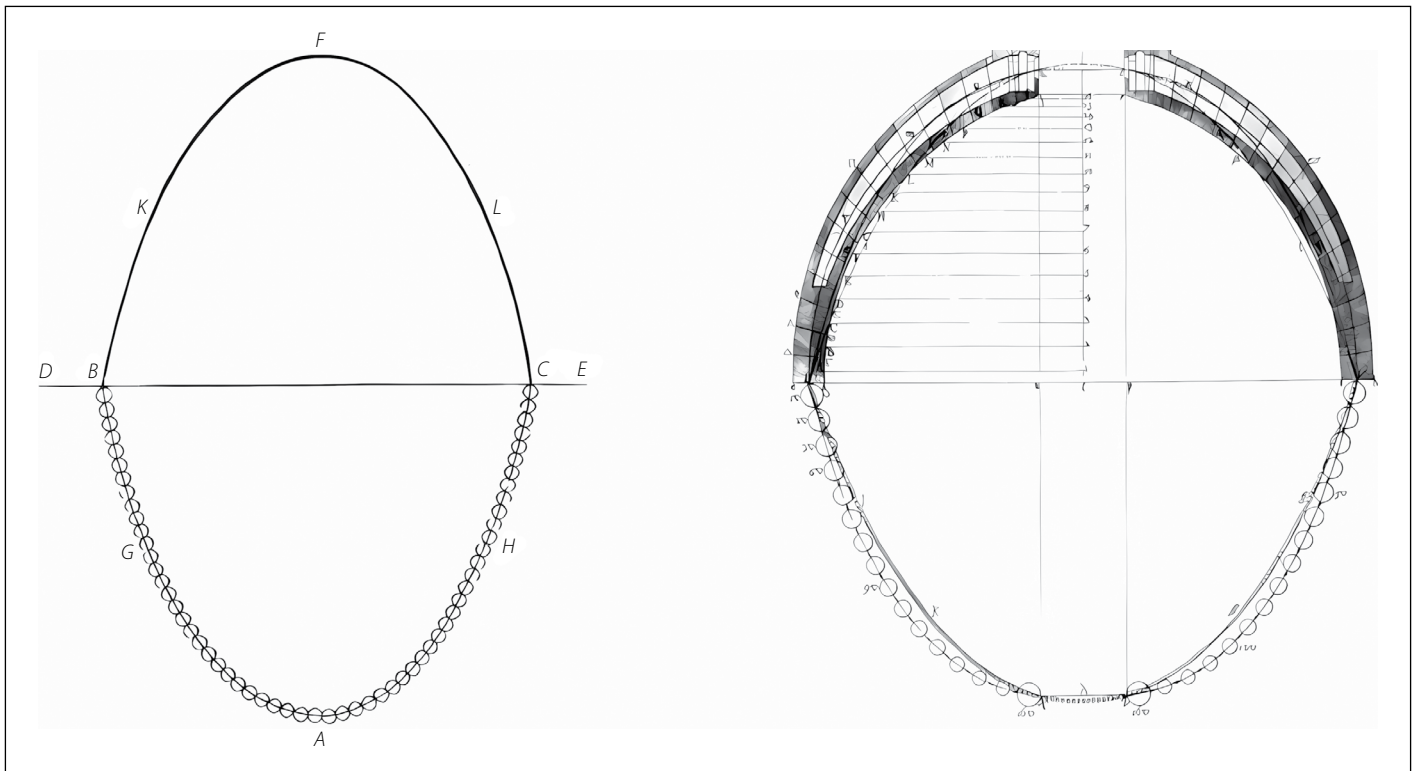


Figure 4 Giovanni Poleni based his analysis of domes on Robert Hooke's hanging chain analogy of catenary form (Poleni 1748, as cited in Jannasch 2017)



Figure 5 Bradley and Gohnert (2016) used this hanging chain model to describe the inverted catenary form of a vaulted structure

might still be considered to represent the funicular shape for a structure exposed to concentrated loads, it is clear that the resulting thrust line form differs from that under uniform self-weight loading (Figure 7). Such concentrated loads may result, for example, when arches support columns or when moving imposed axle loads are applied (e.g. bridge structures).

Similarly, when pattern loading must be accounted for, several theoretical thrust lines may develop. If flexural effects due to eccentricity between the arch element centre line and the theoretical thrust line are to be minimised, the structural depth must be sufficient to resist bending moments due to eccentricities between the structure's geometry and theoretical thrust lines (e.g. Figure 8). This was, for example, considered by Robert Maillart when he designed the arch of the Salginatobel bridge (Figure 9).

Analytically similar to masonry arches, hinges might form in reinforced concrete arches under the application of point loads if the resulting bending moments exceed the flexural capacity of the section. The number of hinges that might form in an arch, therefore, depends on the arch geometry, the position of an eccentric load, and the flexural capacity of the material (Bradley 2021).

While several studies have investigated simple analysis techniques for catenary arches under self-weight in the elastic range up to hinge formation (e.g. Block *et al* 2006, De Bruin 1996, Zhang *et al* 2024), few have explored the practical relevance of such analyses for identifying the successive locations of hinge formation in concrete arches (e.g. Gáspár *et al* 2024). Moreover, the performance of catenary arches under concentrated point loads is often investigated in the context of masonry arches, where pure hinge formation is more likely than for reinforced concrete arches. The extent to which arch geometry influences structural response and hinge formation of concrete arches under such concentrated loading conditions has received comparatively little experimental attention.

Since concentrated loads alter the theoretical thrust line geometry from the classical catenary form, different arch aspect

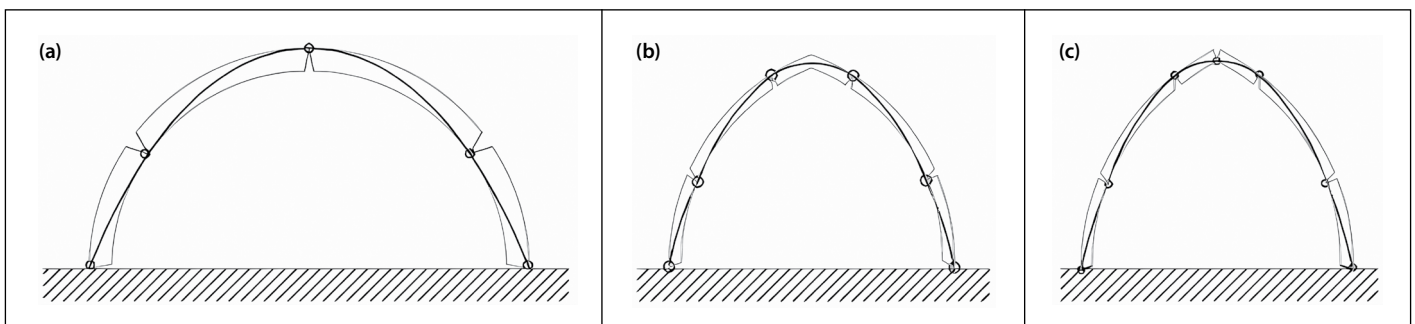


Figure 6 The extent to which arch geometry and theoretical thrust lines differ will determine the location and number of hinges that might form in masonry arches; in this case, (a) 5, (b) 6, or (c) 7 hinges (adapted from Gáspár *et al* 2023)

ratios may perform differently depending on the load position. This study aims to test this hypothesis by investigating arches with two aspect ratios under central and eccentric loading. Geometric deviations from theoretical thrust lines are compared with the positions of crack development and propagation identified from experimental tests.

In addition to evaluating the extent to which the capacity at first hinge formation differs, the study investigates how well a design engineer might identify hinge-formation locations using simple linear elastic analysis methods, as well as the limitations of relying on such simplified methods. The objective of this study is to evaluate the ability of theoretical thrust-line analysis and numerical modelling to predict the location of hinge formation in concrete arches subjected to concentrated loading. Although the applied loads corresponding to hinge formation are reported, the study does not seek to quantitatively evaluate arch member capacities. Conventional flexural stress calculations developed for horizontally spanning beam members are not directly applicable to arches under concentrated loading, where the internal stress state is strongly influenced by combined axial compression, bending, and local stress redistribution.

SCOPE AND METHODOLOGY

To investigate two aspect ratios, concrete arch heights were varied over a 1 m horizontal distance. This section discusses the concrete material, sample preparation, and experimental setup.

Concrete material

A high-strength steel fibre reinforced concrete mixture (developed by Weyers 2020) was used for all arch specimens. Although the strength of such arches lies in their geometry and not high material strength demands, this concrete mixture was used to ensure that small-scale samples could be produced with good quality control during sample preparation, to avoid detrimental drying, shrinking cracks, and damage during demoulding and handling of samples in the laboratory. Moreover, this was deemed an appropriate deviation from potential full-scale structures given the comparative nature of the study's aim and objectives.

In addition to casting arch specimens (tested 14 days after casting), cube and cylinder samples were prepared to determine

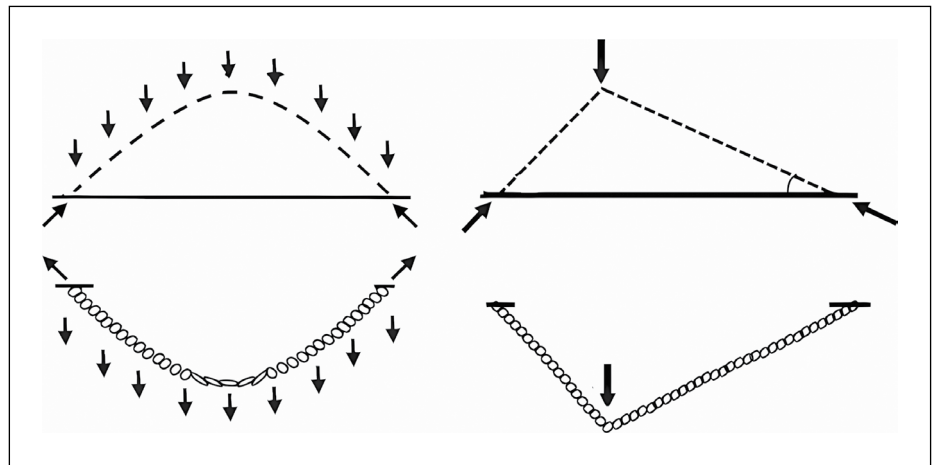


Figure 7 The hanging chain analogy describes the thrust line geometry under self-weight (left) and under applied concentrated loads (right) (adapted from Gohnert & Bradley 2023)

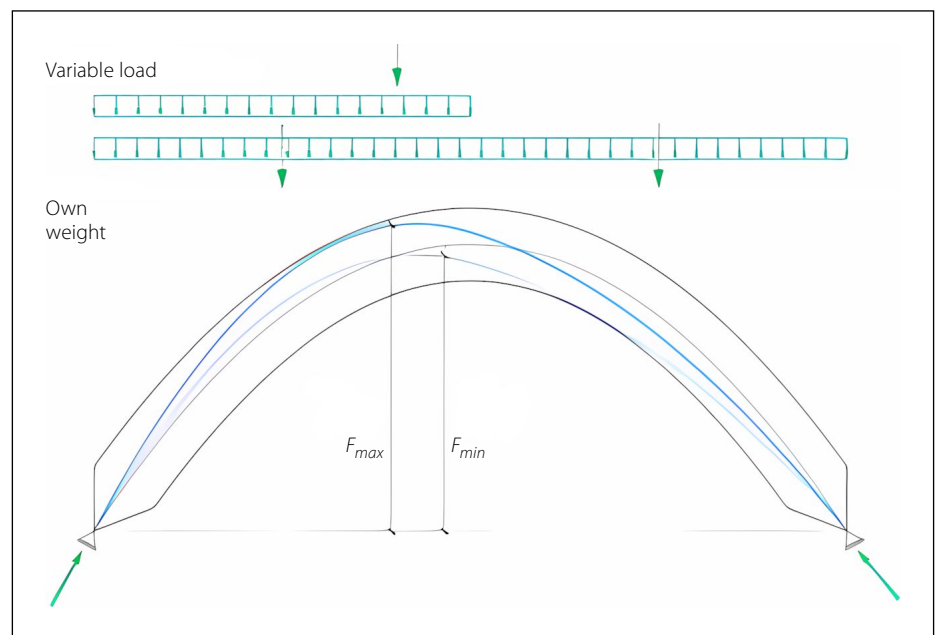


Figure 8 Under the application of variable loads, an arch element should be of sufficient depth to encapsulate the thrust lines resulting from maximum (F_{max}) and minimum (F_{min}) loads

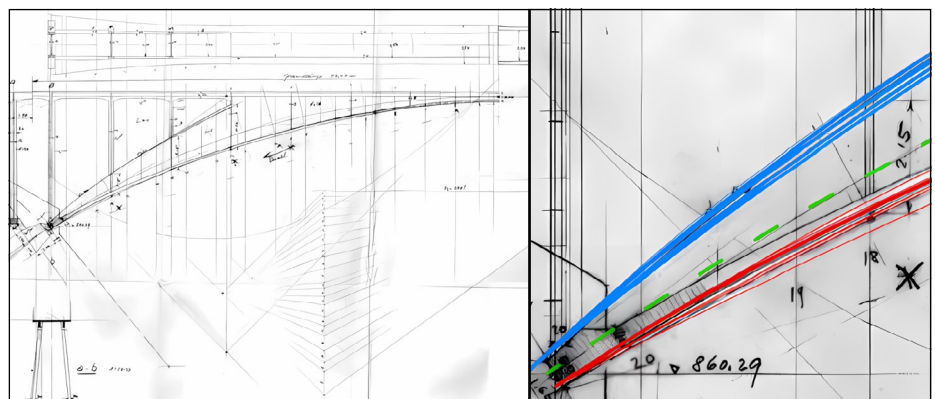


Figure 9 Robert Mallart's working drawing of the Salginatobel bridge with graphic statics calculations (left). The upper (blue) and lower (red) thrust lines (right) due to pattern loading on the bridge deck are all encapsulated in the depth of the arch to avoid excessive flexural effects (adapted from Fivet & Zastavni 2012)

the material properties at 14 days, including compressive strength ($f_{c,14}$), modulus of elasticity ($E_{c,14}$), and splitting tensile strength ($f_{t,14}$). After casting, arches were

left to cure in ambient laboratory conditions (approximately 25°C and 55% relative humidity) while covered with a plastic sheet. To ensure representative results, the

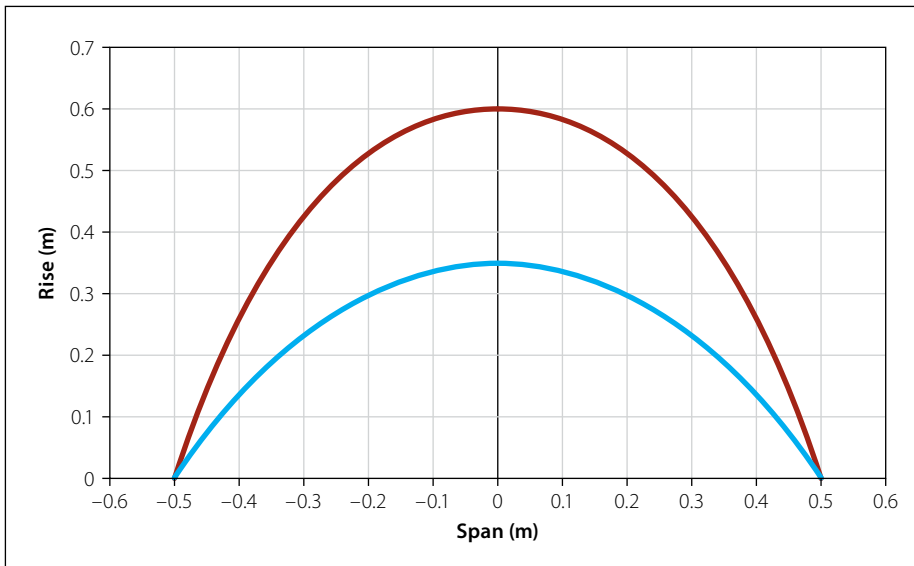


Figure 10 A steep arch and a shallow arch (aspect ratios 0.60 and 0.35, respectively) were investigated

Table 1 Concrete mixture considered in this study

Material	kg/m ³	Relative density
Cement – CEM I 52.5R	542	3.14
Silica fume	146	2.45
Fly ash	146	2.22
Dolomite sand < 4.75 mm	1005	2.85
Dolomite stone < 9.5 mm	251	2.91
Silica sand < 1.5 mm	216	2.67
Superplasticiser Optima 100 Chryso	25.6	1.06
Water	146	1.00
Short steel fibres – 30 mm hooked end	149	7.85

Table 2 Reference concrete properties

	$f_{c,14} / f_{c,28}$ [MPa]	$E_{c,14}$ [GPa]	$f_{t,14}$ [MPa] Pre-crack (post-crack)
Mean	131.5 / 139.1	46.49	7.02 (10.90)
St. dev	4.15 / 3.14	1.61	0.59 (2.75)
CV	0.032 / 0.023	0.035	0.084 (0.252)
CV = coefficient of variation St. dev = Sample standard deviation			

concrete samples for 14-day testing were cured in the same conditions as the arch samples. A set of concrete cubes was also prepared to validate the reference 28-day compressive strength ($f_{c,28}$). Table 1 summarises the concrete mix proportions, while Table 2 summarises the recorded material properties.

Arch geometries

Spanning 1 000 mm, two arch depths were considered to obtain span-to-depth ratios of 0.35 and 0.60 (i.e. arch centreline heights of 600 mm and 350 mm, respectively).

Equation 1 was used to determine the catenary shapes of the two arches, with centreline geometries shown in Figure 10. The geometries match those of physical hanging chain models well (Figure 11). Scaling factors of $a = 0.2733$ and $a = 0.4049$ were determined for the steep and shallow arch geometries, respectively.

Custom moulds were constructed to cast the arch geometries. The cross-sectional dimensions of the arches were 160 mm wide and 50 mm thick. Although this thickness might be considered proportionally greater than what would

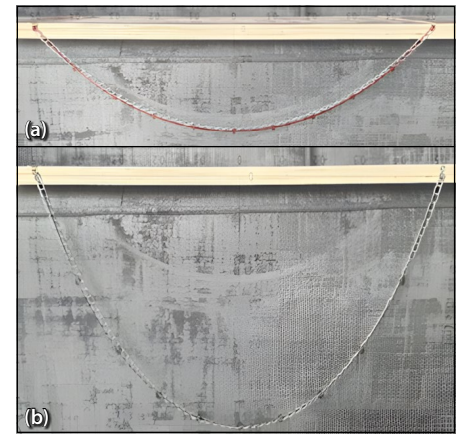


Figure 11 The calculated coordinates of the catenary arch geometries (both (a) shallow and (b) steep) match the shape of hanging chains well

be relevant to full-scale structures of this nature (where the aim is to reduce material volume), it ensured robust samples that avoid drying shrinkage and limit possible damage during handling. Moreover, since the study focuses on a comparison of the effects of geometry and load position up to the point of hinge formation, and not on quantitative effects beyond the linear elastic range, this was deemed adequate.

Figure 12 shows the two arch geometries that were produced. For each arch aspect ratio, one was cast with a smooth upper finish for loading at the apex. One arch of each aspect ratio was cast to apply a concentrated load 200 mm from the centre line. To accommodate the load application in this (inclined) position, an additional volume of concrete was added, connected to the arch with reinforcement dowels, and finished to ensure a horizontal top surface. This localised thickening of the concrete section increased the section's stiffness over this 50 mm length. Although experimental observations show the relevance of this effect on a localised level, it did not appear to have a substantial effect on global arch behaviour.

Experimental setup

Arches were placed on two metal plates with a lubricated interface to provide vertical support while minimising horizontal friction. Rigid horizontal restraints were placed at both supports, with a load cell at one support to record horizontal thrust (Figure 13a).

A displacement-controlled load was distributed over the full width of the arches to simulate quasi-static loading. The side faces of the arches were painted white

and partially sprayed to carefully monitor displacements and crack formation with photos taken at 10-second intervals, as shown in Figure 13b.

When a load was applied at the apex of the arches, a linear variable differential transformer (LVDT) measured the vertical displacement of the soffit at the apex. Due to practical constraints, LVDTs could not be placed directly under the off-centre loading location. In these cases, displacement at the load application was recorded directly from the calibrated hydraulic actuator.

Numerical comparison model

Experimental observations were compared to results from simple linear elastic analyses in Prokon (Prokon Software Limited 2025). The arch geometry was discretised using nodes spaced at 10 mm horizontal intervals along the span, and vertical coordinates calculated according to Equation 1.

To validate the numerical model, theoretical calculations were compared to model output under arch self-weight only. A constant horizontal thrust is expected under self-weight only. It is shown in the appendix that the theoretical constant thrust can be calculated according to Equation 2.

$$H = w \cdot a \quad (2)$$

Where:

H = horizontal thrust

w = self-weight of the reinforced concrete cross-section

a = scaling factor that dictates the proportional shape (span/height) of the catenary.



Figure 12 Steep and shallow arch geometries with the formwork required for the bearing surface for the eccentric load application

Assuming a unit self-weight of 25 kN/m³ for validation purposes, the theoretical constant thrust amounts to $H = 0.055$ kN for the steep arch, and $H = 0.081$ kN for the shallow arch. Two-dimensional linear elastic analyses yielded the same horizontal reaction and horizontal axial force at the apex of each arch, where the internal axial force is horizontal.

The axial force in each of the arch geometries was compared to theoretical values at the apex, at supports, and at the quarter span. It is shown in the appendix that the axial force is related to the catenary arch geometry according to Equation 3.

$$N = H \cdot \sqrt{1 + \sinh^2\left(\frac{x}{a}\right)} \quad (3)$$

Where:

N = axial force

x = horizontal position measured from the apex.

Table 3 compares the results. Linear elastic analysis output agreed well with theoretical axial force values, with a maximum difference of 1% observed for the shallow arch. This suggests that the numerical model can adequately analyse catenary behaviour in the elastic range.

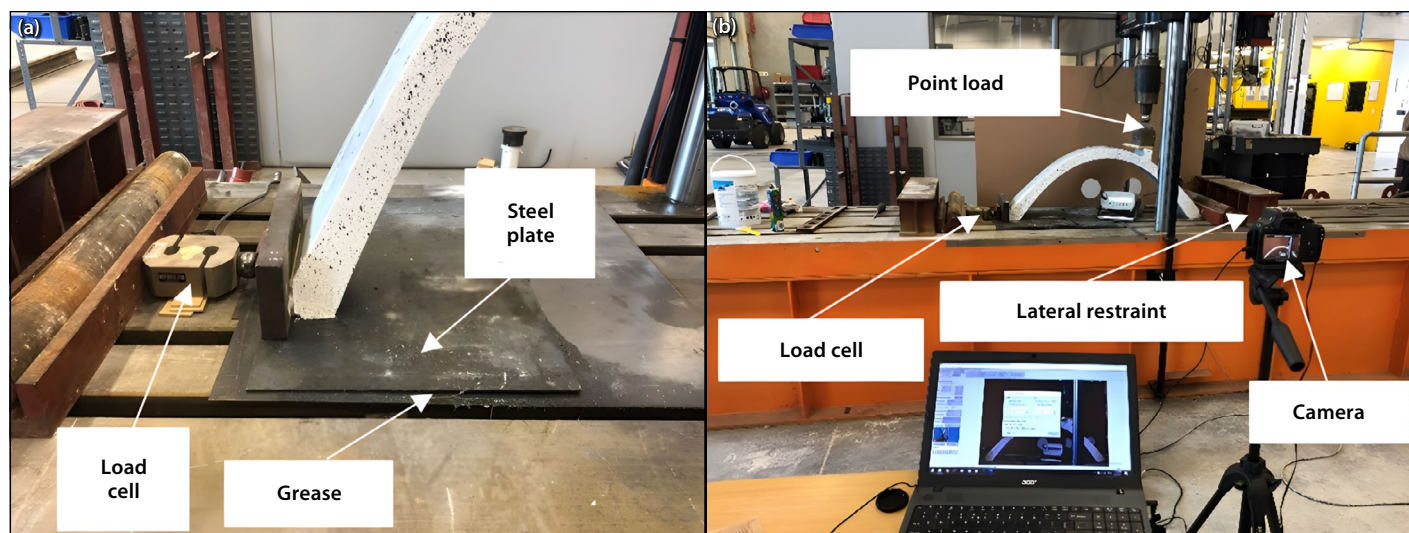


Figure 13 (a) Supports were provided to record the horizontal thrust; (b) The experimental setup comprised displacement-controlled load application and continuous monitoring

Table 3 Comparison of theoretical values for the axial force along the arch geometries with output from linear elastic analyses under self-weight only

Arch	Position	Theoretical value	Analysis output
Steep arch	Support	0.175 kN	0.175 kN
	Quarter span	0.079 kN	0.079 kN
	Apex	0.055 kN	0.055 kN
Shallow arch	Support	0.151 kN	0.149 kN
	Quarter span	0.097 kN	0.097 kN
	Apex	0.081 kN	0.081 kN

RESULTS AND DISCUSSION

The arches' behaviour during experimental testing was characterised by the formation of flexural cracks at locations where the thrust line deviated from the arch geometries. These cracks developed progressively until successive hinge formations ultimately led to collapse. The capacity and failure modes are compared in this section. Theoretical

locations of hinge formation are compared to experimental observations and linear elastic analyses. Although the location of the maximum bending moment obtained from such linear elastic analyses should agree with the location of the maximum deviation from theoretical thrust lines and the locations of hinge formation from experimental observations, it does not allow comparison

with experimental load-deflection behaviour beyond the elastic range. Such analyses do not capture the development and spread of crack formation leading up to final collapse. Differences in the ultimate capacity between a linear elastic analysis and experimental observations are therefore anticipated.

Performance under central load

With concentrated loads applied at the apex of the arches, initial cracks were observed at the apex at applied loads of 20 kN and 25 kN for the steep and shallow arches, respectively. When these concentrated loads are applied to the numerical models, maximum moments of 1.43 kNm and 1.57 kNm are obtained at the apex of the steep and shallow arches, respectively. Axial compressive forces at the apex amounted to 6.19 kN and 13.60 kN for the steep and shallow arches, respectively. The bending moments differ by only 9%, while the resulting tensile

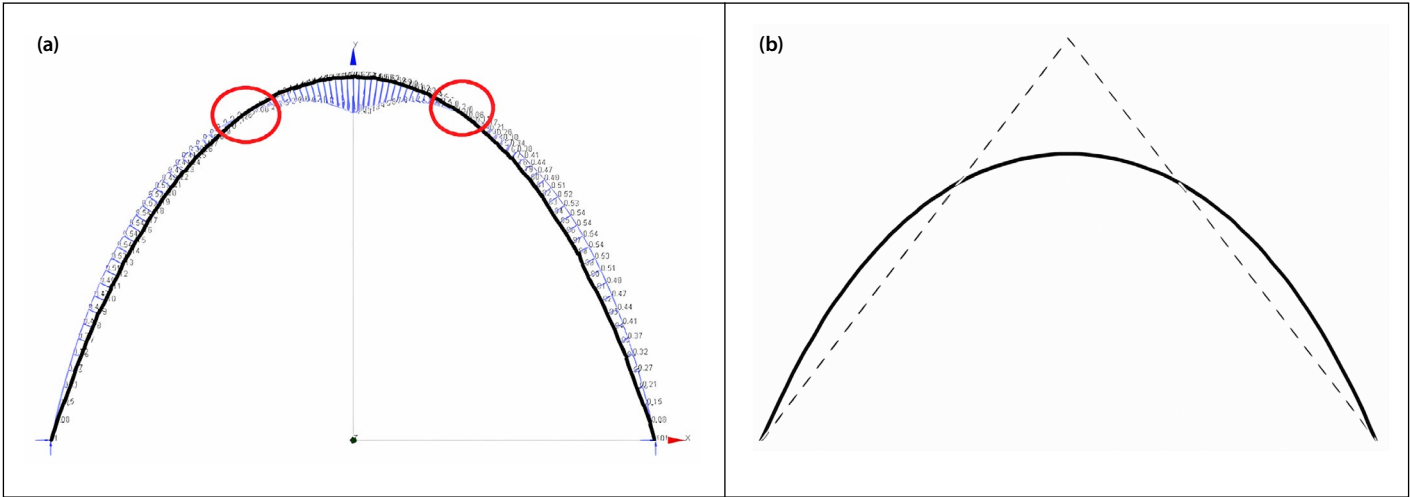


Figure 14 Considering the points of contraflexure from the bending moment diagrams of the arches under central loading (a), as the position where theoretical thrust lines should pass through the arch geometry (b), the maximum deviation between thrust line and arch geometry is observed to be at the apex

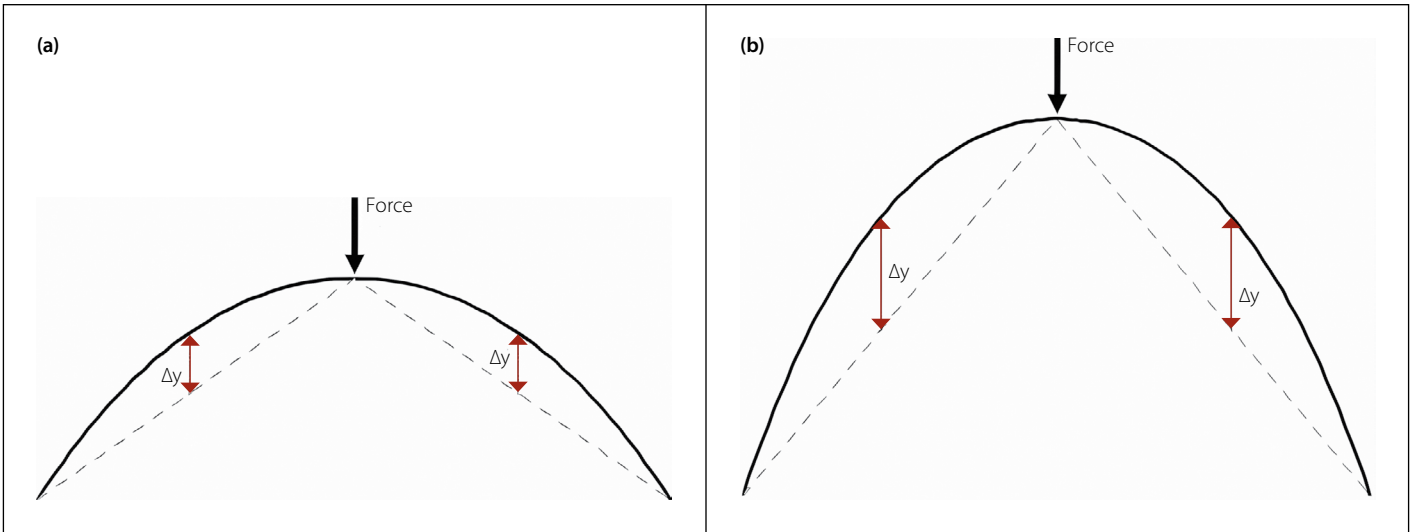


Figure 15 Arch geometry and theoretical thrust lines under central point loading for the shallow arch (a) and steep arch (b). The maximum vertical deviation (Δy) is notably more for the steep arch than for the shallow arch

stresses from combined axial and flexural effects differ by only 5%. The difference in applied load at initial hinge formation, therefore, appears to correspond to similar section capacities. Moreover, the maximum deviation between the theoretical thrust line and the arch geometries prior to hinge formation is at the apex (Figure 14).

Following flexural crack formation at the apex, the linear elastic model was changed from a two-hinge arch to a three-hinge arch, i.e. an arch that now has hinges at the two supports as well as at the apex. Figure 15 compares arch geometries and theoretical thrust lines for concentrated loads, assuming a hinge at the apex. The maximum vertical deviation was calculated to be 179 mm (280 mm horizontally from the apex) and 96 mm (260 mm horizontally from the apex) for the steep and shallow arches, respectively. From Figure 16, it follows that the magnitude of the bending moment imposed in the arch is equal to the product of the (constant) horizontal thrust and this vertical deviation, i.e. $M = H \cdot \Delta y$.

The positions of maximum bending moments obtained from the two-dimensional linear elastic analyses agreed with the theoretical positions of maximum vertical deviation between the thrust line and the arch geometry (Figure 17).

The steep arch finally resisted a maximum load of 25 kN, while the shallower arch resisted a maximum load of 37 kN. Figure 18 shows the arches after failure under a central point load at the apex.

Final hinges were observed to form at positions from the apex that corresponded to the maximum vertical deviation between the theoretical thrust lines and the arch geometry, as well as to the associated

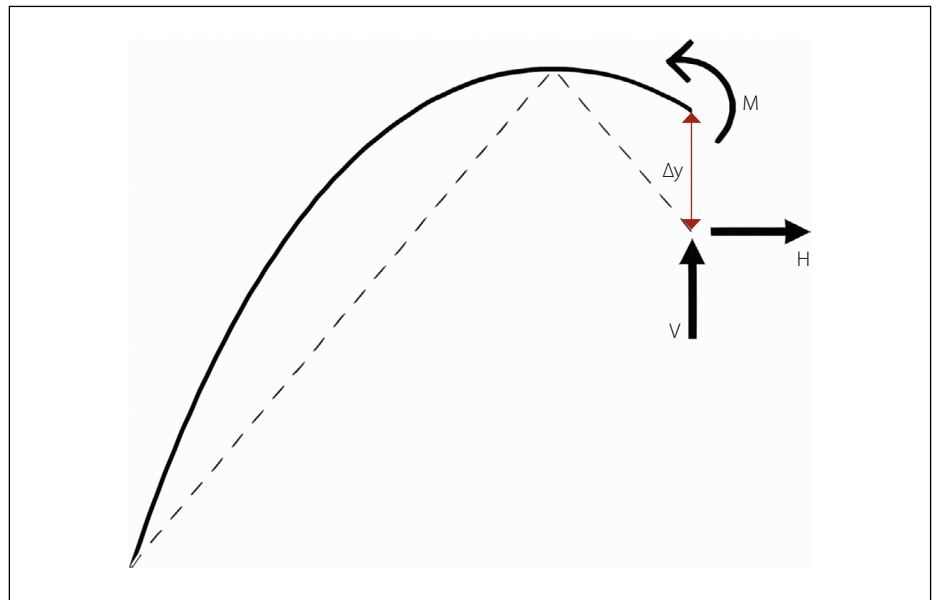


Figure 16 At any given section along the arch, the flexural moment (M) is equal to the constant horizontal thrust (H) multiplied by the vertical difference (Δy) between the arch and the theoretical thrust line

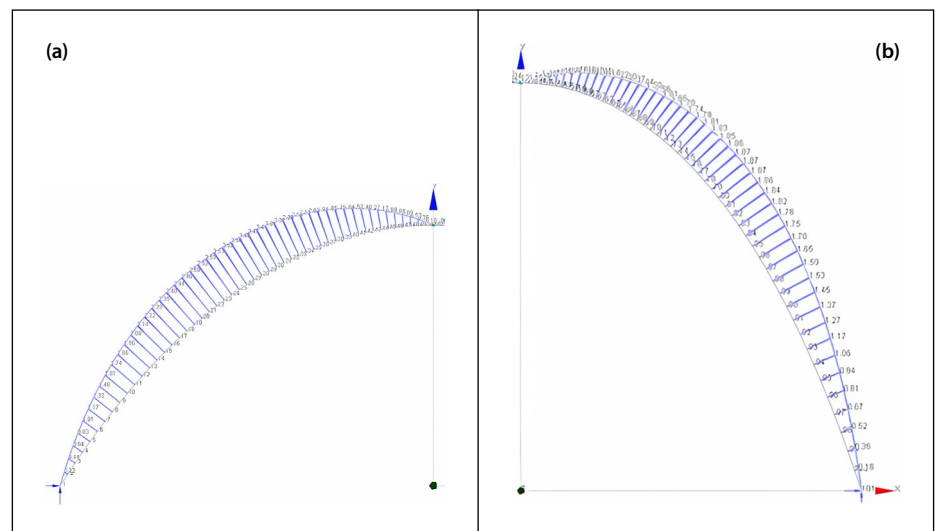


Figure 17 The maximum bending moments obtained from linear elastic analyses of a three-hinge (a) shallow arch and (b) steep arch aligned with the location of maximum vertical deviation between theoretical thrust lines and arch geometries



Figure 18 Both the shallow arch (a) and steep arch (b) formed a five-hinge failure mechanism

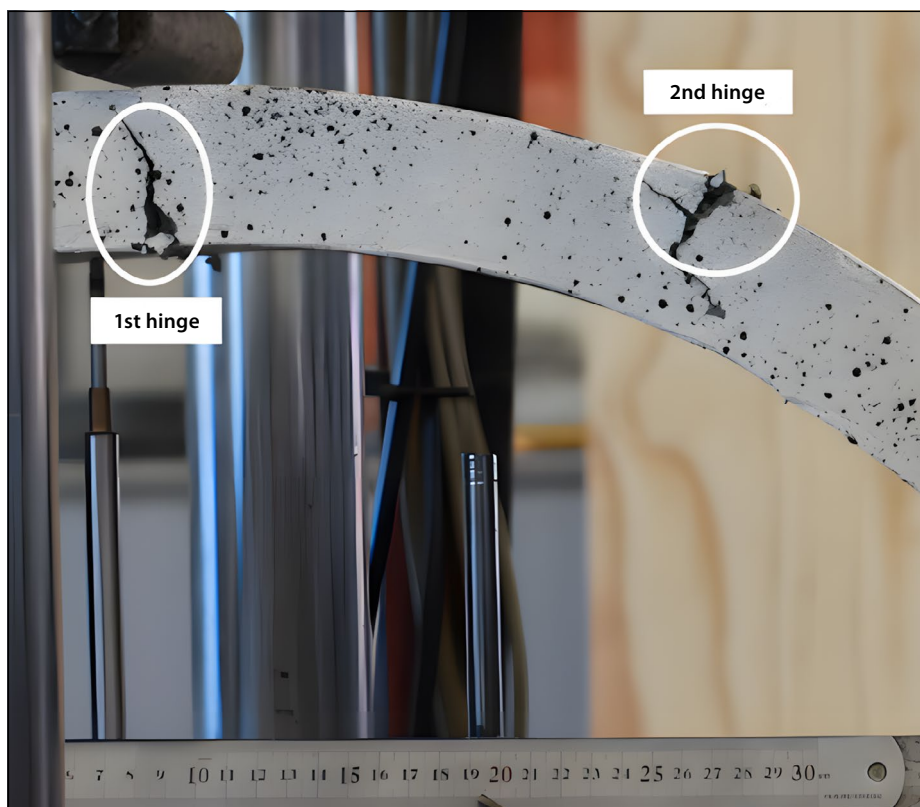


Figure 19 After the first hinge formed at the apex, a second hinge formed at a location that matched theoretical calculations (in this case, 260 mm from the apex for the shallow arch)

Table 4 Comparison of the location of hinge formation under central loading measured horizontally from the apex

	From flexural cracks observed from experimental tests	From maximum deviation from thrust line	From maximum bending moment in numerical analyses
Steep arch First hinge	0 mm	0 mm	0 mm
Steep arch Subsequent hinge	270–280 mm	280 mm	270–290 mm
Shallow arch First hinge	0 mm	0 mm	0 mm
Shallow arch Subsequent hinge	260–270 mm	260 mm	260–270 mm

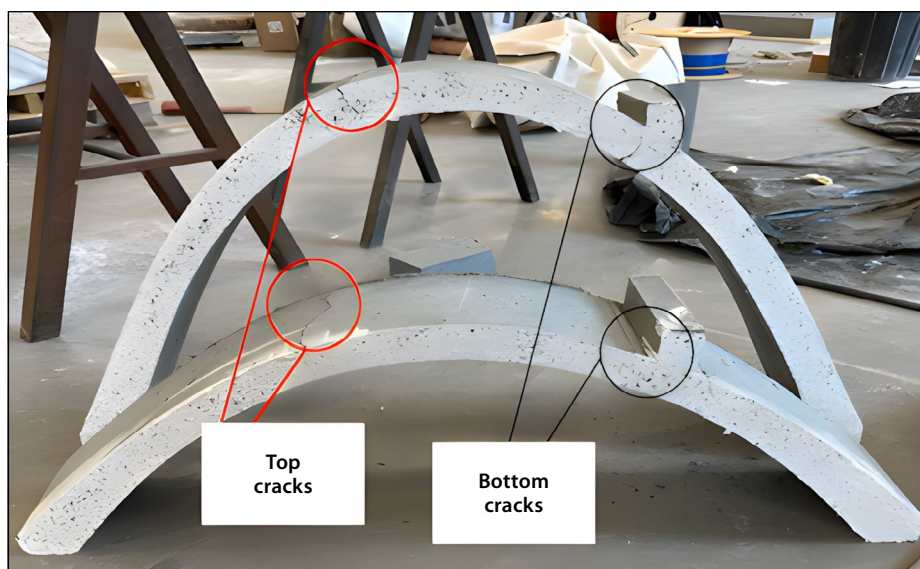


Figure 20 Arches loaded off-centre after failure

maximum bending moment (Figure 19). The tensile stress at the hinge locations was calculated as the combined effect of flexural stress and axial compression from the linear elastic analyses of the three-hinge model when the maximum experimental concentrated loads were applied at the apex. This resulted in a tensile stress in the shallow arch that is 23% greater than that in the steep arch and substantially greater than the concrete's splitting tensile strength. This discrepancy may be attributed to residual flexural stiffness at the apex, as a perfect hinge (assumed in the numerical model) is unlikely in the experimentally tested specimens. This highlights that such simplified analyses might not be sufficient to assess the extent of capacity after initial flexural cracks appear. In contrast, and as shown in Table 4, such simplified analyses might be considered sufficient for identifying the location of hinge formation.

Performance under eccentric loads

Both arch geometries were loaded at a position 200 mm away from the apex. Figure 20 indicates where loads were applied, and shows the position of crack formation after failure.

Both arches resisted very similar ultimate loads, with the steep arch resisting a maximum load of 20 kN and the shallow arch 21 kN. Moreover, the hinge locations seem to agree well between the two arches, first forming near the position of the applied load, and then at similar locations on the opposite side of the apex. This agrees with a comparison of linear elastic analyses of an eccentrically applied point load on both the shallow and steep arches. As shown in Figures 21 to 24, the locations of maximum bending moments obtained from elastic analyses agree with the locations of maximum vertical deviation between arch geometries and theoretical thrust lines. This supports the use of simple elastic analysis as a practical tool for predicting likely hinge locations. It should be noted that bottom cracks did not form directly below the applied load, but rather at the edge of the additional concrete volume added to accommodate load application. This is most likely due to the increased stiffness resulting from the localised thicker section.

The location of the maximum moment that develops in the three-hinge shallow and steep arches was found to differ by approximately 20 mm. The maximum vertical deviation between theoretical thrust lines and arch geometries at these locations, however, is approximately 1.7 times greater for the steep arch than for the shallow arch.

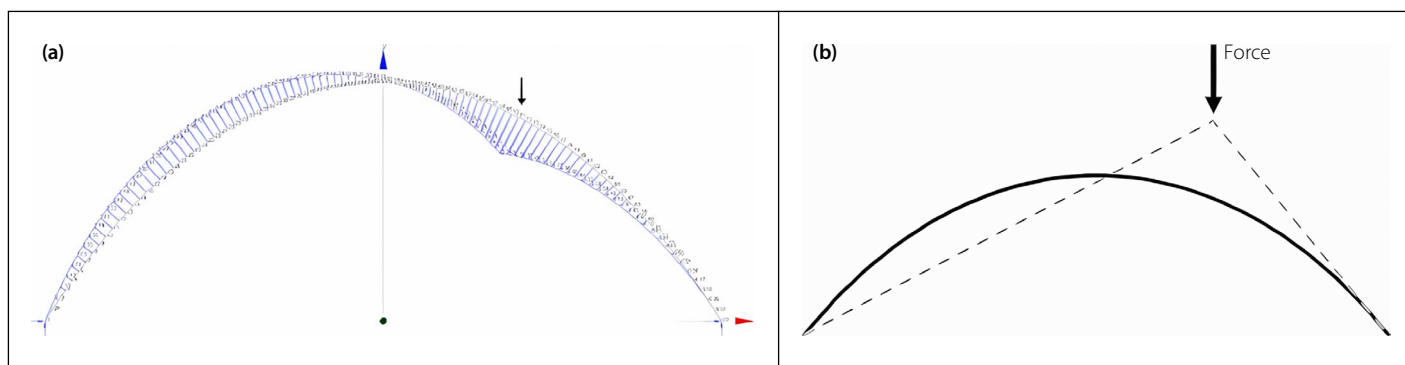


Figure 21 The position of maximum bending moments (a) for the two-hinge shallow arch under eccentric loading agrees with the locations of maximum deviation between the arch geometry and the theoretical thrust lines (b)

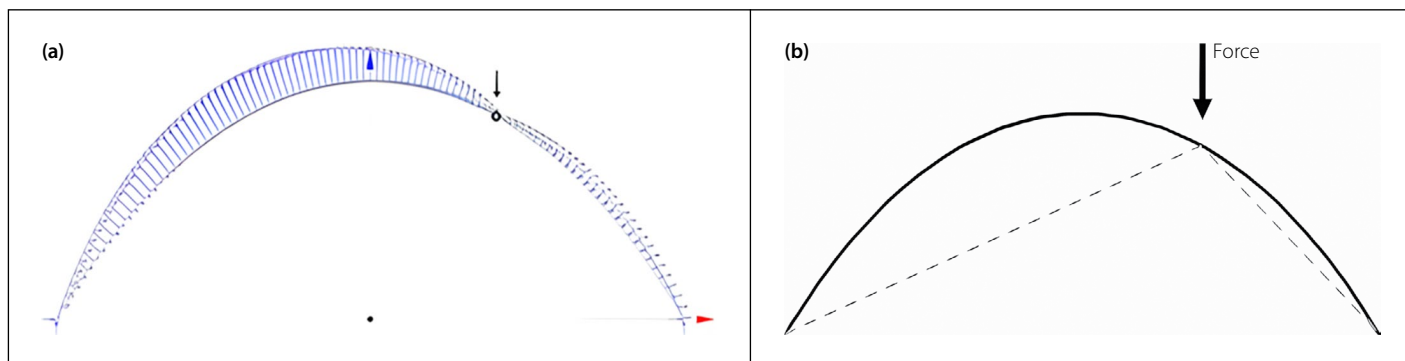


Figure 22 The position of maximum bending moments (a) for the three-hinge shallow arch under eccentric loading agrees with the locations of maximum deviation between the arch geometry and the theoretical thrust lines (b)

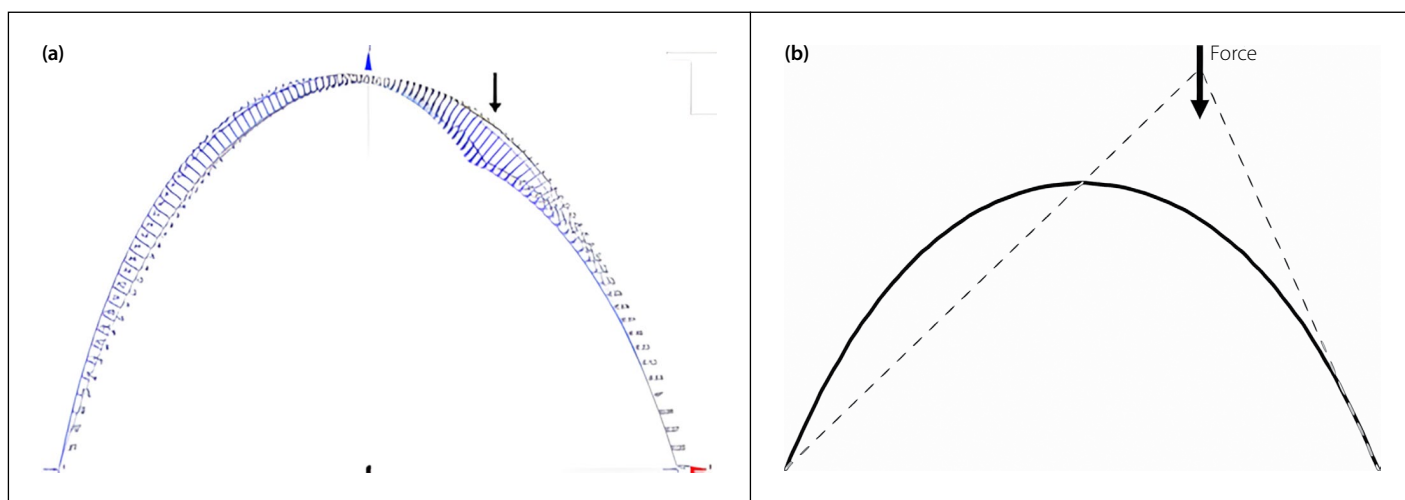


Figure 23 The position of maximum bending moments (a) for the two-hinge steep arch under eccentric loading agrees with the locations of maximum deviation between the arch geometry and the theoretical thrust lines (b)

This, together with a lower axial compressive force identified from linear elastic analyses at this position, suggests that the steep arch should experience substantially more flexural tensile stress under the same level of eccentrically applied load than the shallow arch. This prediction was not observed experimentally, where a pure hinge did not form at the point of applied load. Similar to concentrated loads applied to the apex of the arches, the simple linear elastic analyses appear to accurately identify the locations of hinge formation, even after first (partial) hinge formation (see Table 5 for a

Table 5 Comparison of the location of hinge formation under eccentric loading measured horizontally from the apex

	From flexural cracks observed from experimental tests	From maximum deviation from thrust line	From maximum bending moment in numerical analyses
Steep arch First hinge	175 mm	200 mm	200 mm
Steep arch Subsequent hinge	130 mm	190 mm	170-180 mm
Shallow arch First hinge	175 mm	200 mm	200 mm
Shallow arch Subsequent hinge	200 mm	170 mm	170-190 mm

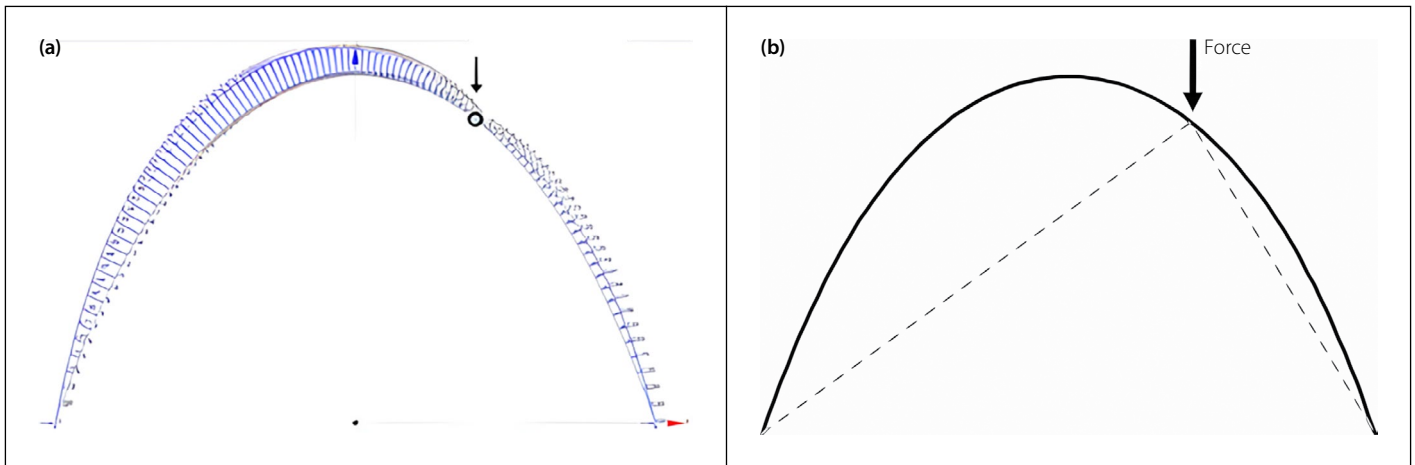


Figure 24 The position of maximum bending moments (a) for the three-hinge steep arch under eccentric loading agrees with the locations of maximum deviation between the arch geometry and the theoretical thrust lines (b)

comparison of hinge locations), but not the ultimate capacity in this nonlinear regime.

Comparison of load position and arch geometry

A comparison of the ultimate capacities of the four arches (steep and shallow arches, with loads applied at the apex and eccentrically) should ideally account for the likely spread of results, especially since the response extends into a nonlinear regime. Since only one arch of each configuration was tested, an approximate range of values was estimated based on the coefficient of variation observed in material property tests (Table 2). Assuming a coefficient of variation of 0.20 to approximately match tensile strength material property tests, the standard deviation, and subsequent upper and lower bounds of a likely 95% confidence interval around observed values were calculated. Results are compared in Figure 25.

A comparison of results highlights that eccentric loading reduces the ultimate load-carrying capacity. This agrees with the general understanding of arch behaviour that greater deviation between arch geometry and theoretical thrust lines results in greater flexural effects. Experimental studies reported in the literature seem to support this observation. Liu *et al* (2025) have shown that arches subjected to asymmetric loading exhibit significantly lower ultimate capacity than under symmetric loading, due to increased bending and cracking near the load location.

Where a concentrated load is applied to the apex of the arches, the shallow arch resists a greater ultimate load. This is likely due to the greater horizontal thrust that counters flexural tensile stresses. Results reported elsewhere have shown that the optimal arch form under point loads tends

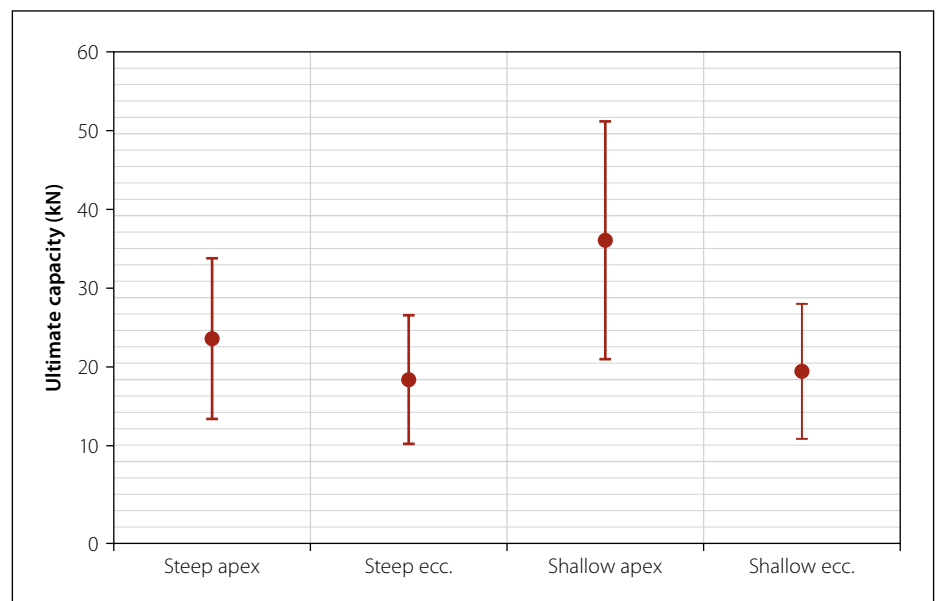


Figure 25 Ultimate capacity against applied load for the shallow and steep arches with loads applied at the apex and eccentrically. Error bars indicate the likely upper and lower bounds of the 95% confidence interval

toward shallower geometries as loading increases, reflecting the beneficial effects of greater horizontal thrust to counter flexural tensile stress (e.g. Zhang *et al* 2024). The difference in ultimate capacity, however, seems to be less when loads are applied eccentrically, where resulting flexural stresses increase.

CONCLUSIONS

The study investigated the response of catenary arches with different span-to-depth aspect ratios (0.35 and 0.60) to concentrated loads at the arch apex and at a distance from it. Two different arch span-to-depth ratios were considered and produced using a steel fibre reinforced concrete mixture. Experimental observations of hinge location and the maximum force that the arches resisted were compared with simple

linear elastic analyses, as well as with the extent of vertical deviation between arch geometries and theoretical thrust lines.

Results highlight that catenary arches can resist greater ultimate concentrated loads when applied at the apex than when applied eccentrically. Nevertheless, experimental results in this study suggest that steep arches might be less sensitive to such eccentric loads than shallower arches.

Simple linear elastic analyses appear well-suited to identify locations where successive hinges will form, even beyond elastic limits. The maximum load that catenary arches can resist under concentrated loads is, however, poorly estimated. This might be due to residual flexural stiffness in hinge regions, resulting in non-linear response. It is hypothesised here that simple linear elastic analyses may be more accurate when catenary arches are produced from materials

with lower rotational stiffness at hinge locations. Future investigations should verify this. Moreover, future studies should consider larger sample sizes to better capture variation in structural resistance.

Although simple linear elastic analyses seem well-suited for identifying hinge formation, results highlight the accuracy of simple geometric calculations that account for the extent of vertical deviation between arch geometries and theoretical thrust lines. From a practical design perspective, the results suggest that arch geometries derived solely from self-weight catenary form may not perform optimally where concentrated loads govern. Shallow arches appear more sensitive to eccentric loading and may therefore require greater structural depth or additional reinforcement to resist resulting bending effects. Simple linear elastic analyses can provide a useful first estimate of hinge locations by comparing theoretical thrust-line deviations, though they should not be relied upon to estimate ultimate load capacity.

Although it is hypothesised that the location of hinge formation should also be similar for thinner arch sections (albeit at lower loads), future studies should verify this experimentally.

DATA AVAILABILITY

The results that were analysed in this study can be made available upon reasonable request.

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APPENDIX

Derivation of the constant thrust in a catenary arch

The total vertical force over an arch at a distance x : $V(x) = w \cdot x$

$$\tan \theta = \frac{V}{H} = \frac{dy}{dx} = \frac{w}{H} \cdot x$$

$$\frac{d^2y}{dx^2} = \frac{w}{H} = \text{const.}$$

From the geometry of a catenary arch described in Equation 1, it follows that:

$$\frac{dy}{dx} = \sinh\left(\frac{x}{a}\right)$$

$$\frac{d^2y}{dx^2} = \frac{1}{a} \cdot \cosh\left(\frac{x}{a}\right)$$

Since the theoretical thrust is constant, consider the position where $x = 0$:

$$\frac{d^2y}{dx^2} = \frac{1}{a} = \frac{w}{H}$$

$$\therefore H = w \cdot a$$

Derivation of axial force in a catenary arch

From the geometry of a catenary arch described in Equation 1, it follows that:

$$\frac{dy}{dx} = \sinh\left(\frac{x}{a}\right) = \tan \theta$$

$$\cos \theta = \frac{1}{\sqrt{1 + \tan^2 \theta}} = \frac{1}{\sqrt{1 + \sinh^2\left(\frac{x}{a}\right)}}$$

At any given location along the arch geometry:

$$N = \frac{H}{\cos \theta} = H \cdot \sqrt{1 + \sinh^2\left(\frac{x}{a}\right)}$$



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Revised simplex method: An alternative solver to the out-of-kilter method for water balance model decision support system

S M Ngoepe, P O Oviroh, T C Jen, G Nyland, G de Jager

Water resource decision support systems are used to support the management of water resource planning networks and catchments. For years, the out-of-kilter algorithm has been the only solver used in the Water Resource Yield Model. The out-of-kilter algorithm can solve a wide range of network problems, including transportation, assignment, shortest path, and caterer problems. However, the Water Balance Model decision support system introduced the revised simplex algorithm, which was used for comparison. The revised simplex algorithm is well suited to large, sparse problems and is widely regarded as fast and robust in practice. This research seeks to revive, explore, and improve the understanding of the decision support system by evaluating the revised simplex algorithm as an alternative to the out-of-kilter algorithm for solving water resource catchment networks. The findings indicate that the out-of-kilter algorithm focuses solely on supply costs, whereas the revised simplex algorithm considers both supply and sink nodes, resulting in improved yield and reduced supply costs. Furthermore, the revised simplex algorithm prioritises satisfying demand from the lowest-cost available sources and avoids using the pumping channel if water can be sourced from elsewhere.

Keywords: out-of-kilter algorithm, revised simplex algorithm, Water Balance Model Decision Support System, Water Resource Yield Model, water resource catchment management planning

INTRODUCTION

Water resource decision support systems (DSS) have been used to improve the management of water resource planning networks and catchments. The development of the Water Balance Model (WBM) DSS, along with an alternative algorithm for existing catchments across South Africa, the Southern African Development Community, and potentially globally, offers an effective solution to current technological limitations. Additionally, the Water Resource Yield Model (WRYM) DSS is used to calculate the volume of water that should be stored or made available to satisfy a specified demand with a designated level of reliability for water catchment systems (Brown *et al* 2015, Coleman 2007, Coleman & Pitman 2008, de Jager *et al* 2004, Jeleni *et al* 2011, Nkwonta *et al* 2017, Nyland & de Jager 2023). The WRYM DSS has a long history

of development and application in water resource catchment studies, building on the WBM DSS, and has been improved to reflect the latest advancements of the Industrial Revolution. This is the same technology that has led to the creation of DSSs such as WRYM DSS and many others used in the water resources industry. The revolution of the 1760s was called the First Industrial Revolution, followed by the Second Industrial Revolution around the 1840s. The 1950s introduced the Third Industrial Revolution to the world and the beginning of the WRYM DSS. This third phase served as a stepping stone to the Fourth Industrial Revolution or Industry 4.0, also known as the 4IR.

The characteristics of technology integration from the Third to the Fourth Industrial Revolutions are blurring the lines between the physical, digital, and biological

Ngoepe S M, Oviroh P O, Jen T C, Nyland G, de Jager G. Revised simplex method: An alternative solver to the out-of-kilter method for water balance model decision support system. J. S. Afr. Inst. Civ. Eng. 2026;68(3), Art. #1907, 12 pages. <http://dx.doi.org/10.17159/2309-8775/2026/v68n3a2>

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realms, presenting both new possibilities and challenges (Datta 2023, Lee *et al* 2018, Sarni *et al* 2018, Schwab 2018, Xu *et al* 2018). The 4IR has significantly impacted the development of WBM DSS technology and policy, as key factors such as artificial intelligence, cloud computing, and the Internet of Things are driving the current team's progress. Among the many innovations from the 4IR, cloud technology offers connectivity, big data, and remarkable computing power. Additionally, advanced engineering provides options for 3D viewing, printing, or renewable energy.

In programming, languages are used to write, analyse, and express algorithms. These algorithms serve as blueprints specifying how a computer should perform specific tasks. Programming languages act as the tools for creating these instructions in a format that computers can understand and execute. Different algorithms are implemented across various water resource DSSs for different purposes, including Lagrangian, out-of-kilter, Monte Carlo, linear programming, interior point methods, and genetic algorithms. The WBM DSS uses the out-of-kilter algorithm, adopted from the WRYM DSS, and includes an alternative revised simplex algorithm, while MODSIM employs the Lagrangian algorithm and incorporates the simplex algorithm. The Water Evaluation and Planning tool uses the primal-dual simplex method, and Mike Basin implements the genetic algorithm (De Carvalho *et al* 2009, Comley 1996, Doulgeris *et al* 2015, Fulkerson 1961, Graham & Butts 2005, Labadie 2006, Nel & Haarhoff 1996, Nyland & de Jager 2023, Vanderbei 2020).

The WBM DSS serves as a long-term planning tool, enabling users to analyse water resources using custom scenarios. Its primary aim is to balance water supply and demand using a water balance method within any selected catchment or group of catchments (Galántai 2021, Nelder & Mead 1965, Nyland & de Jager 2023, Syifa *et al* 2023).

A common method for addressing these issues is the out-of-kilter algorithm, specifically designed to solve the minimum-cost flow problem. It works alongside the primal-dual algorithm, relying on linear programming principles. The main benefit of the out-of-kilter algorithm is its ability to find a circulation within the network that maintains water flow at each reservoir, ensuring that the flow in each channel or river stays within specified maximum and minimum limits while minimising the total cost across the network (Bailes 1989,

Brown 2023a, Brown 2023b, Dantzig 1990, Nelder & Mead 1965, Protsenko 2023, Syifa *et al* 2023, Tejera-Martínez *et al* 2020, Vanderbei 2014).

During the 1970s, two main algorithms for linear network optimisation gained popularity: the simplex method and its variants, and the primal-dual method, along with the out-of-kilter algorithm which is closely related. The 1980s saw the emergence of additional techniques, such as the relaxation and auction algorithms. The relaxation algorithm resembles unconstrained nonlinear optimisation and often outperforms both the simplex and primal methods in many linear programming tasks. Conversely, the auction algorithm utilises principles of complementary slackness and scaling.

The complexity of a water resource network, combined with computational analysis and the use of the out-of-kilter algorithm, made it a more practical algorithm for WRYM DSS compared to the traditional linear programming algorithm (Dantzig 1990, Fulkerson 1961, Nelder & Mead 1965).

As an alternative to the out-of-kilter algorithm, the WBM DSS offers a second option: the revised simplex algorithm, which is based on the simplex algorithm. The simplex algorithm is based on the idea of gradually moving towards one of the nodes or points on the catchment network diagram (Dantzig 1990, Nyland & de Jager 2023). When water flows from one node to another, it encounters the boundary defined by the linear programming constraints. At this boundary, each node represents an extreme point where the simplex algorithm adjusts the non-basic variables flowing to the next node until the optimal solution is reached (Dantzig 1990, Galántai 2021, Nelder & Mead 1965, Sánchez 2006).

When solving a linear programming problem with a digital computer, the simplex algorithm requires storing the entire table in memory. In contrast, the revised simplex algorithm is more memory-efficient because it only computes and stores data needed for the current step to test or improve the solution. The revised simplex algorithm aims to avoid the need to compute the complete dictionary after each pivot. Instead, it focuses on tracking specific information, such as the current basis, and uses matrix formulas to calculate the necessary parts of the dictionary (Arsham 1997, Chivers & Sleightholme 2006, Dantzig 1990, Nelder & Mead 1965, Tejera-Martínez *et al* 2020). There are two

options for the revised simplex algorithm (Al-Mhanna *et al* 2023, Arsham 1997, Dantzig 1990, Galántai 2021, Nadler 1973, Nelder & Mead 1965, Syifa *et al* 2023):

1. The initial algorithm monitors only the current basis variables and solution, performing all computations with the inverse of the basis, which supplies a unique choice rule. By adding slack variables, an identity matrix is formed. This method ensures convergence and typically incurs minimal additional computational cost.
2. The second algorithm uses the standard simplex method, with a small adjustment to handle artificial variables. Instead of the usual two-phase approach, it is adapted to include the artificial variables necessary to create an identity matrix. During each cycle, the coefficients associated with the simplex variables are updated via straightforward recursion relations.

The website was written in PHP, uses an open-source relational management system (RMBMS) named My Structured Query Language (MySQL) database, and is deployed on a LAMP (Linux, Apache, MySQL, and PHP) stack. A LAMP stack is an open-source software stack used to build and deploy web-based decision support systems, with four components: the operating system (CentOS Linux version 8.0), the web server (Apache version 2.4), the database (MySQL version 8.0), and a programming language (PHP version 7.4). SQL is a programming language used to create, modify, and extract data from relational databases, as well as to control user access to the database (Hargreaves *et al* 2008, Mahachandra *et al* 2018, Martinovic *et al* 2012, Microsoft Windows 7 Administrator's Reference 2011, Windows Vista 2005, Tiensivu 2008).

Web communication has been broadly defined as the sharing of information among individuals or groups using interconnected computers and technology-based devices. Communication between the website and the WBM DSS is achieved through the hypertext transfer protocol (HTTP) call. HTTP is the foundation of data exchange on the World Wide Web, enabling seamless communication between clients (like web browsers) and servers (Bourhis *et al* 2020, Brahmia *et al* 2022, Chavarriaga *et al* 2023, Chua Hock-Chuan 2016, Dolnak & Litvik 2017, Frisbie 2023, Nyland & de Jager 2023). It functions as a request-response protocol in which DSS users submit data requests to a server, which then returns the requested

data. Users can configure each study within the model.

Data exchange enables the creation of a more efficient, optimised web-based DSS, with input data formatted in the structured JavaScript Object Notation (JSON) format. When the user accesses the uniform resource locator (URL) or web address of a webpage or file in a browser, a complete communication sequence is initiated between the browser and the server hosting the website. JSON is a lightweight data-interchange format used to transmit data in a web-based DSS, making it easy for humans to read and write (Bourhis *et al* 2020, Brahmia *et al* 2022, Chavarriaga *et al* 2023, Frisbie 2023, Nyland & de Jager 2023). The output data, referred to as export data, is formatted in JSON. The Internet Information Services (IIS) on the DSS server processes the request and forwards it to the PHP script. This script creates a COM object instance and passes the input JSON directly to it without parsing or interpreting it. The DSS receives and parses the JSON, then performs the simulation. After completing the simulation, the model organises the results into a JSON structure and returns it to the PHP script. The script then sends this data back to the website, which unpacks the simulation data from the JSON structure and stores it in the database (Bourhis *et al* 2020, Brahmia *et al* 2022).

METHODOLOGY

Research methods generally fall into two categories: quantitative and qualitative. Quantitative research focuses on numerical data and statistical analysis, whereas qualitative research emphasises words and interpretive meanings. Both are vital for gaining comprehensive knowledge. Typical quantitative techniques include experiments, numerical observations, and surveys with closed-ended questions. Conversely, qualitative methods often involve open-ended interviews, descriptive observations, and literature reviews that explore concepts and theories (Lakshman *et al* 2000, Takona 2024).

Qualitative and quantitative research methods can be used either sequentially or simultaneously within a single study. In a sequential approach, if a study produces unclear quantitative results, the same group can be engaged to provide explanations, which can then inform the development of an instrument to test those reasons. The methodology for the quantitative study is based on a positivist

philosophy that aims to observe an objective reality existing independently of the observer. Quantitative data is considered reliable and reproducible, consisting of factual 'hard' data rather than subjective 'soft' data. Researchers typically use statistically validated tools, aiming for results that are objective, generalisable, and reproducible (Lakshman *et al* 2000, Takona 2024). In the case of a reservoir, this involves data related to water inflow, storage, and distribution. The reservoir serves various users with different water needs, all of which are critical. The main challenge is prioritising these needs, as DSSs analyse data to produce detailed reports and projections, unlike simpler tools that only gather data.

The WBM DSS uses advanced mathematical methods, linear programming algorithms, and programming languages to simulate the dynamics of water resource systems (Fulkerson 1961, Minty 1961, Pegram *et al* 2013). It features a sophisticated yet easy-to-use web-based graphical interface with menu-driven editors for inputting and editing data, displaying simulation results through tables and plots, and offering export options. Additional capabilities allow users to create reservoir and river system schematics by connecting components and selecting options online (Fulkerson 1961, Minty 1961, Pegram *et al* 2013).

The WBM DSS has been developed using the latest programming language technology, and its executable is written in C++ (Delphi 2020, Galanis 2018). The programming language that is used to perform the compilation is Delphi version 10.3, with the Windows Server 2019 operating system, and the Microsoft Internet Information Server (MIIS) used for deployment and to host the website requests (Microsoft Windows 7 Administrator's Reference 2011, Windows Vista 2005, Romashkov 2017, Tiensivu 2008). The hypertext preprocessor (PHP) version is installed and used on Apache on Linux to invoke the COM server, and the use of the virtual cloud server with specific central processing unit (CPU), random access memory (RAM), and hard drive space (Haris & Hasim 2019, Laaziri *et al* 2019, Sotnik *et al* 2023). PHP stands for "personal home page". The MIIS is the web server software that is flexible, secure, and manageable for hosting anything on the website (Microsoft Windows 7 Administrator's Reference 2011, Tiensivu 2008).

The WBM DSS uses the out-of-kilter algorithm along with a second alternative algorithm within the revised simplex

algorithm for its online web solution. The out-of-kilter algorithm, introduced in the early 1960s by Minty and Fulkerson, was designed to solve network flow problems applicable to both physical and non-physical systems (Comley 1996, Fulkerson 1961, Minty 1961). The programming algorithm is considered a distinct linear programming method that has been effectively used to solve various water resource problems, including the Texas Water Plan in the United States of America (Sigvaldson 1976).

The revised simplex algorithm improved on the traditional simplex algorithm version by updating only the active columns at each step, which is particularly beneficial for numerical columns. Additionally, users don't need complete knowledge of all variables in a matrix to decide on the pivot or to identify the next basis. This means that knowing the current value of the objective function at each step isn't necessary, and the effort required to solve the objective mostly depends on the number of constraints rather than the number of variables (Ord 1972).

The out-of-kilter algorithm was selected instead of the simplex algorithm because it effectively distributes flows within a network to lower the overall flow costs (Dantzig 1990, Galántai 2021, Nadler 1973, Nelder & Mead 1965, Syifa *et al* 2023). Table 1 compares and summarises the two algorithms.

Given the numerous factors at play, it is unlikely that one algorithm will always outperform others in every practical situation. Instead, each algorithm performs best when suited to the right kind of problem. Consequently, the planner must understand the traits of different algorithms – such as their convergence speed, adaptability, parallelisation potential, and suitability for problem structures – to make well-informed decisions (Arsham 1997, Dantzig 1990). When dealing with complex problems, choosing the right algorithm often requires testing multiple candidates' options.

Like most water resource DSSs, WBM DSS's main goal is to address the water allocation problem by optimising an objective function to either minimise or maximise the needs of users or demands, considering supply priorities, demand site preferences, mass balances, and other constraints (Coleman & Pitman 2008, Department of Water and Sanitation 2020, Nyland & de Jager 2023). The constraint set is updated step-by-step at each time point to systematically evaluate the demand priorities and supply preferences. Each demand site, reservoir, irrigation block, mine, and wetland is assigned a

Table 1 The comparison between the out-of-kilter and revised simplex algorithms

Algorithm	Out-of-kilter	Revised simplex
Efficiency	It effectively assigns flows in a network to minimise overall flow costs.	It is memory-efficient because it computes and stores only the data needed for the current step to test or improve the solution, and it is known as the simplex algorithm with multipliers.
Objective	To identify the optimal flow within a water resource network, the selected flow set must meet certain relationships.	This approach minimises calculations per iteration by focusing solely on the coefficients needed to identify the pivot element, rather than updating the entire tableau each time. It especially saves effort when handling numerical columns, as it avoids updating all columns at every step.
Complementary slackness	The complementary slackness optimality conditions (CSOC) theorem defines the criteria for the optimality of the out-of-kilter theory and aids in categorising arcs in the network's nodes as either "out-of-kilter" or "in-kilter". Adjustments are made to out-of-kilter arcs until an optimal solution is reached, which occurs when all arcs are classified as "in-kilter".	It is a primal cost improvement method that relies heavily on price vectors and duality concepts. In particular, the complementary slackness (CS) conditions play a crucial role in that, if a variable x is feasible and together with p satisfies these CS conditions, then variable x is considered an optimal solution of the problem, and p is an optimal solution of its dual problem
Advantage/strength	The primary strength of the out-of-kilter algorithm is its capacity to pinpoint a circulation in the network that maintains water flow at each node (reservoir). It ensures that the flow in every channel or river stays within the defined minimum and maximum limits while minimising overall network costs.	The benefit of the revised simplex algorithm over the original method is that it initially removes zero coefficients, retaining only non-zero ones. Subsequently, it stores just eight to ten significant digits for each non-zero coefficient, making most of the coefficients part of the possible matrix.
Focus	It is able to address a wider variety of network issues, such as transportation, assignment, shortest path, and caterer problems.	It effectively manages large, sparse problems and is often quick and reliable in real-world applications.

distinct priority number, from highest to lowest. Figure 1 shows the various catchment elements, each identified by a unique number. The catchment is in Mpumalanga, South Africa. Reservoirs are triangular, nodes are circles, and transfer channels are arrowed lines. Like demand priorities, supply preferences use an integer ranking system to determine which sources supply a particular demand site.

Since power generation, domestic supply, and irrigation often depend on multiple sources to satisfy their needs, an allocation mechanism is necessary to manage these multiple supply choices. The transfer for Eskom, the South African power generator, is shown in channel 509 of Figure 1. It relies on different sources, such as pumping through channel 502 and gravity channel 504 from reservoir 10 (Nooitgedacht Dam); abstraction through channel 500 from node 10 (Gemsbokhoek weir); and transfer from reservoir 26 (Vygeboom Dam) through channel 501. The transfer via channel 501 includes water from Gladdespruit weir through channel 636 to Vygeboom Dam. Additionally, the user can limit the flow through any transmission link to a maximum volume or a percentage of demand, reflecting physical limits (e.g. pipe or pump capacities), contractual limits, or preferences regarding the mixing of supplies.

A reservoir is a crucial node in the catchment network, capable of storing water over time. It is modelled using several variables tied to its physical and operational features. A reservoir is an artificial or natural

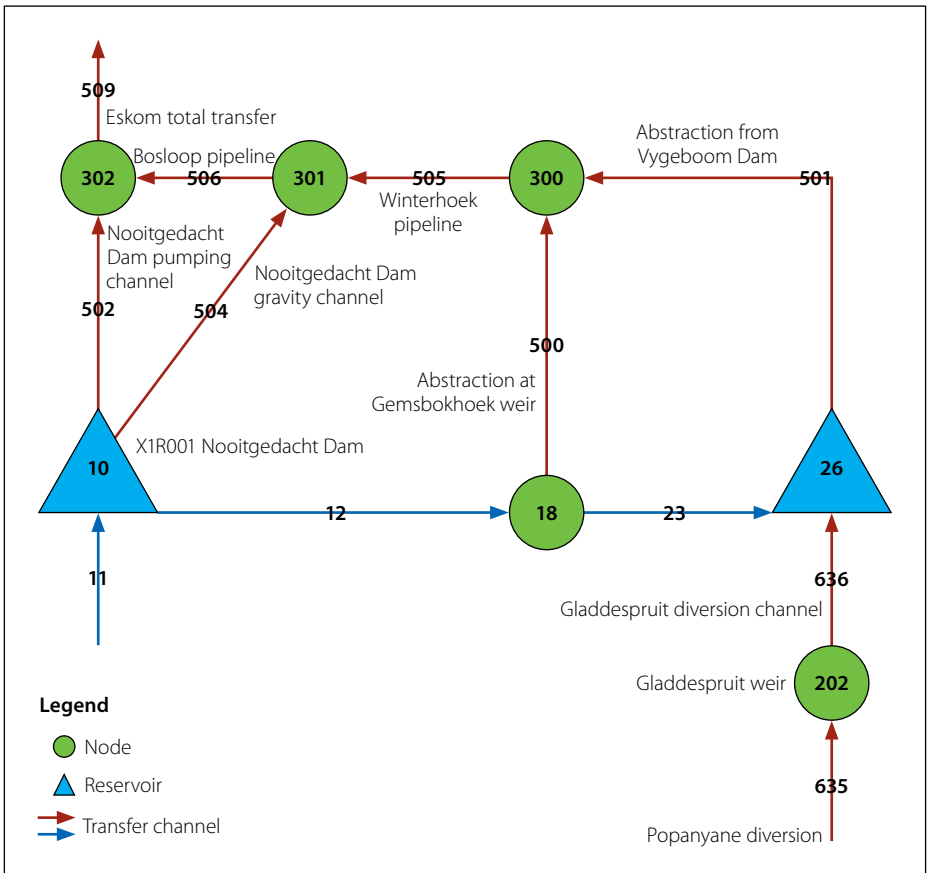


Figure 1 The water supply transfer system to Eskom channel 509

lake with a dammed outlet that stores water and regulates outflow (Manson 1998, Nagy *et al* 2002, Rugumayo & Kizza 2001, Wurbs 2005, Wurbs 2012, Wurbs *et al* 2012). The simulation of reservoir behaviour involves a straightforward calculation of the stored water volume at the end of each month. The initial storage volume at the start of the simulation is known. The storage at the

end of the first month is determined by the change in storage, which equals inflows minus outflows, as shown in Equation 1.

$$\text{Change in storage} = \text{inflows} - \text{outflows} \quad (1)$$

Once the DSS determines the reservoir storage at the end of the first month, the storage at the beginning of any subsequent month

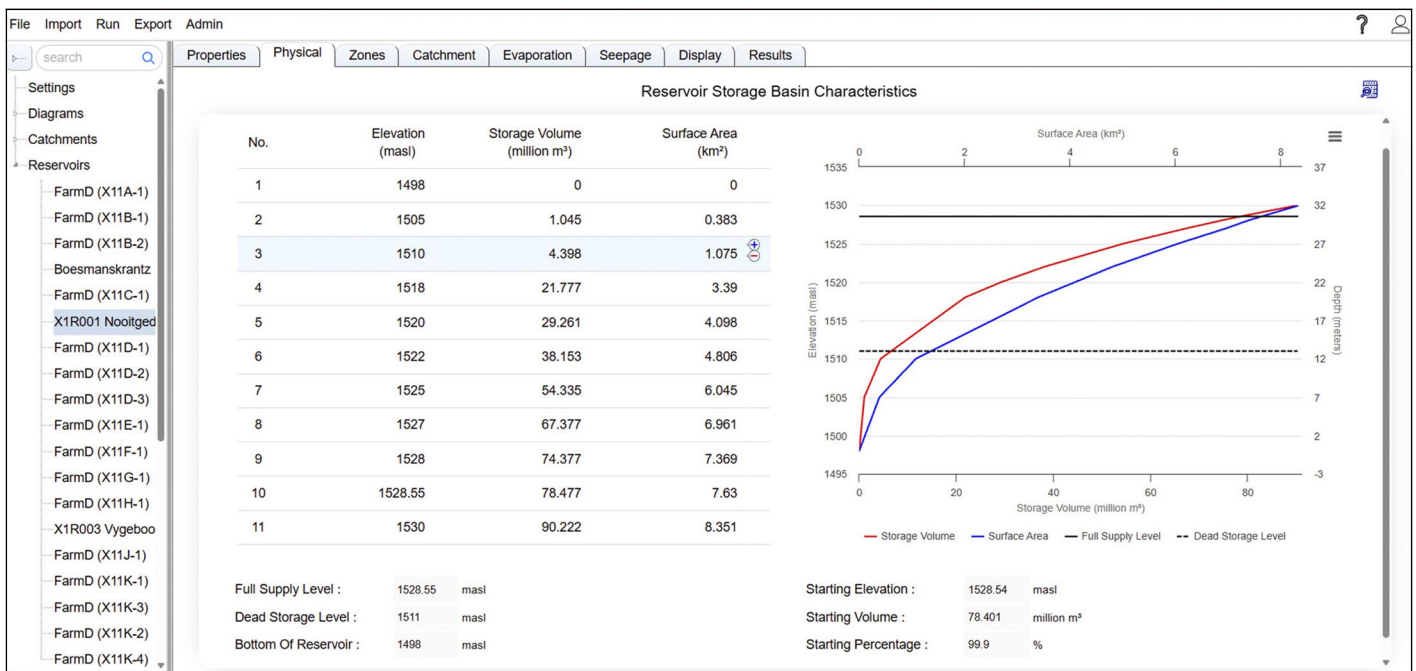


Figure 2 The Nooitgedacht Dam reservoir physical characteristics levels

is assumed to be the same as the storage at the end of the previous month (Draper *et al* 2004, Lund & Ferreira 1996, Manson 1998, Rugumayo & Kizza 2001, Wurbs 2012, Wurbs *et al* 2012). Figure 2 presents the bottom, dead, and full supply levels of the reservoir, accompanied by a table illustrating the elevation-volume-surface-area relationship and a plot of the reservoir. The example provided in Figure 2 is for Nooitgedacht Dam, located on the Komati River, 10 km away from Carolina Town in the Mpumalanga province of South Africa. The WBM DSS is flexible in terms of data editing and not reliant on a specific type of format data set to follow (Nyland & de Jager 2023).

Figure 3 shows the reservoir's catchment area, which is the land area from which water collects and flows into the reservoir. This movement of water is known as runoff. In South Africa, rainfall is the largest contributor to runoff, with snow and hail being less common. The core structure of the catchment network system is shaped by where water flows into reservoirs and other nodes within the water resources system. It is referred to as the incremental catchment for that node (Draper *et al* 2004, Hughes 1992, Lund & Ferreira 1996, Manson 1998, Nagy *et al* 2002, Rugumayo & Kizza 2001, Wurbs 2005, Wurbs 2012). The total area of each incremental catchment, measured in

square kilometres, is included in the calculations. The WBM DSS uses this variable to assess natural runoff from undisturbed parts of each catchment, accounting for areas affected by irrigation, streamflow reductions, and activities such as mining.

Each designated incremental catchment within the water resource network is linked to one or more reservoir and junction node through a reference number. This number is assigned according to the DSS-defined sequence (Beard 1967, Coleman & Pitman 2008, McKenzie & Van Rooyen 1999, Nkwonta *et al* 2017, Rugumayo & Kizza 2001). Flow volumes and water use in the catchment files are allocated to the chosen nodes using

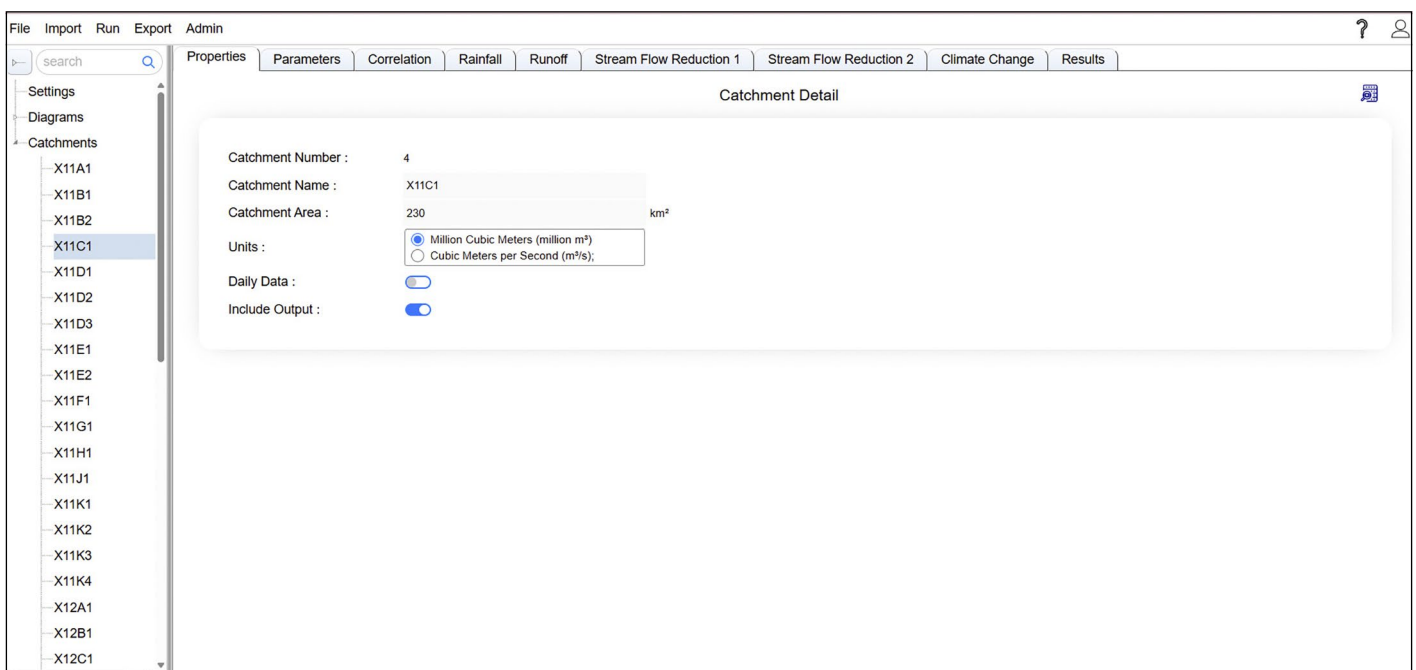


Figure 3 The WBM DSS list of catchment areas with catchment details of X11C1

scaling factors: incremental flow factor α , irrigation area factor β and afforestation area factor C . Figure 4 illustrates the different tabs that present the various values calculated using the net flow formula. The values shown are monthly, but daily values can be displayed when imported. This feature is new compared to the earlier WRYM DSS, which imported and calculated values solely from catchment hydrology data, allowing edits through the graphical user interface (GUI). The net flows entering a particular system node are then calculated using the formula in Equation 2:

$$\text{Net flow} = \alpha \times (\text{Incremental flow}) - \beta \times (\text{Irrigation area}) - C \times (\text{Afforestation area}) \quad (2)$$

The catchment area of a reservoir is accepted as the area contributing to the full supply boundary of the reservoir.

When the reservoir drops below the full supply level, an additional intermediate area becomes visible, which isn't included in natural inflow calculations. Usually, the ratio of this full supply area to the total catchment area is very small, making its runoff impact negligible. However, there are cases where runoff from this intermediate zone can be significant and must be considered. In such cases, the rainfall-runoff coefficient helps estimate the extra runoff as a percentage of rainfall. For example, if the catchment's average runoff is 10% of annual rainfall, a coefficient of 0.1 is used (Ngoepe *et al* 2025). This coefficient is key for evaluating situations in which the reservoir's total supply area accounts for a large share of its catchment.

To verify the system's network inflows, accurately defining net runoff from incremental catchments is crucial. Model results are used to compare simulated node inflows with the corresponding net runoffs from relevant catchments. While calculating net runoffs, note that DSS simulation results are in average m^3/s , whereas time-series files show data in million m^3 . Users should perform appropriate unit conversions. This process should be repeated for each inflow node, using historical model data for a specific day or month during the analysis period, as well as the overall average across the full duration. The WBM-DSS supports daily or monthly time steps, unlike the previous WRYM DSS, which was limited to monthly updates (Ngoepe *et al* 2025).

The total channel transfer allocation to Eskom is divided among various channels. The Bosloop pipeline and Nootgedacht pumping channels are the last two, as shown

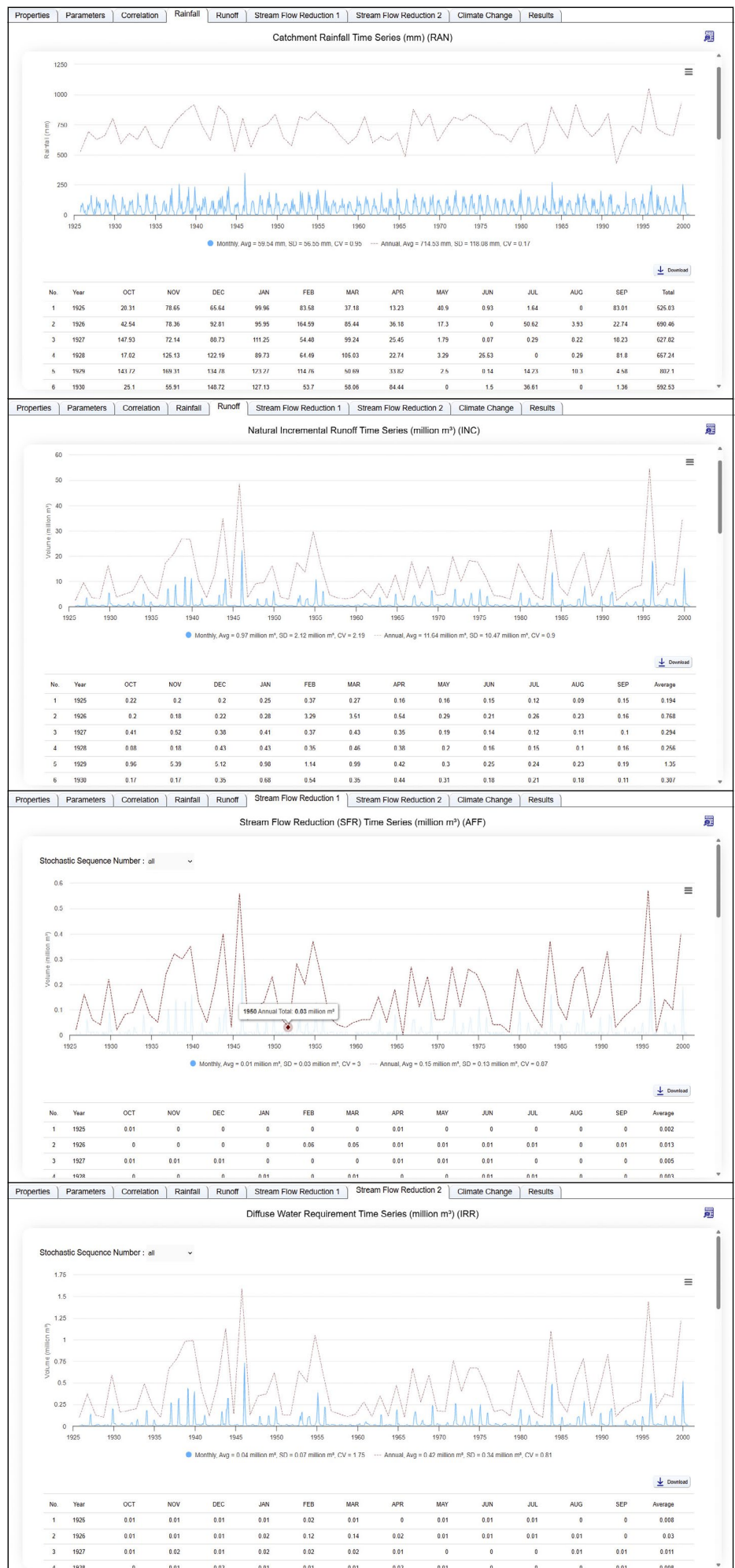


Figure 4 The WBM DSS net flow calculation values

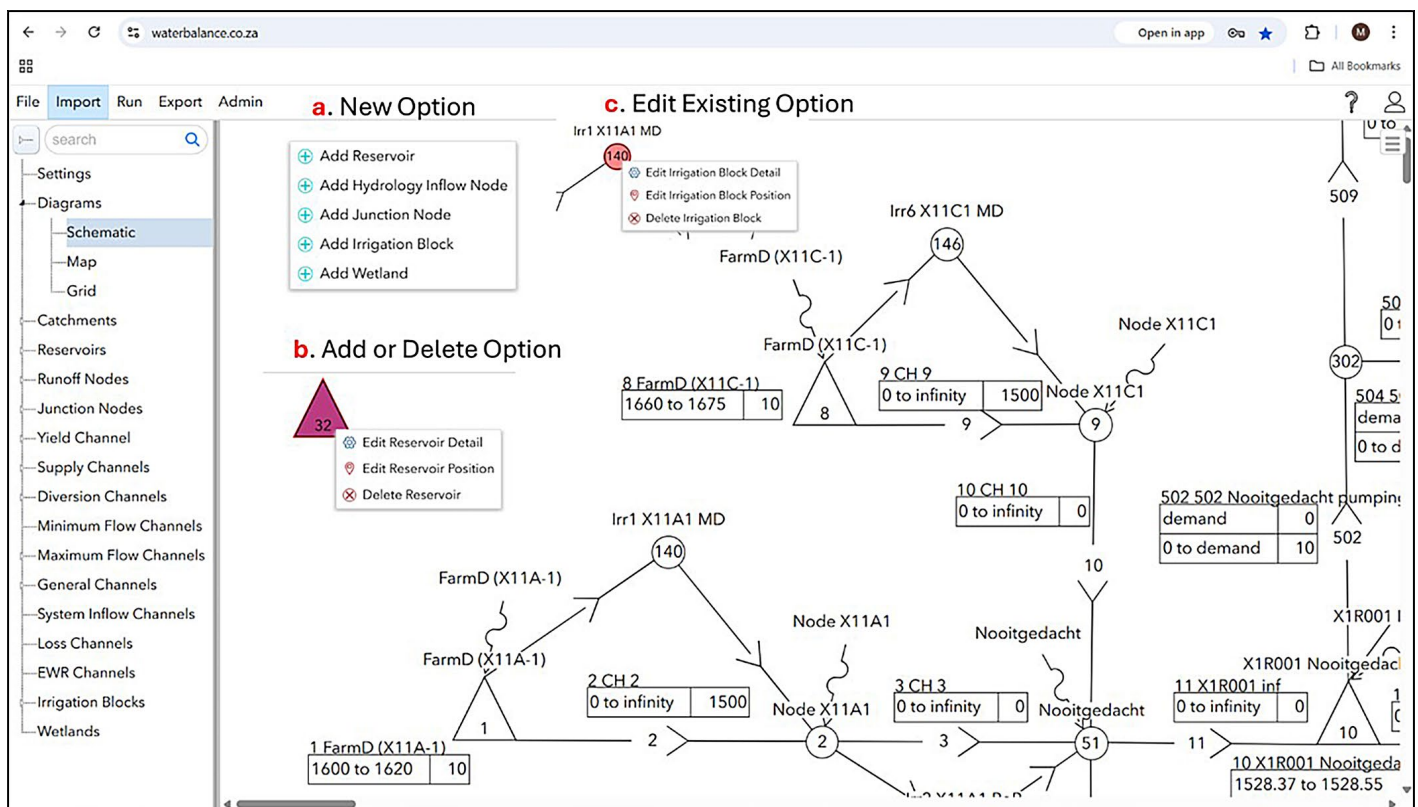


Figure 5 The WBM DSS options for editing the network element

in Figure 1. Red channels indicate transfer pathways, while blue channels denote river flows. The two algorithms allocate resources to each channel based on its maximum supply capacity. Water from Nooitgedacht Dam can be transferred either by pumping (502) or gravity (504), whereas water from Vygeboom Dam can be transferred via abstraction channel 501 including the water transfer through the Gladdespruit weir and the Popanyane pipelines. In addition to these transfers, water is occasionally pumped from the Gembokhoek weir to boost supply.

The input study data includes 17 files, each containing a different catchment dataset. These input files, in their original formats as used by WRYM DSS, can be imported into the web-based WBM DSS, or a new file can be created directly from the web service. The X11C natural historical streamflow data, measured in million cubic metres (Mm³), is listed among the files in Figures 3 and 4. It covers the period from October 1925 to September 1999, totalling 84 years. The X11C is a quaternary catchment that supplies the Nooitgedacht Dam. In addition to the input data and natural historical incremental flows, generating stochastic streamflow data via stochastic analysis is crucial when using the DSS's statistical distribution option, which requires stochastic input parameter sequences.

The user can add, edit, and delete features in the web-based DSS. The user

can click on the "Add Reservoir" option in (a), and option (b) appears as shown in Figure 5. Meanwhile, the DSS provides the option to delete or edit the existing element, as shown in option (c) of Figure 5.

The terminology related to water movement can be confusing for many, but it becomes easier to understand once you grasp the simple concept. The general rule is always to spend less and get a high or maximum return; water moves between nodes or noticeable points within a water resource catchment. Naturally, water flows from an upstream node to a downstream node through channels or rivers, or water is pumped from nodes with water to the node where it is needed via a pipeline. The upstream node is the source, meaning the point where water is sourced, and the downstream node, or the receiver, is the sink. Between the nodes, water is transported via the so-called arcs. Arcs are the rivers, pipelines, and transfer channels.

The objectives focus on the demand and supply of water at a specific cost, regardless of whether demand is fully or partially met. The algorithm considers different options, and the results are always available. The law of flow conservation is strictly applied, ensuring continuous observation of flow between source and sink, with net flow calculated as the water from the source minus the water reaching the sink. Solving water resource problems is straightforward when demand

equals supply (Ploskas *et al* 2013). However, challenging situations arise when demand exceeds supply or vice versa. Does the algorithm handle such cases? When the water supply exceeds requirements, the optimal solution shows how to distribute the surplus. Conversely, if requirements are unmet, it indicates how unmet demand is allocated among destinations. The algorithm's flow from one node to another is based on the profit gained, which must be non-negative; otherwise, no movement occurs. Limitations of the revised simplex and out-of-kilter algorithms include that objective functions and constraints are not always linear, and there is no guarantee of finding a solution. Additionally, large-scale problems may not be solvable using linear programming because their parameters are often fixed and treated as constants.

Any linear programming problem to solve depends on the data and the problem size within a certain range. Key factors include the solution time, the quality of initial solutions, the speed of sensitivity analysis, and the available computing power.

RESULTS

Graphs provide crucial information and are often an excellent way to display data behaviour, offering visual summaries. One of their main purposes is to provide the analyst with insight into the data and showcase essential concepts when explaining results (Helsel

Table 2 Nooitgedacht Dam month-end reservoir volume (mcm) 1925 to 1962

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Avg
1925	76.190	74.665	72.780	71.691	71.505	69.950	67.802	66.057	64.137	61.869	59.294	57.573	67.793
1926	55.662	54.122	52.695	51.695	67.578	78.477	78.477	77.200	75.541	74.699	72.735	70.477	67.447
1927	71.034	71.467	71.008	70.986	70.419	70.634	69.780	67.755	65.715	63.452	60.995	58.521	67.647
1928	55.881	54.526	54.359	54.187	53.669	54.086	53.440	51.610	50.039	47.982	45.547	43.922	51.604
1929	47.828	78.057	78.477	78.477	78.477	78.477	78.185	76.808	75.412	73.975	72.046	69.748	73.831
1935	62.426	59.945	57.911	56.548	57.172	56.896	55.675	55.875	55.140	53.471	51.047	48.626	55.894
1936	46.535	49.220	51.795	78.477	78.477	78.305	77.211	75.321	73.497	71.428	69.009	66.824	68.008
1937	64.655	62.636	78.477	78.477	78.477	78.095	78.477	78.211	77.454	76.148	74.594	72.523	74.852
1938	70.839	69.628	70.548	72.181	78.477	78.477	78.209	77.593	76.622	76.642	75.298	73.998	74.876
1939	73.650	78.477	78.477	78.477	78.477	77.704	77.242	76.862	78.477	78.477	76.924	76.132	77.448
1955	71.083	71.734	78.477	78.477	78.477	78.477	77.453	77.601	77.428	76.217	74.082	72.819	76.027
1956	72.598	73.105	74.071	73.636	73.816	75.141	74.735	73.001	71.692	70.353	68.577	67.577	72.359
1957	67.043	65.779	63.885	63.985	63.944	63.073	63.577	62.650	61.063	58.933	56.439	55.020	62.116
1958	53.527	53.287	53.239	53.162	53.027	51.658	49.817	47.994	46.042	43.904	41.467	39.331	48.871
1959	36.965	36.584	36.242	35.255	35.736	36.205	37.663	37.480	36.162	34.291	32.151	29.874	35.384
1960	28.139	27.961	31.362	34.363	36.596	39.733	42.336	42.710	41.989	40.590	38.585	36.918	36.774
1961	35.859	34.985	35.509	36.118	35.690	35.187	34.710	33.074	31.298	29.257	27.142	24.954	32.815
1962	23.400	41.307	59.383	58.727	56.884	55.030	53.373	51.418	50.892	50.521	48.692	46.256	49.657

& Hirsch 2002). The DSS applies the two algorithms to the data and executes. Once execution is complete, the DSS can present each algorithm's results or combine and compare the results data.

Table 2 presents the comparison results with colour coding: black, blue, and red. It shows end-of-month volume data for the Nooitgedacht Reservoir from 1925 to 1962, covering the following periods: 1925–1929, 1935–1939, 1955–1959, and 1960–1963.

Blue values indicate matching outputs from both algorithms, while red values highlight discrepancies. Reservoir volume is not the primary concern regarding the algorithms, but transfer allocation and priority introduce complexities about supply order and timing. The revised simplex algorithm has not yet been modified to align with the specific data and rules, unlike the out-of-kilter algorithm. The latter employs a benefit/disbenefit mechanism to regulate water flow between nodes,

typically from upstream to downstream, unless water is pumped out of a node.

The results in Table 2 are shown in a graph for each method. Focusing on the yellow highlight for March 1960, plots were extracted to illustrate the differences in the results. The choice of March was random, and any other month could have been selected to demonstrate the output differences. Figure 6 illustrates the results from the two algorithms (out-of-kilter and

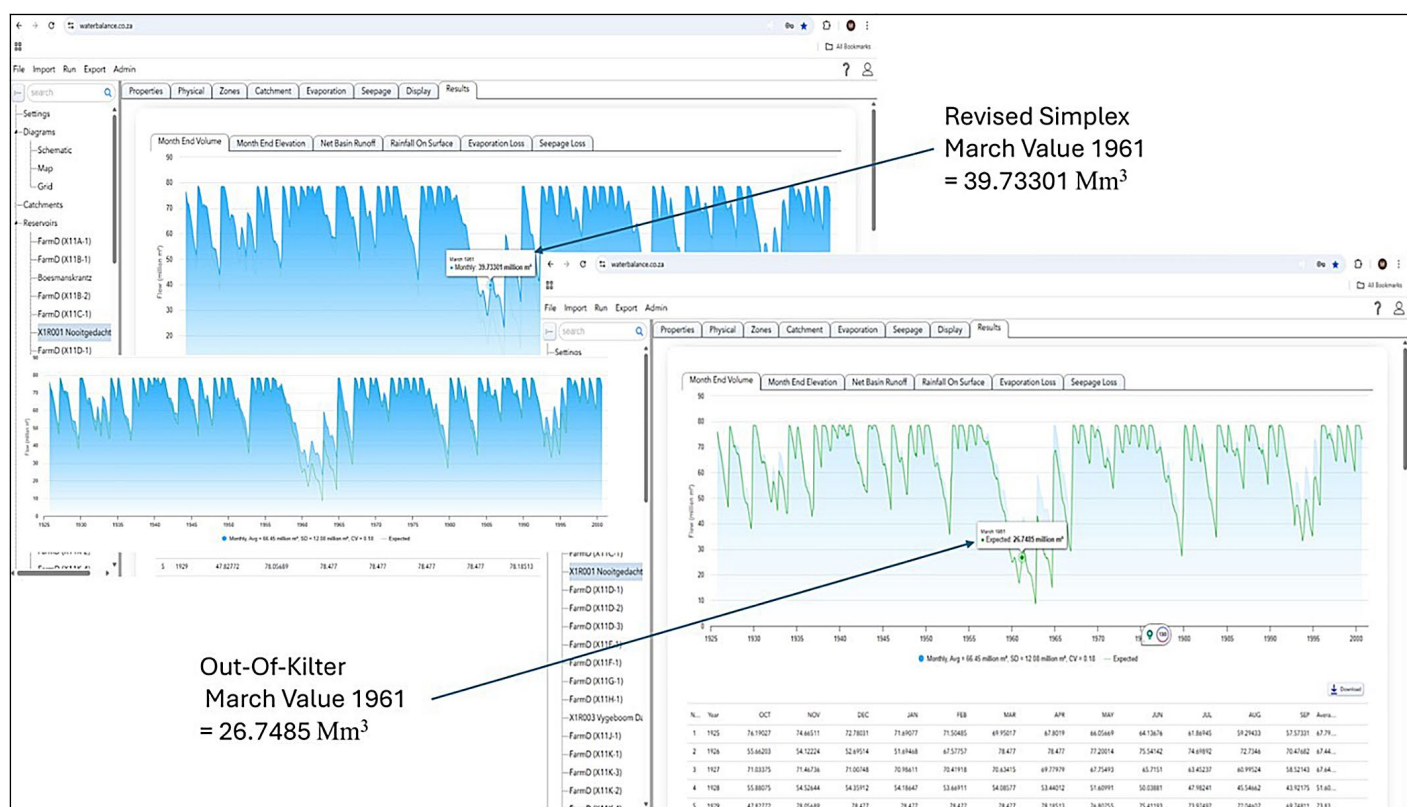


Figure 6 The reservoir results with two different algorithms. The green line is the out-of-kilter, and the blue line is the revised simplex algorithm

Table 3 Monthly reservoir volume variances for Nooitgedacht Dam: Revised simplex minus out-of-kilter algorithms, selected years (1925–1962)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1925	0.00	0.00	0.00	2.25	2.81	0.00	0.00	0.00	0.00	2.86	0.00	0.00
1926	0.00	0.00	4.30	5.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51
1927	0.00	0.00	2.38	3.13	3.20	3.20	0.00	0.00	0.00	0.00	3.16	0.00
1928	0.00	0.00	4.61	5.53	5.71	5.97	5.97	5.95	5.96	0.00	5.88	5.87
1929	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1935	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.63	3.60	0.00
1936	0.00	0.00	5.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1937	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1938	0.00	0.00	2.01	2.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1956	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.83	2.85	0.00	0.00
1957	0.00	0.00	4.29	5.33	5.61	5.60	5.61	5.61	5.61	0.00	0.00	5.54
1958	5.83	6.46	7.49	8.26	8.25	8.21	0.00	8.14	8.11	8.07	8.01	0.00
1959	8.04	8.63	9.62	10.40	10.74	10.86	10.88	10.84	10.82	10.77	10.69	10.59
1960	10.68	11.24	12.17	12.96	12.99	12.98	12.98	12.95	12.93	12.89	12.79	12.72
1961	12.93	13.61	14.55	15.30	15.33	15.29	15.25	15.15	15.06	14.95	14.83	14.66
1962	14.73	15.21	16.24	17.08	17.16	17.12	17.05	16.96	17.12	17.09	16.97	16.83

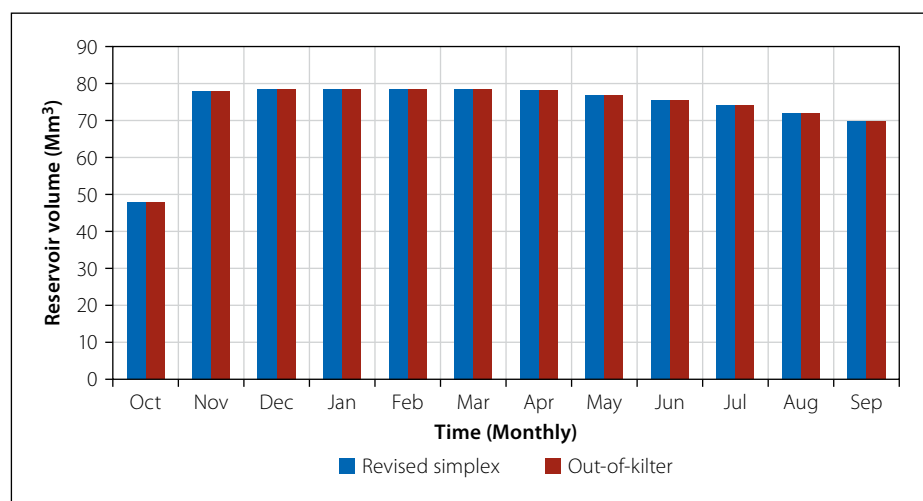


Figure 7 Reservoir volume results comparison for the revised simplex algorithms for the hydrological year 1928/9

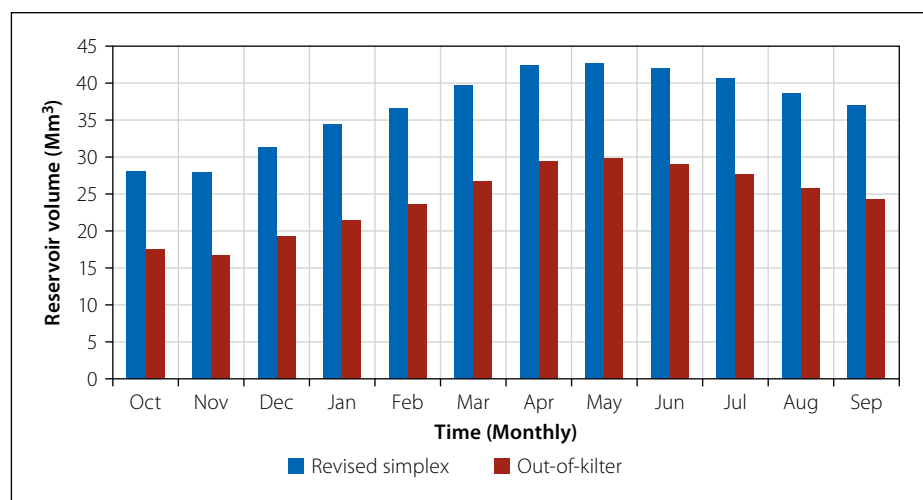


Figure 8 Reservoir volume results comparison for the revised simplex algorithms for the hydrological year 1959/60

revised simplex) for March 1961, specifically noting values 26.7485 and 39.73301 Mm³. In some cases, the monthly values are similar, whereas in others, they differ (Ngoepe 2016, Pegram *et al* 2016). The green line graph represents the out-of-kilter algorithm, while the blue line graph displays the monthly values for the revised simplex algorithm.

The revised simplex algorithm results show that, in some months, the algorithm has a higher reservoir volume than the out-of-kilter algorithm in the same month, or, in some instances, for the entire hydrological year, i.e. the 1957/8 to 1962/63 years, as displayed in Table 3. The results in Tables 2 and 3 are supported by Figure 7, which shows similar results for both algorithms in the hydrological year 1928/29. Figure 8 shows the differences for the full hydrological year 1959/60 and Figure 9 shows fewer differences during the hydrological year 1924/5.

The results from the channels align with the reservoir outcomes shown in Figure 6. Figure 10 displays the results, with the green line representing the out-of-kilter algorithm and the blue line illustrating the revised simplex algorithm. Figure 10 provides an example of the Gladdespruit canal from the study data.

The findings indicate that the developed DSS will enable water resource planners to make efficient, strategic decisions based on comprehensive information. It relies not

only on algorithms but also on effective visualisation of catchment system networks. Moreover, the results allow users to select from a range of linear programming algorithms tailored to specific catchments. This flexibility helps users recognise that different catchments vary in size and complexity, requiring unique algorithms for decision making. Overall, this research offers a streamlined approach for sharing and utilising big data within the user community.

CONCLUSIONS

The out-of-kilter algorithm focuses solely on supply costs, whereas the revised simplex algorithm considers both supply and sink nodes, resulting in higher yields and lower supply costs. The results in Table 2, from hydrological years 1957/8 to 1962/3, support the statement of high yield compared to its counter algorithm. To achieve this, proper penalty configurations in the revised simplex are essential to prevent default channel assumptions. Initially, the out-of-kilter algorithm uses Gaussian elimination to identify the feasible region, then proceeds similarly to the revised simplex approach along the network edges. Both algorithms can unexpectedly operate the network to produce a lower total cost, which might be numerically optimal but practically questionable; thus, comparing their results is recommended. The alternative algorithm aims to meet demand using the lowest-cost sources and avoids using the pumping channel when

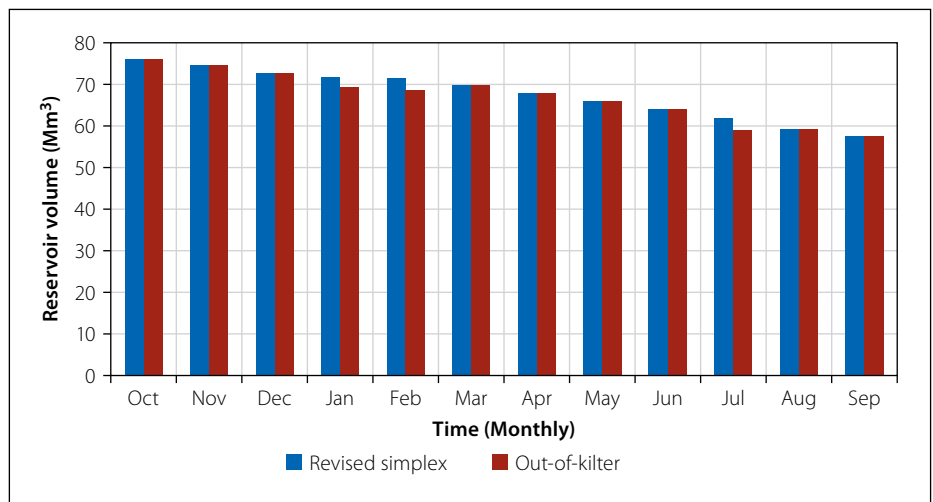


Figure 9 Reservoir volume results comparison for the revised simplex algorithms for the hydrological year 1924/5

alternative sources are available. Both algorithms can unexpectedly yield results with a lower overall cost. The out-of-kilter algorithm applies distinct penalty structures for channels and reservoirs, whereas the revised simplex algorithm uses a standard, uniform penalty.

Future research should investigate adding penalties to both algorithms to see whether a different method or algorithm produces similar or alternative results. While this possibility will be explored, the outcomes could remain unchanged or vary. The DSS was tested on a water resource system that excludes certain advanced catchment components, such as mines and wetlands, which could be incorporated. It is advisable to test the product on a system

that includes all these remaining elements to build confidence in its deployment. A DSS meant to guide management in policy-related decisions should be flexible enough to update with ongoing technological advancements.

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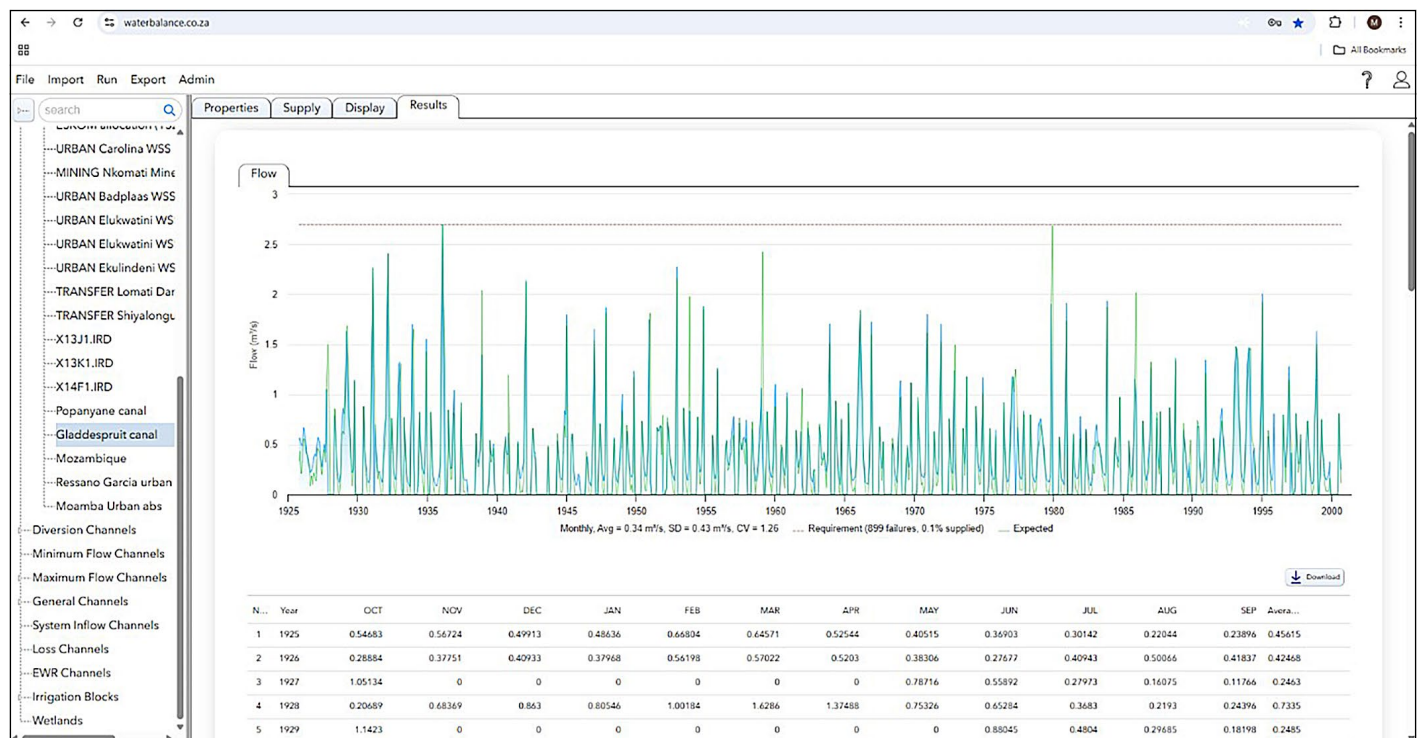


Figure 10 The channel results with two algorithms. The blue line is the out-of-kilter algorithm, and the green is the revised simplex algorithm

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Implication of reliability categories on the structural design of higher-risk buildings

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This paper reviews the impact of reliability-based design considerations for higher-risk buildings (high-rise, hospitals, critical infrastructure, etc.) in South Africa. SANS 10160-1 Annex A and B provide guidance on enhanced partial safety factors for loading, third-party design verification, and additional site supervision requirements for such structures. This work reviews the legal framework governing building design, following the hierarchy from constitution to design standards, emphasising the need for engineering judgement for non-standard and higher-risk buildings. The impact of supplementary legislation such as the Critical Infrastructure Protection Act (8 of 2019) are pointed to, highlighting the increased reliability requirements. The reliability framework in SANS 10160-1 is considered and the assumptions inherent in general building design are presented, identifying how they may not be fully representative when aspects such as post-disaster function, high loss of life, large economic loss, and similar factors must be considered. As a result, anecdotal evidence suggests that the more onerous design and supervision requirements of higher-risk structures, such as increased partial safety factors, third-party checking of structural designs, and construction supervision are not currently being carried out in South Africa, despite SANS 10160-1 proposing it as best practice. Given their ability to prevent both calculation errors and conceptual errors related to structural robustness, improved design supervision and third-party checking are proposed as critical requirements for high-risk structures.

Keywords: structural reliability, higher-risk structures, standardised structural design, design practice

INTRODUCTION

Structures need to be designed to ensure adequate safety and functionality over their intended lifespan while remaining economically viable (ISO 2015). In modern structural design, this is practically implemented through reliability-based design. A structure is designed with a target level of reliability (linked to a probability of failure) which is appropriate to its function and circumstances. The required reliability of a structure should be dependent on a balance between the potential consequences if the structure fails and the cost of increasing safety required to mitigate or avoid failures (JCSS 2001). High-risk structures, which have more dire consequences in the case of failure, require increased levels of reliability, whereas the converse is true for structures where there is little risk or where the consequences of failure are insignificant.

However, when costs to increase safety or mitigate risks become disproportionately high in comparison to the benefit gained from them, lower levels of reliability may be warranted, subject to an absolute minimum required for human safety (Caspeele *et al* 2013, Pandey *et al* 2025). Reliability is practically implemented in structural design and materials codes, but often requires engineering judgement, and especially so in the case of higher-risk structures or those which are innovative or unusual.

In South Africa, structural design codes (e.g. SANS 10160) are not mandated as law, but are rather a way of practically implementing the law through a rational design by a competent person (Retief & Dunaïski 2009), defined as a “registered professional” within the Identification of Engineering Work Regulations (IDoEW). The legal framework for building design in

South Africa initiates with essential human rights of a safe environment within the Constitution (Act 108 of 1996) and extends down through the National Building Regulations and Building Standards Act (103 of 1977). The building regulations are supplemented by other legal documents such as the Critical Infrastructure Protection Act (8 of 2019) (previously the National Key Points Act) and the Engineering Professions Act (114 of 1990), among others. The building regulations are generally functional in nature, setting out qualitative statements about what is required of a building or building element without specifying exact methods, dimensions, or materials. The technical details for the application of the building regulations are then given in SANS 10400, on a deemed-to-satisfy basis. Most typically in South Africa, the rational design of a building structure is performed under a registered professional which, in conjunction with structural design and materials codes, provides a building that should perform at least equivalently to one that complies with the requirements of the relevant parts of SANS 10400.

Reliability in structural design codes is implemented using a framework that accounts for multiple factors, including the design approach, level of supervision, uncertainties in loads and resistance, material properties, geometry, robustness, redundancy, and construction quality. In South Africa, the SANS 10160 suite of codes provides the foundation for structural design, incorporating these aspects. Reliability is semi-implicitly addressed in the codes through the use of characteristic values for material strengths and loads, and more explicitly through partial safety factors for load and resistance. Ensuring adequate reliability also depends on appropriate levels of design and construction supervision, as well as the implementation of specific risk-mitigation measures. For structures with moderate consequences of failure, these considerations can typically be addressed within standard design and supervision practices. For higher-risk structures, however, appropriately adjusted reliability-based design and increased supervision levels are required, frequently requiring greater engineering judgment.

As the design of higher-risk structures is not commonplace, habitual practice may be adopted without consideration of the amendments or additions required for higher-risk structures. Additionally, guidance on identifying higher-risk structures and

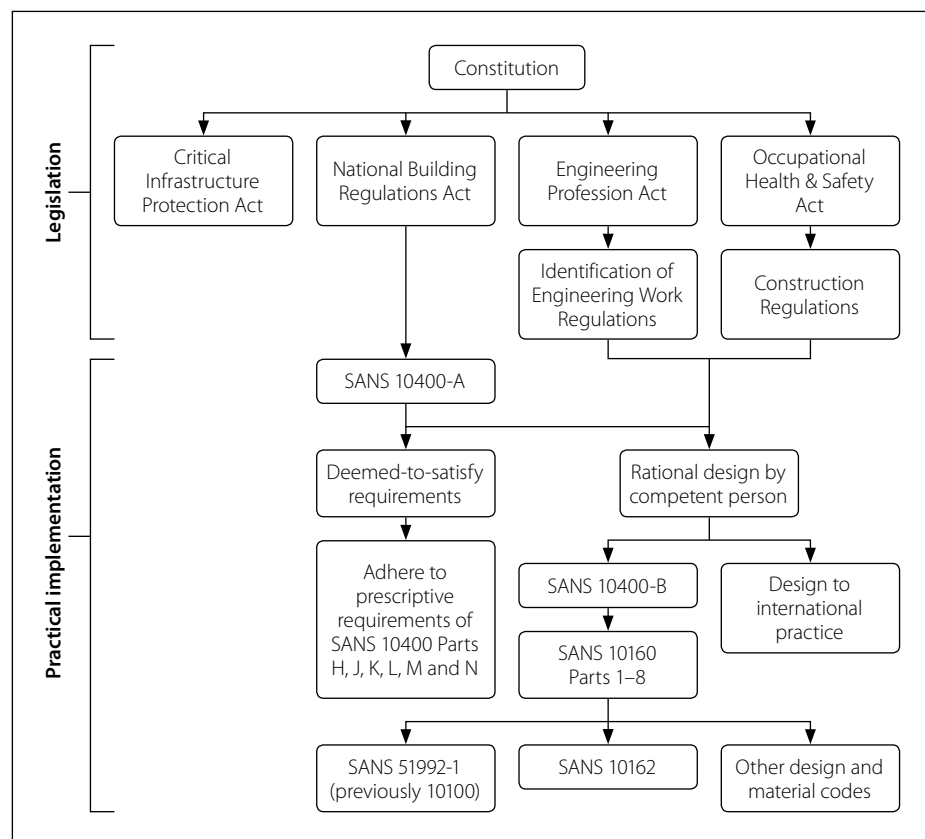


Figure 1 Legal hierarchy of building design in South Africa

the design philosophy/processes for them is placed in informative annexes of regulations and codes in South Africa, which are not frequently consulted as a result. The de-regulation of structural design fees and subsequent discounting required to secure design work in the country further complicates this (Okonkwo & Wium 2018, Van Zijl 2024). The additional time and resources required to properly consider higher-risk structures, and even to do due diligence for “normal” structures is simply in short supply. In a survey conducted in South Africa by Okonkwo and Wium (2018), nearly half of the design consultants who responded indicated that they had offered discounts of up to 27%, and another third up to 60%, of the ECSA-approved fee scales to secure work. Additionally, nearly fifty fatalities and scores more injuries have occurred in the recent catastrophic collapse of the buildings in Ormonde, Johannesburg (2026), Redcliffe, Durban (2025) and Dormehls Drift, George (2024). While two of these buildings would have been on the border between “normal” and higher-risk structures, their collapses have resulted in much discussion in the media regarding the need for regulation and safety in structural engineering. With this as context, in the experience of the authors it appears that higher-risk structures in South Africa are either not being identified as such or are

being designed and constructed using standard practice for “normal” structures.

This paper therefore aims to investigate the implications regarding the design of higher-risk building structures in relation to existing policy, create an awareness of the need for higher levels of reliability, and guide how it may be practically implemented. Through considering the legal framework in South Africa, classifying higher-risk building structures, and illustrating how reliability can be increased through design codes and practice, the paper aims to prompt designers and clients to reflect on whether higher-risk structures in South Africa are currently being designed and constructed with due diligence.

LEGAL FRAMEWORK FOR BUILDING DESIGN IN SOUTH AFRICA

This section considers the legal framework within South Africa, illustrated in Figure 1, and the extent to which it highlights the need for engineering judgement in design. At the highest level, the fundamental right to a safe and sustainable environment comes from Section 24 of the Constitution, which states that, “Everyone has the right to an environment that is not harmful to their health or well-being”. This is carried through to Section 17 of the National

Building Regulations and Standards Act (NBR), which authorises the making of regulations with respect to the “strength and stability of buildings” and “to provide for... precautionary measures against fires or other emergencies”, among others. The practical application of the national building regulations is detailed in SANS 10400.

SANS 10400-A indicates two ways of satisfying the NBR, in addition to adhering to the prescriptive regulations in the relevant parts of SANS 10400. All functional regulations need to be satisfied either by adopting building solutions that comply with the deemed-to-satisfy criteria in the relevant parts of SANS 10400, or by engaging a competent person (under the Engineering Profession Act 46 of 2000) to prepare a rational design for a building structure that will at least satisfy the relevant parts of SANS 10400. Typically, the latter route is followed, satisfying the relevant parts of SANS 10400 by following SANS 10400-B and other relevant SANS codes (10160, 51992-1-1, 10162, etc.).

The philosophy behind SANS 10400, as the application of the NBR, is to set out requirements for the design and construction of buildings that provide a safe and healthy environment in the simplest and most economical way possible. That is, it aims to set performance requirements without being overly prescriptive in how they are implemented. As such, it states in the introduction to SANS 10400-A that “designers and building owners should be aware that the mere fact that a building complies with the National Building Regulations does not necessarily indicate that it is a desirable building”. This is one of the first indications that engineering judgement is required even at an overarching level of design. Rational designs follow this in that best practice should be used to propose a design solution appropriate to the function of the building structure and the needs of the client, naturally

requiring engineering judgement. Applying only the mandatory parts of a structural design code does not automatically fulfil a designer’s obligation of providing a satisfactory structural solution. This is especially true in the case of higher-risk structures, or structures that are innovative or unfamiliar in relation to the experience of the project team. Further allusions to, and illustrations of the need for, engineering judgement are given in the following section. Ultimately, however, Section A2 of SANS 10400-A states that it is the responsibility of the owner to appoint, and maintain the appointment of, competent persons for the rational design work to be undertaken. Furthermore, the client should ensure that best practice is followed.

RELIABILITY IMPLEMENTATION IN STRUCTURAL DESIGN

This section details the implementation of reliability within structural design. Commentary on how reliability principles are to be amended for higher-risk structures is presented in the following sections. A reliability framework within structural design aims to ensure that structures fulfil their specified requirements throughout their working life with an acceptable level of reliability (ISO 2015, JCSS 2001). In South Africa, the basis of this reliability framework stems from SANS 10160-1, which addresses the requirement for controlling risks to structural safety in SANS 10400-A Appendix B.9. SANS 10160 follows a limit states design format and is based on the first generation of Eurocodes. The target level of reliability, as a balance between structural safety and economy, forms the basis of structural design and is structure-dependent. SANS 10160-1 indicates that the choice of target reliability for a structure is dependent on:

- The possible cause or mode of failure for a limit state

- The consequences of failure
- Public aversion to failure
- The costs of increasing safety (or mitigate risks).

Target reliability is expressed through the reliability index (β), which is inversely related to a probability of failure (p_f) over a specified period of time, i.e. as the reliability increases, the probability of failure decreases. Appendix A in SANS 10160-1 gives minimum ultimate limit state (ULS) β values for a design life of 50 years as a function of the consequences of failure, reproduced here as Table 1. Table 1 shows that typical structures (in Reliability Class (RC) 2) should be designed to have a target reliability of $\beta_t = 3.0$, which equates to a probability of failure, p_f approximately equal to 1 in 1 000 in a 50-year return period (not considering human error). The reliability class descriptions come directly from the Eurocode (EN 1990), except class RC4, which is an additional higher-risk class typically for post-disaster structures, similar to that in the American ASCE 7-16 code (ASCE 2017). The values of β_t in Table 1 are based on back-calibration to existing practice in South Africa (Kemp *et al* 1987) and are slightly lower than those in EN 1990. Table 1 indicates that increasing consequences of failure warrant increasing target reliability levels. Despite the given examples, the qualitative descriptions for the type of structures in each class are not highly specific in assisting designers when identifying the appropriate class.

In limit states design codes, target reliability is achieved through the use of a framework of both “quantitative” and “qualitative” measures, as discussed in the following sections.

Quantitative reliability implementation

Target levels of reliability are quantitatively achieved in codes primarily through the use of partial safety factors (PSFs), typically

Table 1 Reliability class descriptions and associated 50-year target reliability (β_t) and probability of failure (p_f) for ULS from SANS 10160-1

Reliability class	Consequences of failure/function of facility	Examples	Minimum β_t (p_f)
RC 1	Low for loss of human life, economic, social or small for environmental consequences	Agricultural buildings with infrequent human occupancy (e.g. storage buildings, greenhouses)	2.5 ($\approx 5 \times 10^{-3}$)
RC 2	Moderate for loss of human life, economic, social or considerable for environmental consequences	Residential and office buildings, public buildings where consequences of failure are moderate (e.g. office buildings)	3.0 ($\approx 1 \times 10^{-3}$)
RC 3	High for loss of human life, or extremely high for economic, social or environmental consequences	Grandstands, public buildings where consequences of failure are high (e.g. concert halls)	3.5 ($\approx 1 \times 10^{-4}$)
RC 4	Post-disaster function or consequences beyond the boundaries of the facility	Hospitals, communication centres, fire and rescue services	4.0 ($\approx 3 \times 10^{-5}$)

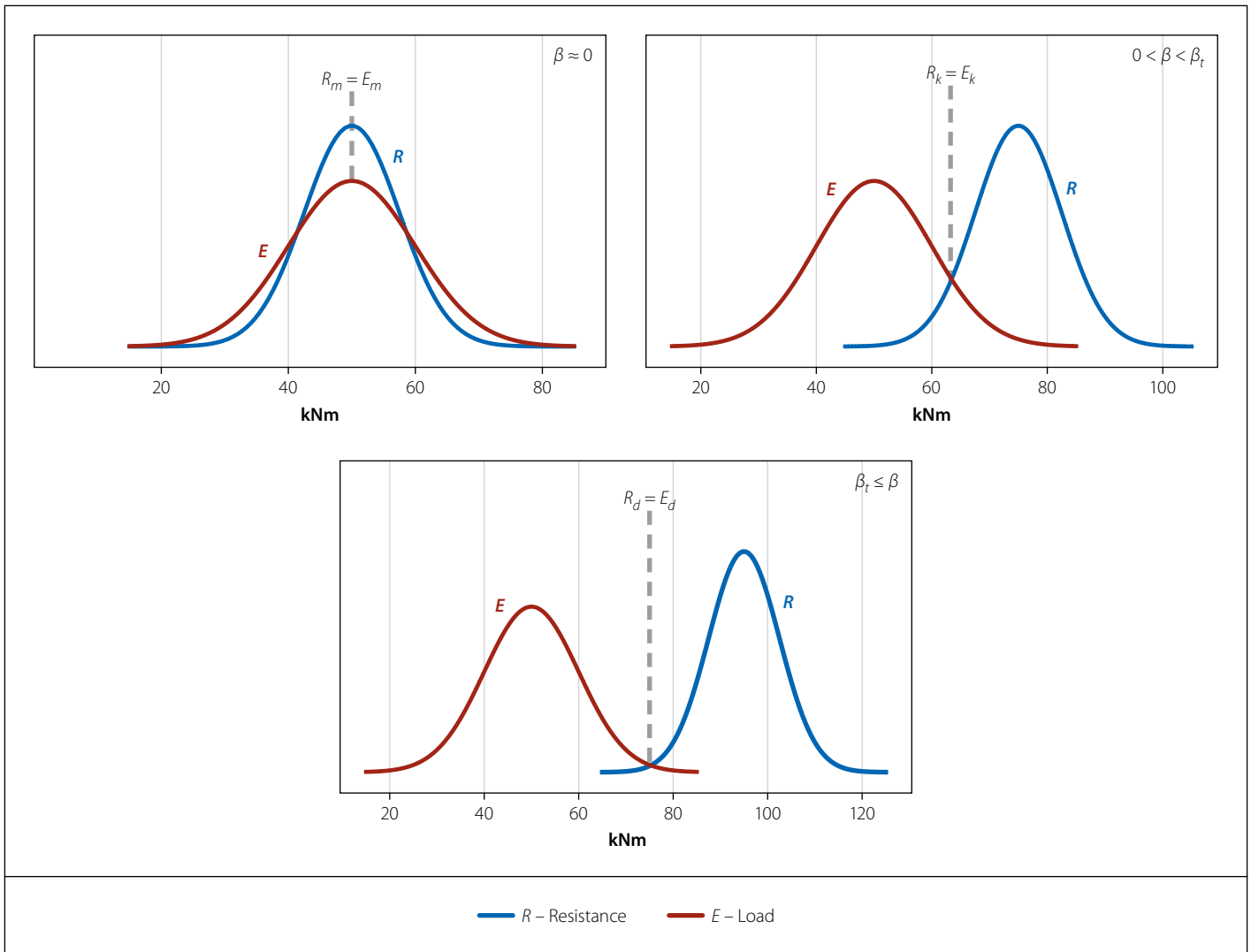


Figure 2 Effects of characteristic values (R_k, E_k) and subsequently partial factors to achieve design values (R_d, E_d) to increase reliability for the bending strength of an RC beam

with symbol γ_i , (e.g. 1.2 and 1.6 for permanent and imposed loads, and 1.15 for reinforcing steel strength, respectively) and the use of characteristic values of load and resistance, F_k and X_k , respectively. The use of PSFs and characteristic values intentionally increase the load (E) and decrease the resistance (R) in design so that when design parameters are calculated (e.g. area of tension reinforcement), they provide more capacity than is actually required to resist the average load. This is graphically illustrated in Figure 2, for the example of the bending resistance of a reinforced concrete (RC) beam, where the area of tension reinforcement increases the resistance. In reality, load and resistance vary due to inherent uncertainty, and are therefore represented as distributions in Figure 2. The reliability index, β , can be understood as a measure of the “overlap” between E and R , and the variation in each. The less overlap between E and R , the higher the reliability, and vice versa; interested readers may refer to Holický (2009) for a more technical

definition. In the top left of Figure 2, the load (applied bending moment) and resistance (bending moment resistance) are shown for the highly dangerous case where the average resistance (R_m) is determined based on the average load (E_m). The top right shows how the reliability is increased (overlap reduced) by using characteristic values within the resistance (R_k) and load (E_k). The bottom shows how the additional use of partial safety factors further separate the resistance and load to their design values, R_d and E_d , respectively, to provide at least the target level of reliability.

For limit states design, the design resistance, R_d , must be greater than the design load (or action effect), E_d , for all considered limit states, as shown in Equation 1 (SANS 10160-1) and expanded in Equation 2, where ψ is a combination factor for accompanying variable loads. In limit state design codes, the load, resistance, and associated PSFs are typically treated independently of one another from a reliability perspective, with each contributing a set proportion

of reliability towards the total target reliability.

$$E_d < R_d \quad (1)$$

$$E(\sum \gamma_f \psi F_k) \leq R \left(\sum \frac{X_k}{\gamma_m} \right) \quad (2)$$

Partial safety factors

PSFs are used to increase and decrease the characteristic load and resistance, respectively, as shown in Equation 3. The PSFs account for uncertainties in load and material resistance achieving their characteristic values, and also for model uncertainties in their prediction. The PSFs in SANS 10160 were adopted from SABS 0160, the precursor to SANS 10160, following an extensive reliability calibration by Kemp *et al* (1998) and Ter Haar *et al* (2001). When used in conjunction with the characteristic loads and resistances, the combination of the PSFs for load and resistance were shown to achieve a minimum value of $\beta = 3.0$ in 50 years. These were further found to be

satisfactory by Retief & Dunaiski (2009) when adopted for SANS 10160. The PSFs for materials (e.g. γ_c for concrete and γ_s for steel) are generally developed within each material code, and are carried through to the relevant part of SANS 10160, 10162, 51992-1-1, etc.

$$F_d = \gamma_f F_k \quad X_d = \frac{X_k}{\gamma_m} \quad (3)$$

Characteristic values of load and resistance

Characteristic values are statistically defined values of load or resistance used to account for variability and uncertainty within the load or material. For material strengths, this is the value below which fewer than 5% of test results are expected to fall (e.g. characteristic concrete compressive stress). For loads, the characteristic value is that which is rarely exceeded. For variable loads which fluctuate notably with time (e.g. variable live load in an office), this is typically taken as the 98th percentile for a reference period of 1 year. For permanent loads, where there is little or no variability with time, the characteristic value is taken as the mean value.

Qualitative reliability implementation

In addition to the quantitative elements within a design code, there are also elements that contribute to the target reliability in a qualitative sense. That is, the quality control of design and construction supervision and robustness requirements

need to be commensurate to that given to the quantitative aspects of design.

Robustness and structural integrity

Largely catalysed by the Ronan Point building collapse in the UK in the late 1960s, the design of modern structures needs to consider how to mitigate the risk of accidental actions that may cause disproportionate or progressive collapse (Pearson & Delatte 2005). This is typically provided for by ensuring that structures have sufficient robustness to withstand a degree of local collapse due to unspecified accidental actions. This requires a system that ensures that parts of the structure remain connected after local failure events, often in the form of horizontal and/or vertical ties. Robustness requirements are given as a function of consequence or risk classes. SANS 10160-1 recommends general strategies for robustness in Sections 4.4, 7.4.2, and Annex B which are summarised here in Table 2 (see full details in SANS 10160-1).

Structures in higher consequence classes require greater degrees of robustness to counteract the risk of increased consequences of failure. Notably from Table 2, which stems from EN 1991-1-7, even for medium risk structures (class CC2), which make up a large proportion of structures, there is a basic requirement for horizontal ties and anchorage of floors to columns or walls as a means of creating continuity to limit disproportionate damage from accidental loads. For structures in

class CC3, disproportionate collapse needs to be explicitly considered through either more extended tie-requirements than for RC2 or, alternatively, a notional-removal strategy can be adopted. If excessive damage is likely to occur if a supporting member fails, then the element should be designed as a key element, able to resist the likely accidental loads that might occur. The code recommends a full systematic risk assessment instead for class CC4 structures, making reference to risk assessment principles in EN 1991-1-7, but does not specify how such an assessment should be performed.

Supervision in design and construction

The second notable “qualitative” attribute contributing to the reliability framework is the consideration of design and construction supervision. The minimum recommended requirements are presented in Annex A of SANS 10160-1, summarised here in Table 3. For design, this encompasses the internal quality control process of design within an organisation, and that required for independent design checking, depending on the reliability level of the structure. This relates particularly to the checking of design assumptions, calculations, drawings, and specifications. Similarly, higher levels of reliability necessitate a greater degree of construction supervision, which may be a combination of a greater frequency of inspection, more stringent tolerances, and/or using independent inspectors/those with greater expertise.

Table 2 Robustness strategy as a function of consequence class, from SANS 10160-1 Table B1

Consequence class	Description ^a	Robustness measure for accidental actions
CC1	Low risk: Single occupancy residential buildings ≤ 3 storeys, agricultural buildings, buildings where people rarely enter.	Other than following materials-based design standards, no other requirements.
CC2	Medium risk: Residential, apartment, hotel and office buildings ≤ 4 storeys, industrial buildings ≤ 3 storeys, retail buildings ≤ 3 storeys with max floor area of 1 000 m ² per storey, educational buildings ≤ 2 storeys, public gathering buildings with max floor area of 2 000 m ² per storey ≤ 2 storeys.	Effective horizontal ties or effective anchorage of suspended floors to walls/columns in frame buildings. Grid-like, cellular form of construction to provide interlocking of components and mechanical anchorage of floors to walls in load-bearing wall construction.
CC3	High-risk: Residential, apartment, hotel, office buildings ≤ 14 storeys, hospitals ≤ 3 storeys, stadia with < 5 000 spectators, public gathering buildings with max floor area of 5 000 m ² per storey.	Disproportionate collapse upon notional removal of supporting elements must be considered through either: ■ Implementing requirements for CC2 together with vertical ties in all supporting columns and walls, or ■ Systematic notional removal of a supporting column, beam, or wall section in each storey to ensure building remains stable and local damage is less than minimum of (100 m ² , or 15% of floor area) ^b in two adjacent storeys. If limit exceeded, design member as key element.
CC4	Very high-risk: All buildings exceeding the limits of CC3, all buildings where significant numbers of the public are admitted.	Systematic risk assessment required, considering foreseeable and unforeseeable hazards (see e.g. EN 1991-1-7).

^a Note: Descriptions are shortened for the sake of brevity

^b Recommended value

Table 3 Supervision as a function of reliability class, from SANS 10160-1 Table A.2 and A.3

Reliability class	Characteristics	Minimum recommended design supervision level	Minimum recommended construction inspection level
RC1	Basic supervision/ inspection	Self-checking	Self-inspection
RC2	Normal supervision/ inspection	Separate checking by someone within the organisation other than the original designer(s), as per internal quality control procedure	Inspection as per organisation procedures
RC3	Extended supervision/ inspection	Third party checking performed by an organisation independent from original designer(s)	Third party inspection by an independent organisation
RC4	Regulated supervision/ inspection	Regulated third party checking performed to adhere to requirements of a regulatory or supervisory authority	Regulated third party inspection performed to adhere to requirements of a regulatory or supervisory authority

CONSIDERATIONS FOR HIGHER-RISK OR UNUSUAL STRUCTURES

Most South African structures fall into reliability class RC2, and are referred to as “normal” structures here. Typical design and supervision practices employed in South Africa appear to generally be sufficient for structures within this category. Although, with the current pressures on the construction industry related to fee discounting, what used to be standard practice is potentially changing. Van Zijl (2024) highlights that the number of cases of structural failures, faults, or construction accidents reported to the Engineering Council of South Africa (ECSA) increased from 40 in 2014 to 115 in 2022. This, in conjunction with the 2024 George apartment building collapse, where there were 34 fatalities, is likely an indication that this may be happening. For higher-risk structures or those with novel materials or unusual behaviour, the more stringent requirements set out in the codes may not currently be appropriately implemented for various reasons, as already highlighted by Watermeyer and Smith (2016) and Mallin (2019). This section aims to discuss and give guidance on how to identify a higher-risk structure and to highlight the differences in design between “normal” and higher-risk structures, emphasising the heightened need for engineering judgement in design.

Classifying structures with regard to risk

Risk in structural engineering is generally concerned with the product of the consequences of structural failure (C_F), and the probability of that failure occurring (p_f), shown in Equation 4 (Høj *et al* 2025). Consequently, a reduction in either C_F or p_f lowers risk. Table 1 classifies reliability classes for structures exposed to levels of risk from low to very high,

and recommends commensurate levels of increasing reliability (which lowers p_f) to counter increasing C_F .

$$Risk = C_F \times p_f \quad (4)$$

One of the main hindrances to identifying higher-risk or unusual structures is that guidance on the definition of higher-risk structures is limited and is often placed in informative annexes in code documents that are seldom consulted as a result. Table 1 from SANS 10160-1 Appendix A gives overarching, qualitative descriptions of risk that are difficult to interpret for individual structures without the more detailed descriptions in Table 2 (SANS 10160-1 Appendix B). However, the relationship between reliability classes and consequence classes in SANS 10160-1 Appendices A and B is not clear. As Table 2 and Appendix B are focussed on the consideration of robustness requirements and are in a different annex, it is unclear whether practising professionals understand that the consequence classes relate largely to the reliability classes. In both the first- and second-generation Eurocodes (EN 1990), the reliability classes are directly related to consequence classes, and it is assumed that this was intended in

SANS 10160, given its Eurocode-basis. In the new generation of EN 1990, there is an explicit link between consequence classes, reliability classes, and the level of design and construction supervision. Combining the information in Table 1 with that in Table 2 already gives designers significantly more guidance and clarity on assigning appropriate levels of risk for structures.

Other sources provide alternative ways of evaluating the consequence/reliability class of structures. The Joint Committee on Structural Safety (JCSS) Probabilistic Model Code (JCSS 2001) gives indicative ranges for the ratio (ρ) of the consequences of failure (C_F) to the construction cost (C_0) of the structure as an alternative to the qualitative descriptions for reliability classes, as shown in Table 4. Note that the K_F value in Table 4 is described in the following section. The C_F due to ULS failure is comprised of: repair or replacement of structural damage, repair or replacement of damage to non-structural components or contents, loss of structural function, compensation for injuries or fatalities, psychological damage, and legal costs. As an illustration from Table 4, the total failure costs for normal structures in class RC2 would indicatively be within a range of 2 to 5 times the construction cost, as a

Table 4 Alternative means by which to classify structures with regard to risk

Class	Description	$\rho^a = C_F/C_0$	Number exposed to risk ^b	Expected fatalities ^c	K_F
RC1	Low risk	$\rho \leq 2$	$N < 10$	0 – 5	0.9
RC2	Medium risk	$2 \leq \rho \leq 5$	$10 \leq N < 1\,000$	5 – 50	1.0
RC3	High risk	$5 \leq \rho \leq 10$	$1\,000 \leq N < 5\,000$	50 – 500	1.1
RC4	Very high risk	$10 < \rho$	$5\,000 < N$	500 <	1.2

^a ρ – ratio of total failure cost to construction cost from JCSS (2001)

^b Indicative number of persons at risk, from the *fib* Model Code 2020

^c Indicative number of expected fatalities, from ISO 2394

reference. The *fib* Model Code 2020 (*fib* 2024) gives another alternative by considering the number of people at risk in the case of failure (N_{risk}) for each reliability class. Guidance on approximating the number of people/m² based on the function of the structure is given in SANS 10400 Annex A.20 and A.21. Similarly, ISO 2394 (ISO 2015) proposes an indicative range of casualties in the case of ULS failure as a means by which to differentiate between reliability class.

In addition to the qualitative guidance given in the combination of Table 1 and Table 2, Table 4 summarises the quantitative guidance, giving registered professionals a greater set of tools with which to identify the appropriate risk/reliability class of a structure. In some cases, it is also possible to differentiate between the reliability class required for the structure and that required for individual members/parts. If only a part of the structure has higher consequences of failure, that part may be classified as RC3 while the rest of the structure may remain RC2. Helpful commentary and further guidance on consequence classes and structure classification, including mixed-use structures, can be found in a guide by the Steel Construction Institute (Way 2011). It is worth noting that, based on the qualitative risk descriptions in Section 16 of the Critical Infrastructure Protection Act, most, if not all, structures classified as critical infrastructure (previously National Key Points) will fall into RC4.

Once a structure is identified as having a higher degree of risk (RC3 or RC4), quantitative and qualitative measures need to be put in place to reduce the risk of the increased consequences of failure. Table 1 shows that the required reliability should be increased by a value of $\beta = 0.5$ for each increase in reliability class (e.g. RC1 to RC2). It should be noted here that structures in class RC4 are recommended to have a *minimum* value of $\beta_t = 4$, however, a higher value may be appropriate for certain structures where exceptionally high risks are present (as informed by the full risk assessment), for which the recommended K_F will not be sufficient.

Quantitative measures

From a quantitative perspective, the use of the standard PSFs in SANS 10160-1 are adequate to achieve the level of reliability required for normal structures, i.e. $\beta_t = 3.0$ for RC2 (Holický *et al* 2019). For higher-risk structures, Annex A.3.2 proposes

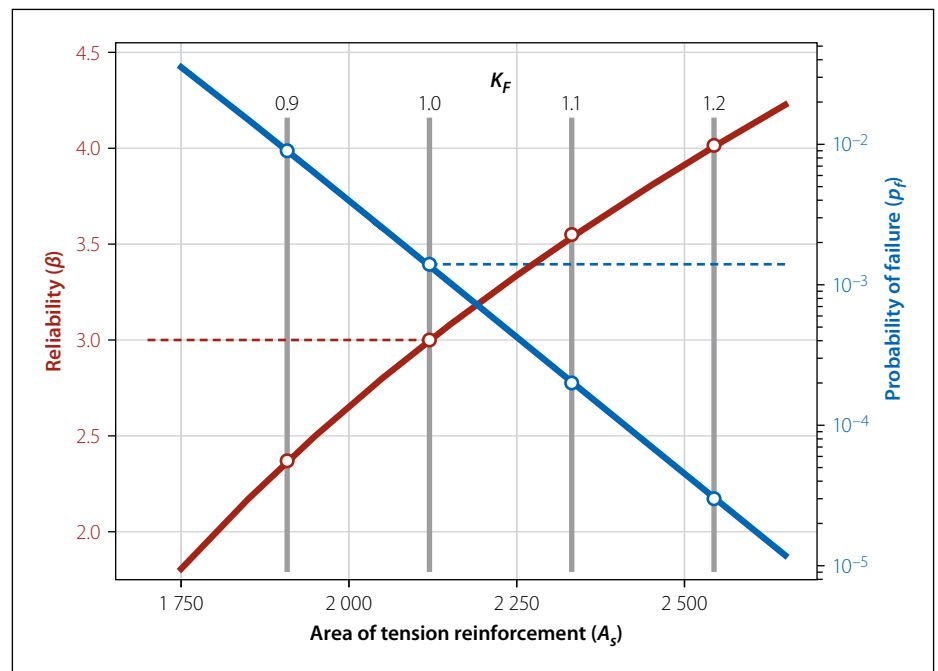


Figure 3 Multiplication factor (K_F) for load PSFs to increase reliability

increasing the PSFs for unfavourable loads (not for favourable loads or resistances) so that an appropriately higher level of reliability is achieved. This simple PSF multiplication factor, K_F is shown in Table 4 and its use is illustrated in Equation 5 and Figure 3. The familiar form of $E_d \leq R_d$ is used in Equation 5 for the (simplified) design case of a sagging bending moment applied to an RC T-beam in a building structure, where the area of tension reinforcement, A_s , is the decision parameter which most effectively increases reliability. The sagging moment has components of permanent load (M_{DL}) and variable load (M_{LL}), and the resistance is affected by the yield stress of the reinforcement (f_y) and the lever arm (z). The K_F value is used to increase permanent and imposed PSFs, γ_G and γ_Q , which subsequently increase the required value for A_s and thus the reliability. Figure 3 shows how each increase in the K_F factor increases the reliability by $\Delta\beta \approx 0.5$, shown in red (which decreases the probability of failure by roughly an order of magnitude, shown in blue), as is required for an increase for each reliability class from Table 1. Dashed lines are used to illustrate the β and p_f values for RC2. While the initial material cost increases with using higher PSFs, the increased capital cost is ultimately outweighed by the reduced probability of the failure costs being realised in future. The magnitude of this change should be appreciated in that the design loads for RC3 and RC4 structures are increased by 10% and 20%, respectively, potentially resulting in

changes to all members throughout a typical structure. However, it should be noted that the total cost of the structure is only likely to increase by a few percent, as the decision parameter usually represents a relatively small fraction of the total cost.

$$K_F (\gamma_G M_{DL} + \gamma_Q M_{LL}) \leq \frac{A_s f_y z}{\gamma_s} \quad (5)$$

Qualitative measures

Quantitative-related measures like increased PSFs are important to increase baseline reliability. However, they cannot root out the occurrence of human errors or provide robustness against unforeseen accidental loads (e.g. accidental vehicle impact, explosions) beyond designing members in a ductile fashion (Gulvanessian *et al* 2012). If the assumptions of the design philosophy are not correct or have not considered certain scenarios, increasing partial factors further will have little effect on increasing the overall reliability. In contrast, providing structural robustness and appropriate supervision in the design and construction process can identify and mitigate both quantitative errors as well as human errors in judgement. As such, commensurate quality control measures on supervision and the provision of robustness against accidental actions are arguably more important to providing appropriate levels of safety.

Robustness and structural integrity

As a safeguard against unforeseen risks and disproportionate collapse, robustness requirements should be provided

as suggested in Table 2 (SANS 10160-1 Section 7.4 and Annex B). Effective horizontal ties and continuity between floors and supporting columns/walls are considered adequate to provide robustness for RC2. Higher-risk building structures (RC3) additionally require effective vertical ties between columns, walls, and floors from foundation to roof, as illustrated in Figure 4, to allow for loads to be redistributed via alternative load paths. Special requirements for vertical ties in load-bearing wall construction are prescribed in Annex B.6 of SANS 10160-1. In framed buildings, supporting columns and walls are required to withstand an accidental tension force equal to the largest vertical column load from any one storey, so that if the member fails, the forces can be redistributed through catenary action in the floors above. For reinforced concrete structures, where continuity of elements is commonplace, these requirements can be implemented without much adjustment to the design approach for “normal” structures. For steel, precast, timber or load-bearing masonry structures, however, these requirements are not as easily met. As a result, an alternative method is proposed whereby supporting beams, columns, or supporting wall sections are removed one at a time to evaluate the damage that would result if such a member failed due to unforeseen accidental actions. The resulting damage may not cause overall structural instability, nor be disproportionate. In this scenario, “disproportionate” damage is proposed as the failure of the minimum of 100 m² or 15% of the floor area in each of two adjacent storeys. In cases where the removal of an element causes disproportionate damage, the member should be designed as a key element. Key elements should be designed to withstand a notional accidental load of 34 kN/m², simulating a gas explosion, acting simultaneously with normal loading on the member and connected components to test structural robustness and integrity. In-depth guides on practically implementing robustness in design can be found in various guides by the Institution of Structural Engineers (IStructE 2010) and the Steel Construction Institute (Way 2011), among others.

Due to the dire consequences of failure for structures in RC4, a full systematic risk assessment should be carried out considering both foreseeable and unforeseeable hazards. This consists of at least a qualitative part through, for example, a decision

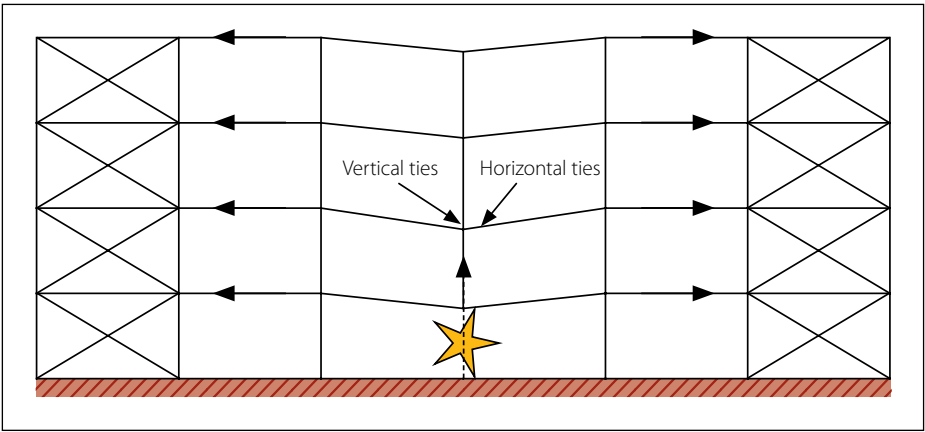


Figure 4 Illustration of the function of ties and alternate load paths

Consequences	Catastrophic 50 > deaths	Intolerable	Intolerable	Intolerable	Intolerable	Intolerable
	Major 5 < deaths ≤ 50	ALARP	ALARP	Intolerable	Intolerable	Intolerable
	Moderate 1 < deaths ≤ 5	ALARP	ALARP	ALARP	Intolerable	Intolerable
	Minor Some injuries	Tolerable	Tolerable	ALARP	ALARP	ALARP
	Insignificant Minimal injuries	Tolerable	Tolerable	Tolerable	Tolerable	ALARP
		Rare 1 in 50 years	Unlikely 1 in 10 years	Possible 1 in 5 years	Likely 1 in 2 years	Almost certain 1 per year
		Likelihood				

Figure 5 Example of a qualitative risk assessment matrix

tree analysis or causal network to identify risks and risk scenarios that may arise. Risks are assigned a qualitative likelihood of occurrence and the consequences of the event. A risk matrix is typically used to identify notable risks, as illustrated in Figure 5 (as an example), and strategies can be developed to avoid or mitigate these risks. The more detailed the likelihood and consequences are in the matrix, the more useful it will be in decision making.

Risk acceptance in structural design is often modelled using the ‘as low as reasonably practicable’ (ALARP) principle (Pandey *et al* 2025, Vrouwenvelder *et al* 2024). Following this principle, risks within a matrix are generally classified as being tolerable, tolerable if ALARP, or intolerable. A risk within the ALARP zone may be accepted if it has been shown that mitigation strategies have been implemented to the point where further risk reduction is impracticable, or where the cost of additional or further measures becomes grossly disproportionate to the reduction of risk gained (ISO 2015).

In extreme cases, a quantitative probabilistic cost optimisation can be performed and the resulting solution can be checked for societal acceptance using measures like the Life Quality Index principle (Pandey & Nathwani 2004, Way *et al* 2022) or using frequency-consequence diagrams (also known as F-N diagrams). Although it is not explicitly mentioned, it is reasonable to assume that the requirements for RC3 should be adhered to as a minimum for RC4, in addition to further requirements identified through the risk assessment. Further risk assessment guidance can be found in EN 1991-1-7, JCSS (2008), ISO 2394 and Vrouwenvelder *et al* (2024).

Supervision in design and construction

The typical design supervision model used in South Africa involves a senior designer (typically a Pr Eng) establishing an overarching structural design philosophy, after which more junior designers (typically candidate engineers) perform the majority of the detailed design in consultation with the

senior designer. The senior designer, who will take responsibility for signing off the structure as the competent person, then performs checks on the design work of the candidate(s). Following Table 3, this typical supervision model should be sufficient for structures in RC1 and RC2. It should be noted though, that any gross errors that may be made by the senior designer in the design philosophy are unlikely to be identified. As such, although not explicitly recommended for RC2 structures, it is generally good practice for senior designers to at least discuss the structural design philosophy with a colleague of similar or greater experience wherever possible to avoid gross errors in design, ideally at preliminary design stage.

Many RC3 structures are not classified as such due to the previously mentioned difficulties in classification, and it is subsequently unlikely that clients are insisting on independent third party design checking, as recommended in Table 3. Structures in class RC4 require “regulated third party checking to satisfy the requirements of the regulatory or supervisory authority” (SANS 10160-1 Table A.2). While such regulatory or supervisory design checking authorities may exist as part of European practice (e.g. The Federal Association of Design Review Engineers in Germany), they do not exist in South Africa. The term “regulated third party checking” is not clarified in the rest of the code, and is subsequently open to interpretation. It is probable that the “regulated” component refers to the need for creating formalised guidance and verification processes that are followed by independent, experienced practitioners. A comparative local example of this is the Council for Geoscience, which maintains a list of regulated experts who check designs for all projects on category D4 dolomite sites in South Africa, as required by SANS 1936.

The same problem of the non-identification of RC3 structures exists for construction supervision, which requires third party inspection, from Table 3. It is, however, highly unusual practice for a third party to perform construction supervision in South Africa and, as such, it would probably be more realistic to increase the frequency and/or scope of site inspections for RC3. Part of this could, for example, include a requirement for the competent person responsible for signing off the structure to inspect at practicable intervals during the construction of the

structural frame. A second inspector, even at less frequent intervals, would also give additional oversight and other benefits of the two-person rule (four-eyes principle). The large consequences of failure of RC4 structures would warrant independent third party inspections. Similarly to design supervision, the lack of a definition for regulated third party inspections leaves the application open to interpretation.

RECOMMENDATIONS AND CONCLUDING COMMENTS

Given the foregoing discussions, it is clear that the following reliability- and engineering judgement-related issues are concerns for the South African structural design industry:

1. It is highly likely that higher-risk structures (RC3 & RC4) are not being identified as such, due to either the limited or unclear guidance in the informative appendices of SANS 10160-1 or engineers not applying the guidance.
2. Consequently, higher-risk structures are likely not being designed with the appropriate reliability framework measures, namely:
 - Quantitative measures: Increased partial factors required for loads
 - Qualitative measures: Robustness required to mitigate disproportionate and progressive collapse; greater degrees of design and construction supervision required.

As the identification of higher-risk structures is the main trigger for the subsequent issues, the illustration of the link between the qualitative descriptions of reliability classes in Table 1 and consequence classes in Table 2, and the quantitative criterion presented in Table 4, aims to provide practicing engineers with guidance to better identify higher-risk structures. Once a structure has been identified as higher-risk, the appropriate measures can be put in place to provide an adequate level of reliability. These include:

- The quantitative aspect of using a factor (K_F) to increase unfavourable load partial safety factors to appropriately increase reliability through strength reserves is illustrated in Table 4, and is fairly simple to apply.
- The qualitative robustness requirements for RC3 of effective horizontal and vertical tie elements, or the notional removal of supporting elements and the subsequent design of key elements,

are described in Table 2. While these requirements do require additional design time and consideration, they are well-detailed and relatively simple to apply.

- While not clearly stated, the robustness requirements for RC3 are likely implied as a minimum requirement for RC4, in addition to measures that should be identified and implemented through a structure-specific risk assessment for the notable consequences of failure.

The over-generalised requirements for design and construction supervision of higher-risk structures are where further clarity is required. No delineation is made between third party checking for RC3 and regulated third party checking for RC4 for design checking. The intent was clearly to recommend a more rigorous and/or extensive check for RC4. As such, it may be sensible to be more specific about the extent of the third party design check. A possibility is to propose, at minimum, a conceptual design check for RC3 and both a conceptual and full design check for RC4. For RC3, a conceptual design check by a suitably experienced designer would help to identify and correct gross errors in the design philosophy and approach at an early stage of design without unnecessarily hindering the design process. For the notably high-risk structures in RC4, the combination of a conceptual and full design check would identify both conceptual design errors as well as non-compliance with codes and errors in detailed member design. Table 5 combines these, as well as proposals for experience requirements of checkers with the recommendations in Table 3 from SANS 10160-1 Appendix B. Responsibility and liability with respect to reviewers needs to be clearly defined such that the review process is neither a proverbial rubber stamp exercise with no benefit, nor a task that transfers disproportionate risk to the reviewers.

In terms of the lack of clarity for construction supervision, the recently-published ECSA Guideline Scope of Services and Professional Fees (ECSA 2025) proposes guidelines for three levels of construction supervision, which by qualitative description seem broadly comparable to those describing RC1 to RC3. They give guidance on the typical frequency of inspections as well as conceptually describing typical tasks carried out during inspection. They also seem to support the

Table 5 Proposals for minimum supervision (black text is derived from SANS 10160 Appendix B, blue text is from the ECSA (2025) fee guidelines, and red text reflects the authors' suggestions)

Class	Minimum recommended design supervision level	Minimum recommended construction inspection level	
		Frequency	Typical task description
RC1	Basic: Self-checking.	Basic: Infrequent self-inspection (e.g. fortnightly inspections).	Review limited numbers of samples of material and work procedures for conformity to contract documentation, and review some samples of important completed work prior to covering up, or on completion, as appropriate. Inspector to be performing under supervision of a registered professional according to IDoEW.
RC2	Normal: Separate checking by someone within the organisation other than the original designer(s), as per internal quality control procedure. Checker must be a registered professional.	Normal: Part-time inspections as per internal quality control procedure (e.g. weekly to daily inspections).	Review regular samples of materials and work procedures for conformity to contract documentation, provide design/technical clarifications where required, and review regular samples of important completed work prior to covering up, or on completion, as appropriate. Inspector to be performing under supervision of a registered professional according to IDoEW.
RC3	Extended: Third party conceptual design check performed by independent organisation. Checker must have 10+ years' structural engineering experience, be Pr Eng registered, and have 5+ years' experience with similar structures.	Extended: Full-time presence on site during construction.	Constantly review samples of materials and work procedures for conformity to contract documentation, provide design/technical clarifications, and review completed work prior to covering up, or on completion, as appropriate. Assist with the compilation of record and/or as-built records and drawings to the extent required in the agreement with the client. Inspector should have 5+ year's relevant experience, and either be a registered professional (IDoEW) or supported by regular inspections by a registered professional. Preferable that the lead designer be involved in the process on an ongoing basis.
RC4	Regulated: Full third party design check performed by independent organisation. Checker must have 15 years' structural engineering experience, be Pr Eng registered, and have 10+ years' experience with similar structures.	Regulated: Full-time presence on site during construction and third party inspection.	Inspector should be a registered professional (IDoEW) and full-time on site with at least fortnightly inspections by independent third party registered professional with 10+ years' relevant experience. Preferable that lead designer be involved in the process on an ongoing basis.

notion of an increased frequency of supervision (to full-time), rather than third party inspections for what would be RC3. Due to the notable consequences of failure for RC4, third party inspections would be warranted, in addition to the requirements for RC3. This guidance, as well as some proposals for experience-related requirements for construction inspectors are combined with the requirements from Table 3 and are shown on the right of Table 5. The ECSA Fee Guidelines document highlights that requirements for supervision should always be explicitly agreed upon with the client prior to commencement of the services.

Critical infrastructure such as large hospitals, courts, power stations, and important government buildings should inherently be classified as RC3 or RC4 structures due to the consequence of their loss of function to society. The additional structural costs associated with increased reliability will typically be small in relation to the economic cost associated with the non-functioning of that building (e.g. as seen in the loss of the Cape Town Parliament building due to a severe fire in 2022). Furthermore, higher-risk structures are more likely to be targets for sabotage, arson, or terrorist attack, and so may require a systematic risk analysis.

This work has sought to bring together the various policy and design frameworks in South Africa with an emphasis on the design and construction of higher-risk structures. It appears that such structural classifications are often not identified, or the design requirements for them are not known/applied by registered professionals, leading to a lack of usage of the SANS 10160-1 reliability-based guidance on increased partial safety factors, third party review, increased construction supervision, design of redundancy and so on. Structural systems such as precast concrete, load-bearing brickwork and mass timber often have little continuity and are therefore at higher risk of disproportionate collapse, but even reinforced concrete structures with more ductile members and possibilities for load redistribution need to be considered in order to mitigate the potential risks.

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A socio-technical systems (STS) analysis of road fatalities in Gauteng province (2015–2019)

F N Masuku, M Sinclair

Road safety in Gauteng represents a persistent and complex socio-technical challenge, shaped by dynamic interactions between human factors, engineering design, institutional governance, and socio-economic contexts. This study employs a socio-technical systems (STS) framework to analyse the multifaceted contributors to road traffic fatalities in the province for 2015 to 2019; data from 2020 was excluded due to covid-19 mobility distortions that would have confounded analysis of underlying systemic risk factors. Utilising a mixed methods, convergent design, the research integrates qualitative institutional data with quantitative fatality and exposure metrics to model the interplay of social and technical subsystems. Key findings reveal that temporal variables (time of day, seasonal weather patterns), infrastructural and operational factors (road class, posted speed limits), and socio-economic pressures (unemployment rates, population density, GDP per capita) are interconnected within the STS and collectively exacerbate fatality risk. The Spatially Aware Poisson Random Forest (SAPRF) model achieved $MAE \approx 0.031$, $RMSE \approx 0.109$, and $R^2 \approx 0.958$, substantially outperforming standard random forest ($R^2 \approx 0.872$) and Poisson regression ($R^2 \approx 0.06$). The novelty lies in the first application of SAPRF in a South African road safety context, integrating STS theory with spatially aware machine learning. The study concludes that prevailing behaviour-centric interventions are insufficient and argues for a paradigm shift toward integrated, multi-level policy and design interventions targeting the root systemic couplings and feedback mechanisms inherent in the road transport system.

Keywords: socio-technical systems, road safety, Gauteng, infrastructure, modelling, fatality risk

INTRODUCTION

Road fatality rates in South Africa, and within the province of Gauteng specifically, remain at a critically elevated and unacceptable level. This constitutes a significant public health crisis and imposes severe economic burdens on communities, a challenge emblematic of many low- and middle-income countries (LMICs). Prevailing road safety interventions frequently adopt a reductionist focus, targeting individual road user behaviour in isolation. However, a more comprehensive understanding is demanded by the rapidly evolving and interconnected landscape of contemporary risks. This landscape is characterised by dynamic pressures such as climate variability, shifting demographics, evolving mobility patterns, and the disruptive integration of new technologies. Within this complex environment, fatal crash outcomes are demonstrably shaped

by the intricate interplay of these social and technical factors. Socio-technical systems (STS) theory offers a robust, holistic framework for analysing such complexity, as it explicitly examines the interdependent relationships between human actors, physical infrastructure, governing institutions, technological artefacts, and broader socio-economic contexts.

This study employs an STS lens to diagnose the systemic weaknesses contributing to persistent roadway risk in Gauteng between 2015 and 2019. Methodologically, the research advances a novel synthesis by integrating foundational STS principles with quantitative spatial and statistical modelling techniques. This integrated approach enables the systematic analysis and fusion of multidimensional data streams including social variables (e.g. population density, gender), economic indicators (e.g. GDP per capita, unemployment,

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gross fixed capital formation), and geographical factors (e.g. road hierarchy, land use, influence of townships) into a unified predictive-analytical model.

The primary objective is to identify critical factors influencing road safety within an integrated socio-technical system, moving beyond isolated variables to model interactions and emergent effects. Three gaps motivate this study: no published work has applied a spatially aware Poisson ensemble to road fatalities in Gauteng; existing South African safety research relies on parametric methods unable to capture nonlinear STS interactions (Washington *et al* 2020); and the integration of STS theory with advanced machine learning for road safety remains absent from the South African literature. This study addresses all three by combining STS theory, spatial statistics, and ensemble machine learning in a unified framework.

LITERATURE REVIEW

According to the World Health Organization, road traffic crashes (RTCs) claim approximately 1.19 million lives globally each year (WHO 2024). This burden is starkly unequal: while high-income countries possess extensive road networks, they account for only 8% of these fatalities. In contrast, over 92% of all road deaths occur in LMICs (WHO 2024). South Africa exemplifies this disparity, reporting a disproportionately high rate of RTCs and fatalities, a finding consistent across global and national data (RTMC 2023). According to the South African Road Traffic Management Corporation’s annual publication, a total of 12 545 fatalities were recorded nationally between January and December 2021 data (RTMC 2023). Provincial data for this period reveals that Gauteng (2 293 fatalities), KwaZulu-Natal (2 143 fatalities), and the Western Cape (1 088 fatalities) were among the most severely affected regions, with Gauteng recording the highest number of deaths (see Table 1).

The evolution of technology and automation has fundamentally reconfigured the nature of human work, shifting the

primary demands from physical labour to tasks requiring sophisticated cognitive engagement. This shift necessitates an understanding of work not in isolation, but embedded within a complex matrix of technological tools, physical environments, and socio-cultural dimensions, including psychosocial climate, established work practices, procedural norms, and their evolution across both space and time (Carayon *et al* 2015). Transport, as a critical domain of human activity, has been theorised as a typical STS – a complex collection of interconnected elements such as physical artefacts, engineered infrastructure, formal regulations, specialised knowledge, supply networks, and embedded cultural meanings. Consequently, modern transport systems are intricate structures wherein technological, social, economic, political, legal, and environmental components continuously interact to produce mobility services.

The traditional conceptual model for deconstructing these systems has centred on a foundational triad: infrastructure, vehicles, and users. However, scholars like Auvinen and Tuominen (2014) convincingly argue for the inclusion of a fourth, critical element: management. This addition explicitly accounts for the essential governance, regulatory, and oversight functions that orchestrate the system. It is the dynamic, reciprocal influence among these core elements – infrastructure, vehicles, users, and management – that causes the transport system to operate as a cohesive, adaptive, and interconnected whole. A socio-technical systems approach, which meticulously examines the interdependencies among technology, individuals, organisations, and broader societal factors, therefore provides a powerful and appropriate analytical framework. It is particularly suited to interrogating persistent disparities in road safety performance across different regions, even those with ostensibly comparable technological capabilities but markedly divergent safety outcomes.

Kling (1991) provides a foundational definition of a socio-technical system as an integrated configuration of people, equipment, data, and varied resources encompassing financial, skill-based, and

status-related assets alongside documents, messages, legal arrangements, and political forces, all of which dynamically shape collective system behaviour. This comprehensive lens is indispensable for explaining the stark variations in transport safety outcomes between high-income countries and LMICs, where profound differences in institutional governance, infrastructure quality, enforcement capacity, and prevailing cultural norms create fundamentally different risk landscapes (Horton *et al* 2005).

Factors in road crash fatalities

Developing effective countermeasures for RTCs necessitates a systemic understanding of their complex, multifactorial causes. Traditional approaches often isolate individual risk elements, yet a socio-technical perspective reveals that causality emerges from the dynamic interplay between diverse social, technical, economic, and environmental subsystems. Pertinent socio-technical features influencing RTC outcomes encompass demographic variables (e.g. gender distribution, population density), economic indicators (e.g. gross domestic product (GDP), unemployment rates), vehicle fleet characteristics, roadway infrastructure (e.g. classification, condition), and contextual factors such as weather, temporal patterns (e.g. time of day, season), and enduring spatial legacies (a critical consideration in South Africa given the persistent distortions from its apartheid-era urban planning).

The multidimensional nature of crash causation is well documented in the literature. Qin *et al* (2019) demonstrated that crash frequency is shaped by interacting demographic, environmental, and institutional factors, including total land area, population density, vehicle ownership, gender and racial composition, and the density of alcohol outlets. Building directly on the analytical framework and variables identified by Qin *et al* (2019), systemic crash risk factors can be organised into the following interdependent domains:

- **Infrastructure and engineering:** Road classification, geometric design, pavement condition, and intersection density.
- **Road environment and exposure:** Weather conditions, traffic volume and

Table 1 Number of road fatalities per province 2021

Year	Eastern Cape	Free State	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape
2021	1 533	799	2 561	2 409	1 400	1 261	403	908	1271

composition, vehicle population, and fleet safety standards.

- **Socio-demographic and economic context:** Population age and gender structure, educational attainment, Human Development Index (HDI), unemployment levels, and income inequality.
- **Behavioural and institutional factors:** Alcohol availability and consumption patterns, enforcement effectiveness, and post-crash response capacity.
- **Spatio-temporal context:** Geographic location, land-use patterns, and temporal variation such as peak travel periods and weekends.

Available methods of analysis

The integration and analytical synthesis of these heterogeneous data streams present a significant opportunity. As Mehdizadeh *et al* (2020) argue, advanced data analytics applied to this socio-technical pattern hold considerable potential to decode complex crash etiologies, moving beyond description towards predictive modelling and the development of targeted, systemic safety interventions.

This predictive modelling paradigm, however, is demarcated by a fundamental methodological divergence. Classical statistical approaches, including negative binomial, Poisson, and multiple linear regression provide interpretable, parametric frameworks but are inherently limited in their ability to capture the non-linearities, high-dimensional interactions, and spatio-temporal dependencies that define contemporary transport systems as complex socio-technical entities (Washington *et al* 2020). In response, advanced computational models have emerged as robust alternatives. By leveraging machine learning (ML) and artificial intelligence (AI), these data-adaptive techniques autonomously learn intricate, non-linear relationships from multifaceted datasets without imposing restrictive statistical assumptions, yielding superior predictive performance (Yan & Shen 2022). Their capacity to process large-scale, complex data solidifies their role as indispensable tools in modern traffic safety analysis.

Within this advanced analytical repertoire, tree-based ML models, such as decision trees and their ensemble derivatives, have proven particularly effective for tasks like severity classification and strategic traffic management. These models excel at revealing latent patterns

and high-order interactions within data, facilitating the identification of previously obscured risk relationships (Vincent *et al* 2024). Consequently, the transition toward ML-based predictive analytics encompassing random forests, gradient boosting, and support vector machines has gained substantial momentum. Empirical validation of this shift is evident; for instance, integrated applications of ML models with high-resolution geospatial data have demonstrated predictive accuracy exceeding 85% in crash severity forecasting (Tejashwini *et al* 2024). This progression underscores a broader evolution toward predictive analytics capable of grappling with systemic complexity. Random forest (RF) ensembles discover non-linear interactions and rank predictors by variance-reduction importance without distributional assumptions (Yan & Shen 2022). A limitation of standard RF is that it optimises squared error, mismatched to over-dispersed count data. Replacing this with Poisson deviance aligns the learning objective with crash count distributions and improves calibration (Lord & Mannering 2010, Mathlouthi 2015). Adding spatial covariates further accounts for geographic autocorrelation without imposing a parametric spatial structure (Aguero-Valverde & Jovanis 2006). The resulting SAPRF synthesises these strengths and forms the primary analytical tool of this study.

METHODOLOGY

This study operatively implemented a mixed-method STS analytical framework to examine road safety dynamics. This approach facilitated the concurrent analysis of quantitative, objective metrics and qualitative, contextual factors, recognising their interdependence within the system. Quantitative data comprised fatality records from the Road Traffic Management Corporation for the period 2015 to 2020 and the Gauteng Department of Community Safety, integrated with socio-economic indicators, meteorological data, detailed road infrastructure inventories, and demographic statistics.

Central to the analysis was the explicit classification of all data into technical and social subsystems, a categorisation fundamental to the STS lens. This structured classification enabled a systematic investigation of the interactions between engineered artifacts and human/social elements.

Technical subsystem factors pertained to the physical and operational components of the transport system:

- **Vehicle fleet dynamics:** Population growth, spatial distribution, and composition by type (e.g. light/heavy passenger vehicles, light/heavy freight vehicles, motorcycles), including the safety implications of vehicle age distributions.
- **Road infrastructure and design:** Network hierarchy (Class 1–6), structural characteristics of intersections, and design standards influencing safety performance.
- **Traffic exposure and infrastructure condition:** Annual average daily traffic volumes as a core exposure metric and the visual condition index as an indicator of pavement quality and maintenance.
- **Spatial-physical configuration:** The geographic layout of the road network and the location of key land uses, such as townships and formal traffic analysis zones (TAZs).

Social subsystem factors encompassed human, institutional, economic, and environmental influences:

- **Demographic and behavioural vulnerabilities:** Population characteristics, including the age and gender distribution of fatalities, highlighting groups at disproportionate risk.
- **Economic context:** Indicators such as GDP per capita, unemployment rates, the Gini coefficient (inequality), and gross fixed capital formation, which shape both individual travel behaviours as well as public infrastructure investment capacity.
- **Land use and activity generators:** The spatial distribution of schools and liquor outlets, which critically influence localised traffic patterns, pedestrian activity, and alcohol-related risk.
- **Environmental conditions:** Meteorological factors (e.g. rainfall, temperature) that interact with the technical subsystem to modify road surface friction and visibility.
- **Historical-institutional legacy:** The enduring impact of past social policies, particularly apartheid-era spatial planning that created peripheral townships disconnected from economic centres, fundamentally structuring mobility patterns and exposure risks in Gauteng.

By disaggregating factors into these two interdependent subsystems, the analysis

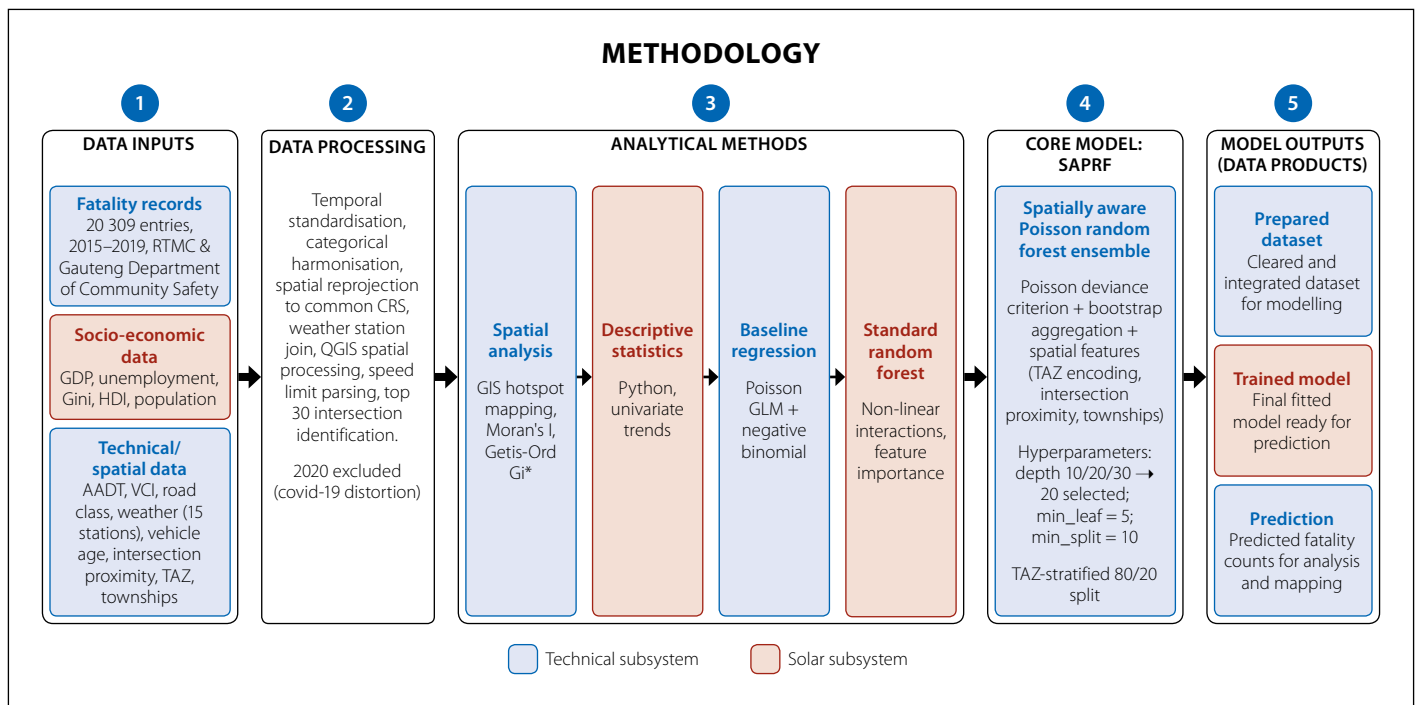


Figure 1 Integrated socio-technical methodological framework

moves beyond siloed examination, enabling a holistic investigation of the socio-technical interactions that collectively produce systemic risk.

Data collection and processing

A comprehensive data preprocessing pipeline was implemented to ensure consistency and analytical integrity across all datasets prior to modelling. The primary fatality dataset, comprising 20 309 entries, underwent temporal standardisation, with disparate date and time formats converted into a single, uniform schema. Categorical variables, including demographic descriptors, road user types, and vehicle classifications, were harmonised from varied source terminologies into common, consistent categories. To align with the 2015 to 2020 study period, historical economic data series (2010 to 2020) were extracted and formatted to cover the relevant years. Meteorological data from 15 weather stations, capturing temperature and rainfall, were standardised into decimal formats and spatially joined to the analysis units based on proximity to the nearest station. All geospatial data was reprojected to a common coordinate reference system to enable accurate spatial integration and analysis.

The pre-processed data was subsequently analysed using a sequential, multi-method analytical strategy designed to leverage both exploratory and inferential techniques:

- **Spatial analysis and hotspot identification:** Geographic information

systems (GIS) were employed to visualise the spatial distribution of fatalities and to statistically identify high-risk clusters or hotspots using spatial auto-correlation measures.

- **Descriptive statistical analysis:** Python was used to summarise key trends, distributions, and univariate relationships within the data, providing a foundational understanding of the dataset.
 - **Traditional statistical modelling:** To establish baseline relationships and account for the count nature of the outcome variable, generalised linear models, specifically Poisson and negative binomial regressions, were applied. These models helped quantify the association between predictor variables and fatality counts while controlling overdispersion.
 - **Advanced machine learning modelling:** A standard RF model was implemented to capture complex, non-linear interactions among variables and to provide an initial ranking of predictive feature importance.
 - **Integrated socio-technical modelling:** The core analysis employed the SAPRF, which synthesises the strengths of the above methods. This model integrates Poisson-based loss for count data, ensemble learning for robust prediction, and embedded spatial features to explicitly account for geographic dependencies and exposure.
- This layered methodological approach was explicitly designed to address the socio-technical interplay of risk factors, from

identifying high-risk areas and temporal trends to modelling the complex, systemic relationships that underpin fatality outcomes in Gauteng (see Figure 1).

The study focused on the province of Gauteng (see Figure 2), leveraging its diverse urban and rural road networks to provide insights applicable to similar contexts.

Spatially Aware Poisson Random Forest Ensemble (SAPRF)

Data analysis was conducted using an SAPRF. This advanced model extends the standard RF framework by implementing a Poisson deviance criterion for node splitting, making it explicitly suitable for modelling over-dispersed and zero-inflated count data such as traffic fatalities (Lord & Mannering 2010). Its spatial awareness is engineered through the direct incorporation of geospatial covariates, including proximity to intersections, TAZ target-encoded indicators, and binary township location variables to explicitly capture local heterogeneity in infrastructure and risk exposure.

This integrated methodology overcomes key limitations of conventional machine learning and regression techniques, which frequently fail to account for spatial auto-correlation and nuanced exposure effects, thereby aligning with foundational principles of spatial econometrics and safety modelling (Aguero-Valverde & Jovanis 2006). The model leverages an ensemble of decision trees trained on a comprehensive feature set encompassing traffic exposure metrics (annual average daily traffic,

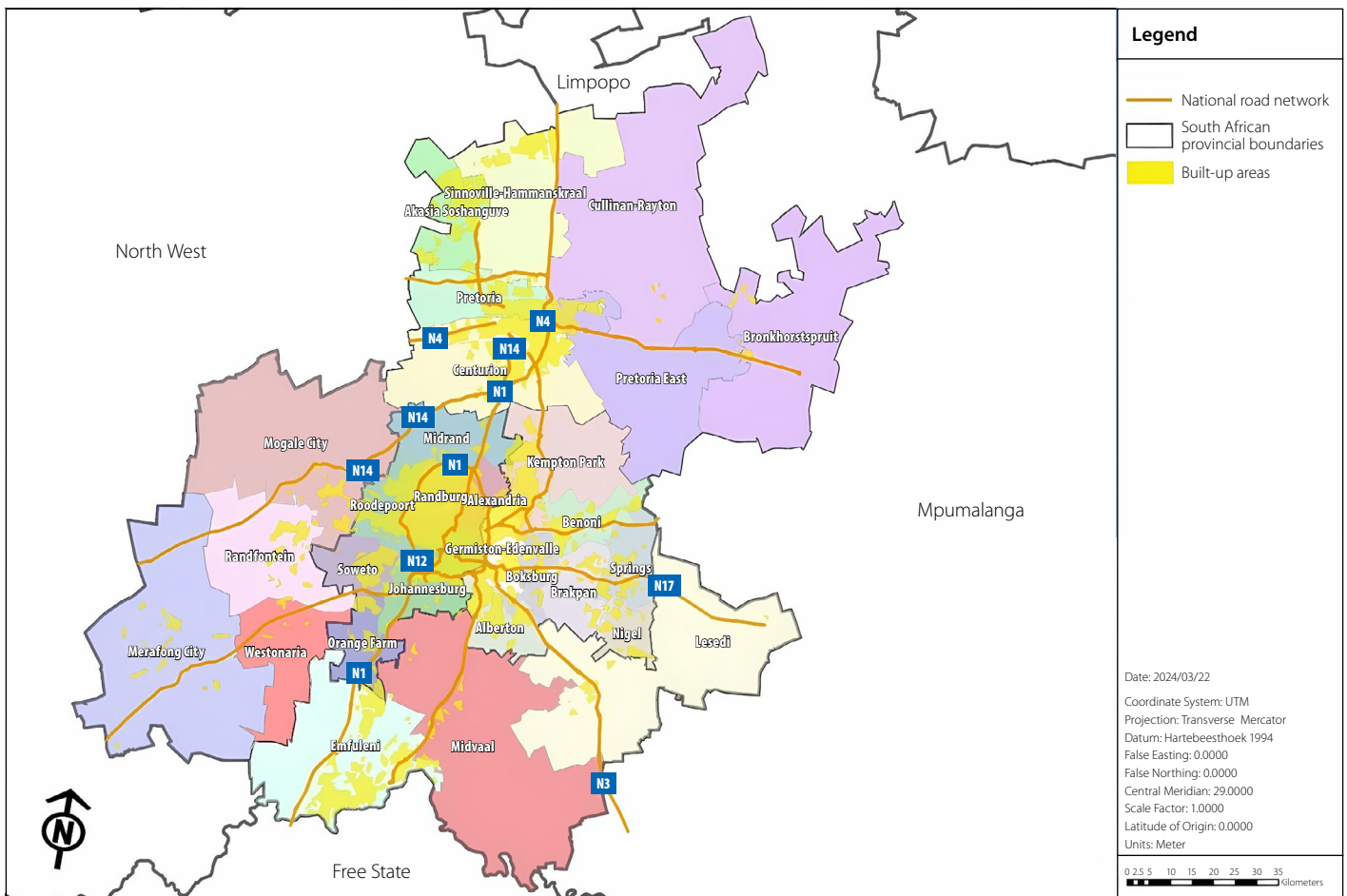


Figure 2 Map of Gauteng province

visual condition index), meteorological data, socio-economic and demographic indicators, and vehicle fleet characteristics. Crucially, exposure is explicitly parameterised to normalise predictions, countering bias from variations in traffic volume or population density (Shauna *et al* 2015).

The SAPRF was specified as an RF with Poisson deviance for node splitting, optimising for count data likelihood:

$$D(y, \hat{y}) = 2(y \log \frac{y}{\hat{y}} - (y - \hat{y})) \quad (1)$$

Where:

y is the observed fatalities

$\hat{y}$ is the predicted value, a positive real number representing the expected count from the model

$D(y, \hat{y})$ is the deviance, a measure of how well the model fits data.

The SAPRF was selected over standalone Poisson regression or standard RF models because it uniquely synthesises the Poisson framework's appropriateness for count data, the ensemble's capacity to model complex, non-linear interactions in high-dimensional data, and spatial feature integration to address location-specific risk. This makes

it an ideal analytical tool for the Gauteng context, where complex interactions between spatial, temporal, and socio-economic factors necessitate a model with both high predictive accuracy and interpretable, actionable outputs for safety planning. The training dataset used for the SAPRF was identical to that prepared for the baseline RF model.

To validate the model's predictive accuracy and generalisability beyond the data on which it was trained, a holdout validation strategy was employed. The complete dataset was randomly split into a training subset (80%) used to build the SAPRF model and a separate, unseen test subset (20%) reserved for final, unbiased evaluation. This procedure ensures that reported performance metrics reflect the model's capability to generalise to new data, a critical step for generating reliable insights for policy application.

Modelling process

The modelling process was structured into three sequential phases to ensure methodological rigor, from data preparation to model deployment and interpretation.

Phase 1: Data processing

All source datasets were cleaned, integrated, and standardised for the 2015 to

2019 study period, guided by the socio-technical framework. A key pre-processing decision was the exclusion of data from the year 2020 from the final analysis. This was necessary to avoid the severe distortions in traffic patterns, exposure, and fatality rates caused by the stringent covid-19 lockdown measures implemented in South Africa, which would have confounded the analysis of underlying systemic risk factors. Variables were explicitly selected to represent both social and technical subsystems:

- **Social variables:** Population, unemployment rate, GDP per capita, HDI, a binary township indicator, and vehicle age distribution shares.
- **Technical variables:** Traffic exposure (total vehicles), road hierarchy class, distance to the nearest intersection, meteorological conditions (temperature, rainfall), temporal effects (time of day, day of week), and TAZ identifiers for spatial encoding.

Specific transformations ensured consistency: the Gini coefficient was harmonised from a master file; annual population totals were imported from yearly Excel files; unemployment data was reshaped into a time-series format; vehicle age was converted to proportional shares (0–5, 5–10, 10–15, >20 years); weather data

was aggregated to daily means; and HDI values were manually compiled. Geospatial processing in QGIS derived key features, including intersection proximity and binary township flags. Speed limits were extracted from descriptive strings using a custom parsing function. Fatality locations were spatially joined to the road network, and the top 30 high-fatality intersections were identified for subsequent analysis.

Phase 2: Model training and validation

The pre-processed dataset was partitioned into an 80% training set (see Figure 2) and a 20% validation set, stratified by a TAZ identifier to prevent spatial leakage. A sensitivity analysis confirmed less than 3% RMSE difference versus a random split, validating this approach. Hyperparameters were tuned via grid search cross-validation: maximum tree depth evaluated at 10, 20, and 30 (depth 20 selected); minimum samples per leaf = 5; minimum samples per split = 10. The SAPRF was implemented using Breiman's ensemble framework employing bootstrap aggregation and random feature selection. Feature scaling was applied to continuous variables. A log (+1) transformation was applied to the target variable for exploratory visualisation only; the SAPRF model operates on raw count data, with the Poisson deviance criterion handling the skewed, zero-inflated distribution. There is therefore no conceptual inconsistency between this preprocessing step and the Poisson learning objective.

RESULTS

Annual fatality trends were analysed by aggregating individual data points by year. Figure 3 illustrates the resulting annual fatality counts for the study period. The year 2019 recorded the highest number of fatalities, followed sequentially by 2016, 2017, 2018, 2015, and finally 2020. The trend shows an increase from 2015 to 2016, a slight decrease in 2017, relative stability in 2018, a sharp peak in 2019, and a significant decline in 2020.

This pronounced drop in 2020 is directly attributable to the onset of the covid-19 pandemic. The first case was confirmed in South Africa in March 2020, after which varying levels of government-mandated travel restrictions were implemented. These restrictions drastically reduced traffic exposure, leading to the observed decrease in fatalities. Consequently, the core socio-technical systems analysis for this study focuses on the pre-pandemic period (2015

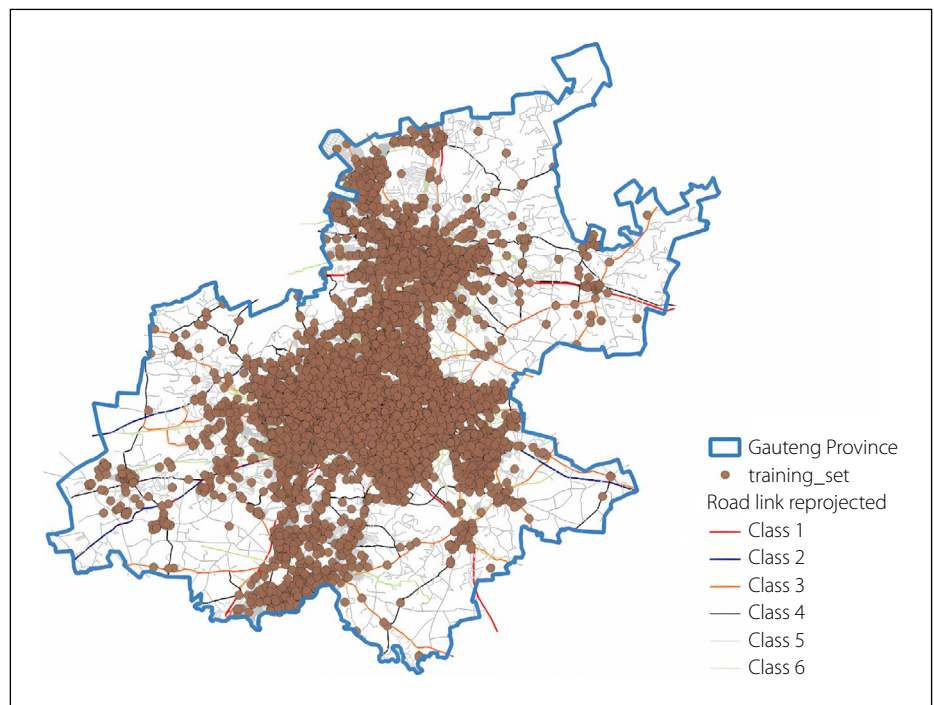


Figure 3 Map of SAPRF fatalities training set

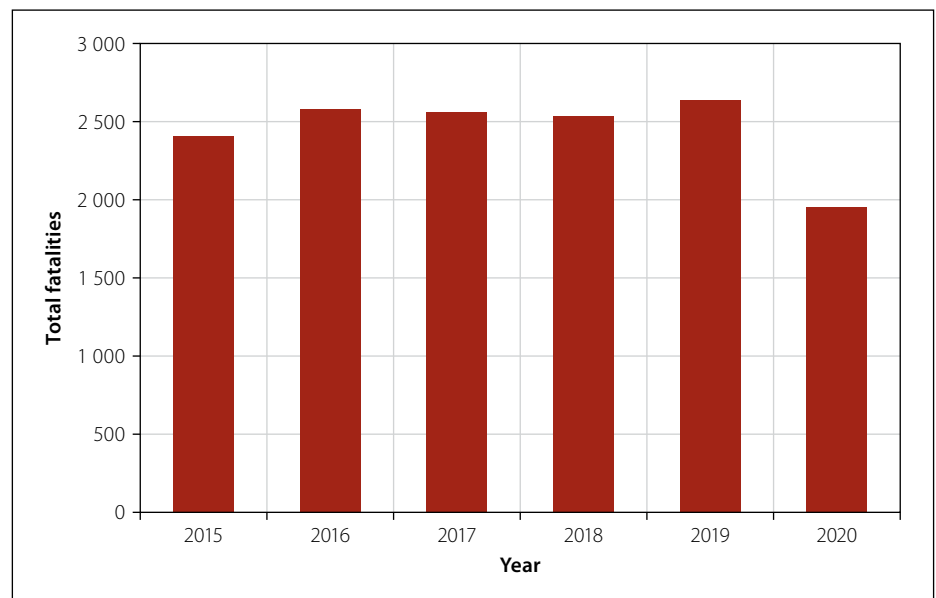


Figure 4 Total fatalities per month 2015 to 2020

to 2019) to examine typical systemic risk factors. The anomalous patterns of 2020 are treated separately in a subsequent temporal analysis of monthly and weekly fatality data for that year, which contextualises the impact of the lockdown phases.

Analysis of the pre-pandemic period (2015 to 2019) reveals a distinct seasonal trend in road fatalities. The data indicates that mid-year and late-year months were associated with elevated risk, while the early months consistently recorded lower proportions of annual fatalities. Specifically, July accounted for the highest proportion of fatalities at 10.1%, followed by August (9.6%), October (9.3%), and December (9%). Conversely, January recorded the lowest

proportion (5.5%), with February (7%), March (7.8%), and April (7.8%) also representing periods of relatively lower incidence.

This seasonal pattern suggests that road safety risk is influenced by temporal factors beyond random distribution. The peaks in July, August, and December may correlate with periods of increased long-distance travel, such as holiday migrations and festive season journeys, combined with potentially shorter daylight during winter weather conditions in the mid-year months. The consistent trough in early-year fatalities may reflect reduced travel volumes after post-holiday periods. The annual breakdown of monthly fatalities is presented in Figure 5.

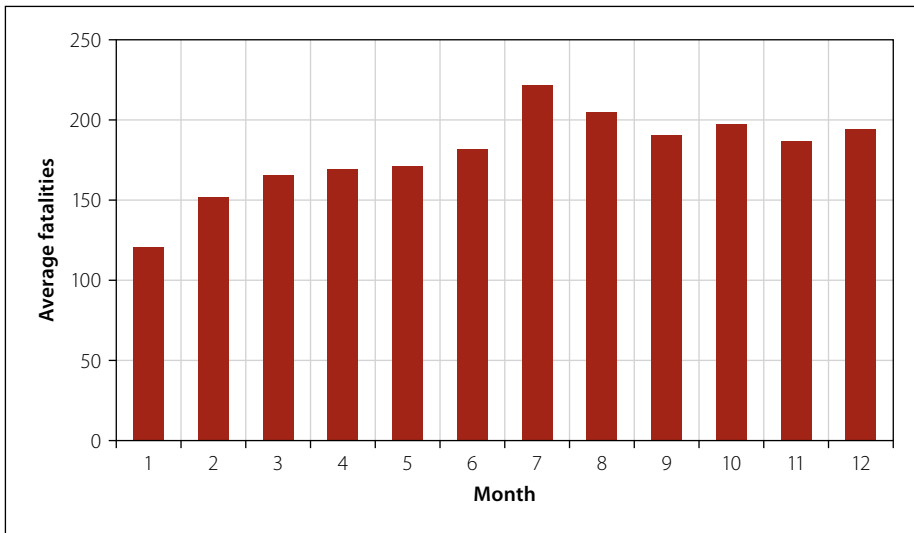


Figure 5 Average monthly fatalities (2015 to 2019)

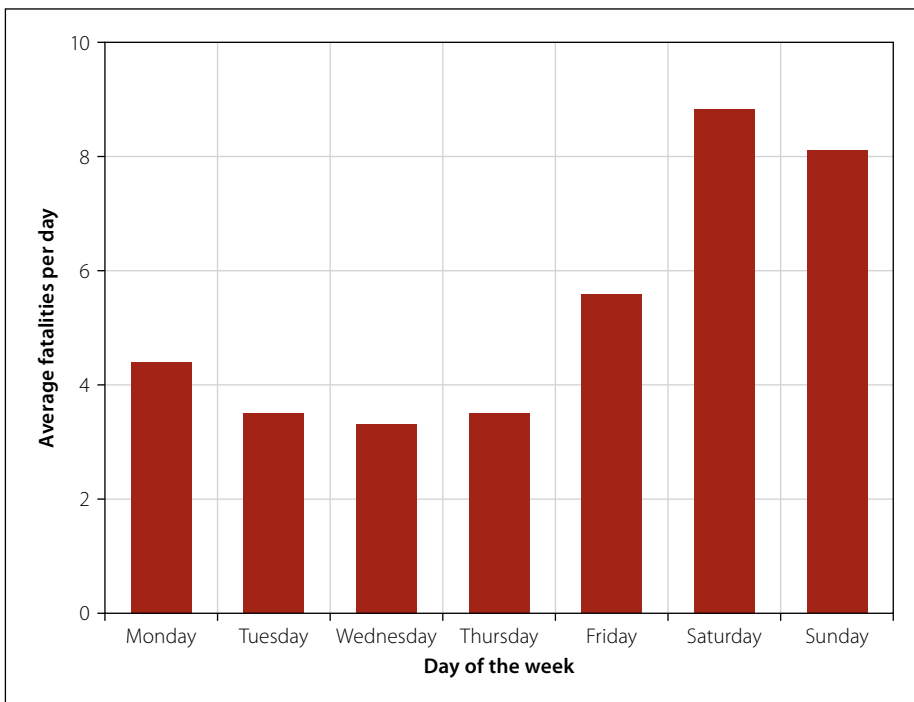


Figure 6 Average daily fatalities by day of week (2015 to 2019)

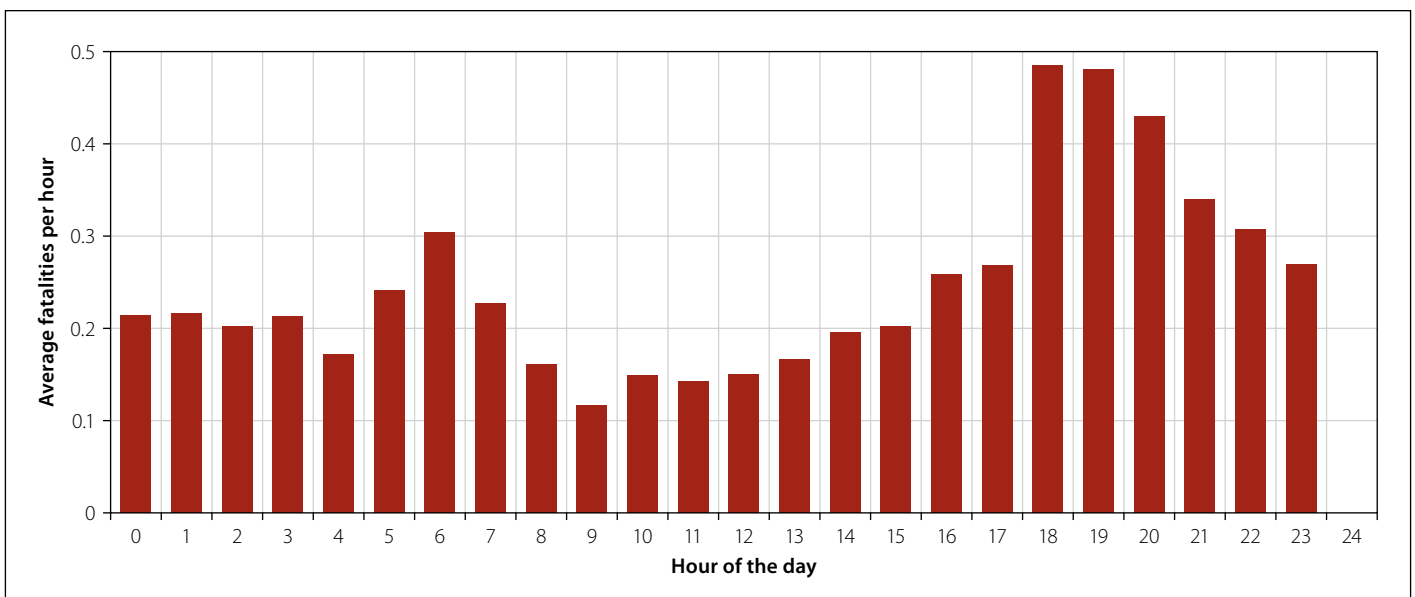


Figure 7 Fatalities per hour of the day (2015 to 2019)

An analysis of daily fatality distribution for the 2015 to 2019 period reveals a pronounced concentration of fatalities on weekends. This is a common phenomenon worldwide, so it is not unexpected, however the scale of concentration is unusually high. Saturdays and Sundays collectively accounted for 45.5% of all fatalities, with Saturday representing the peak at 23.7%, closely followed by Sunday at 21.8%. Weekdays demonstrated significantly lower proportions, with Thursday (15%) being the highest among them. The lowest fatality rates were recorded on Tuesday (8.9%), while Monday and Wednesday shared identical proportions (9.4% each). Friday occupied an intermediate position at 11.8%. This pattern underscores the heightened risk associated with recreational travel, differing traffic compositions during weekend periods, and the potential impact of increased alcohol consumption on weekends. The annual breakdown of fatalities by day of the week is detailed in Figure 6.

The temporal analysis reveals a robust diurnal pattern in fatality occurrence, characterised by two pronounced peak periods. The morning peak, defined as 05:00 to 08:00, accounted for 15.8% of total fatalities from 2015 to 2019. A significantly longer afternoon peak, spanning 17:00 to 21:00, was responsible for 35.1% of fatalities during the same period. This pattern demonstrated notable consistency across individual years, with the morning peak proportion ranging from 13.4% to 16.4% and the afternoon peak varying between 31.4% and 35.7%.

These distributions, visualised in Figure 7, point to a systemic relationship between commuting traffic flows, visibility conditions,

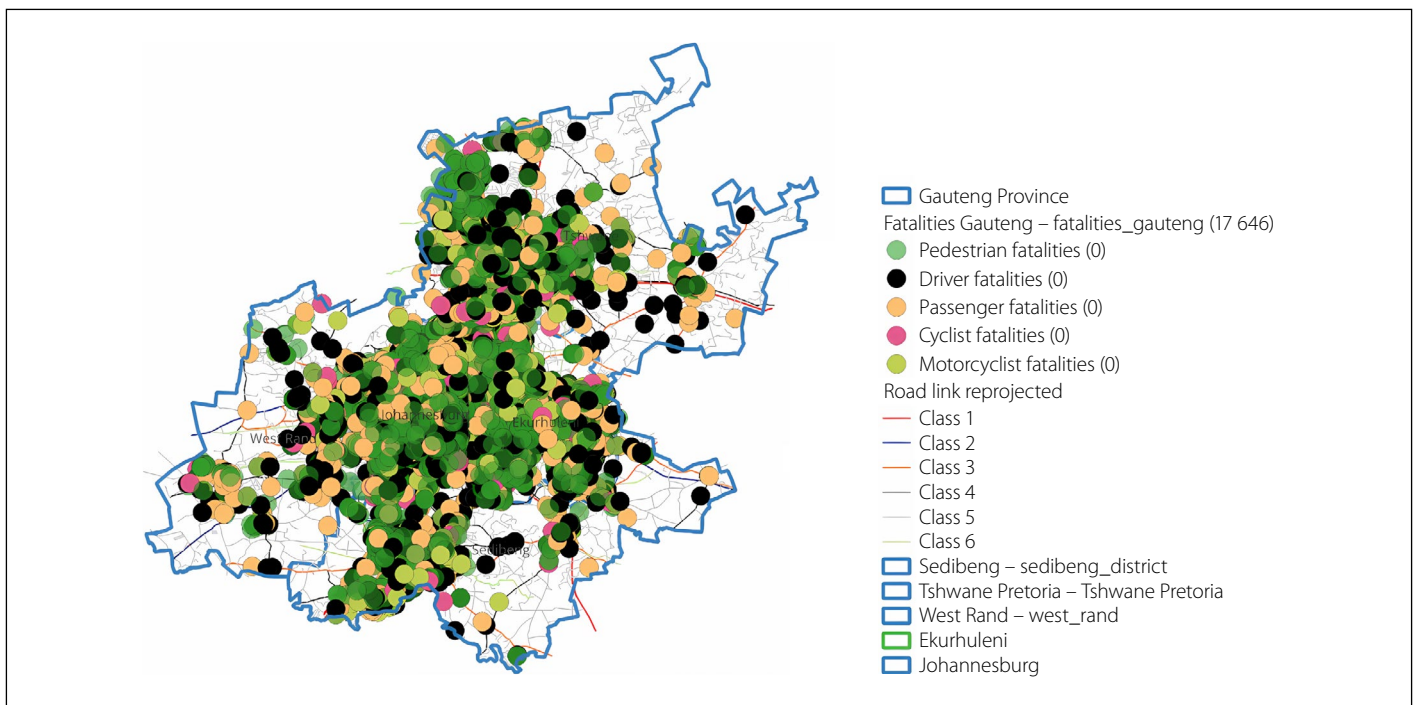


Figure 8 Map of road fatalities in Gauteng (2015 to 2020)

and driver fatigue with elevated fatality risk. The predominance of the extended afternoon peak, encompassing the evening commute and early nighttime, suggests a compounding of risk factors including higher traffic volumes, potential driver impairment, and reduced visibility. The consistency of this pattern underscores the necessity of temporally targeted interventions, such as dynamic speed enforcement, enhanced road lighting, and public awareness campaigns during these high-risk windows, to disrupt the systemic conditions that propagate fatalities.

Spatially aggregating to the district municipality scale and using the conventional per 100 000 metric reveals a distinct geographic pattern. The West Rand District (29.39) and Sedibeng District (27.88) exhibited the highest regional fatality rates, markedly exceeding the rates for Tshwane (18), Johannesburg (15.53), and Ekurhuleni (15.11). This spatial disparity highlights pronounced inequities in road safety outcomes across Gauteng, suggesting that risk is not uniformly distributed but concentrated in specific regional systems, potentially reflecting underlying variations in infrastructure quality, enforcement regimes, or socio-economic vulnerabilities.

Analysis of Gauteng road fatalities (2015 to 2019) reveals a persistent and inequitable crisis defined by specific, high-risk demographics and temporal patterns. The burden is distributed unevenly across road user groups:

- Pedestrians bear the greatest toll, constituting 46% to 49% of all fatalities.

This crisis is most acute for children (aged 0 to 14), among whom 86.3% of fatalities are pedestrians.

- Drivers account for the second-largest share (23% to 25%), with risk heavily concentrated during late weekend nights.
- Passengers represent 20% to 24% of fatalities, disproportionately affecting young adults (aged 15 to 19).
- An analysis of modal share against fatalities data reveals a critical overrepresentation of vulnerable road users in fatal collisions. Despite minimal mode shares (cyclists 0.2% to 0.3%; motorcyclists 0.1%), these groups constitute 1.9% and 4.3% of fatalities respectively.

Fatality risk peaks predictably during weekend evenings and nights across all major user groups. This evidence confirms that Gauteng's road safety challenge is not uniform but a series of interconnected, population-specific epidemics. Achieving meaningful reductions requires moving beyond generic measures to precision interventions that directly target the most vulnerable users, highest-risk times, and most dangerous locations.

The descriptive spatio-temporal and socio-technical patterns identified above – including pronounced peaks during evenings and weekends, pedestrian dominance, intersection and arterial hotspots, and municipal disparities – provide a foundational diagnosis of systemic risk factors in Gauteng. To quantify these interactions, capture non-linear relationships, and generate interpretable predictors for engineering and policy

applications, a predictive modelling phase was undertaken. This employed the SAPRF model, which integrates Poisson deviance-based learning with ensemble methods and explicit spatial encoding. The following sections present the model's performance evaluation against benchmarks (classical Poisson/negative binomial regression and standard RF) and detailed feature importance analysis derived exclusively from the trained SAPRF. These results directly build on the descriptive findings by revealing the relative influence and interactions of infrastructure, exposure, temporal, and contextual variables in driving fatality outcomes.

Performance of the SAPRF model

The SAPRF model demonstrated superior overall performance and offered the most theoretically coherent treatment of the data. While classical Poisson regression provided interpretable incidence rate ratios, its restrictive log-linear assumption failed to capture the complex non-linearities and interactions inherent in the crash system, resulting in a poor fit ($MAE \approx 0.21$, $RMSE \approx 0.51$, $R^2 \approx 0.06$). A standard RF model substantially improved predictive accuracy by automatically learning complex patterns ($MAE \approx 0.043$, $RMSE \approx 0.189$, $R^2 \approx 0.872$), as it is not constrained by parametric assumptions.

The SAPRF synthesises the strengths of both approaches. It retains the ensemble's flexibility to model high-order interactions (e.g. between distance-to-intersection, time-of-day, and rainfall) but uses Poisson deviance as its splitting criterion. This

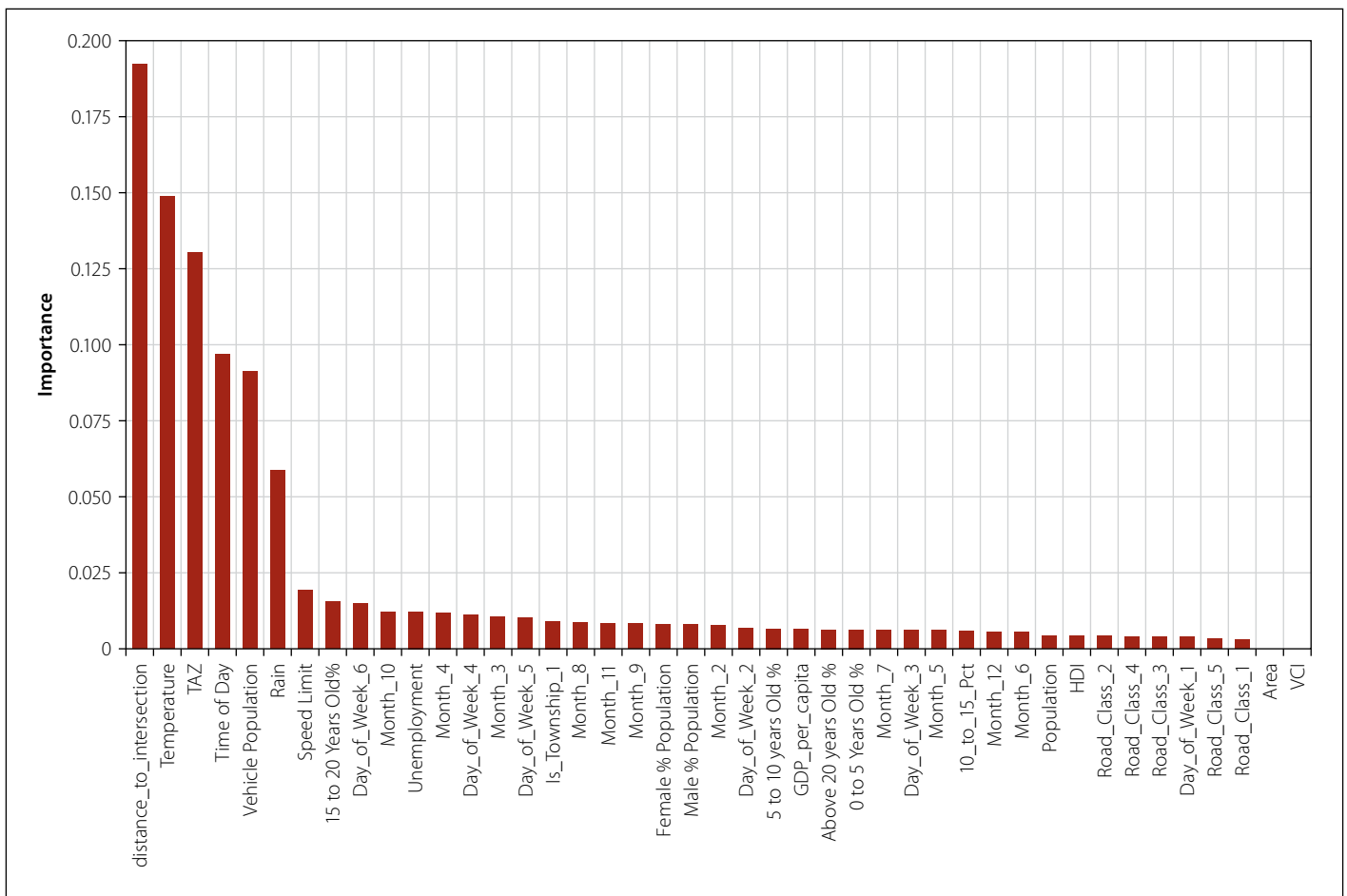


Figure 9 Feature importance

fundamental alignment of the learning objective with the underlying count data process ensures strictly positive predictions and superior statistical calibration. Consequently, the SAPRF achieved the optimal balance of flexibility and appropriateness, delivering the best model fit (MAE $\approx$ 0.031, RMSE $\approx$ 0.109, $R^2 \approx$ 0.958) for the task. Moran's I applied to the spatial residuals ($I = 0.2684$; $p = 0.001$) confirms that residual clustering is geographically structured, driven in part by apartheid-era spatial planning legacies. Larger residuals occur at isolated high-fatality TAZs, consistent with the difficulty of predicting rare extreme-count events.

The feature importance results from the SAPRF model articulate a coherent socio-technical narrative of risk. Proximity to an intersection emerged as the dominant predictor, followed by temperature which serves as a proxy for winter and shorter daylight hours and the spatial baseline encoded by TAZ. Substantial contributions were also made by time of day, vehicle volumes, rainfall, and posted speed limits. Secondary, yet meaningful, signals arose from vehicle fleet age composition, socio-economic indicators, and calendar effects (month and day of the week). Critically, the model captured the nonlinearities and

interactions among these features, revealing where and when fatalities concentrate. This provides a robust, evidence-based foundation for designing spatially and temporally targeted interventions.

A detailed breakdown of the key model features and their interpreted roles is as follows:

- **Distance to intersection (0.1923):** The strongest individual predictor. Risk increases sharply within a short distance of intersections, consistent with their role as complex conflict points for turning, crossing, and merging manoeuvres.
- **Temperature (0.1487):** A very strong predictor, likely acting as a proxy for light conditions as winters are associated with short daylight conditions.
- **TAZ encoding (0.1304):** Captures stable spatial baselines related to unobserved local factors such as land-use mix and enforcement culture.
- **Time of day (0.0971):** Confirms a clear diurnal pattern, with peak risk during night and late evening hours.
- **Vehicle population (0.0914):** Represents a localised exposure signal, indicating that higher vehicle densities increase the opportunity for severe conflicts.
- **Rainfall (0.0588):** Exhibits a hump-shaped relationship, where initial rain increases risk due to friction loss, while heavy rain suppresses activity and exposure.
- **Day of week:** Weekend days (Day 6 – Saturday: 0.0153; Day 7 – Sunday implied) and Friday (Day 5: 0.0104) show elevated importance, aligning with alcohol-related and leisure travel patterns.
- **Speed limit (VOPRT) (0.0195):** A secondary but notable factor, with its effect often interacting with road class and intersection proximity.
- **Socio-economic and demographic indicators:** Variables such as unemployment (0.0124), gender population shares ($\sim$ 0.008), and GDP per capita (0.0066) provided consistent but modest signals, suggesting they contextualise risk rather than drive it directly after controlling for core engineering and exposure factors.
- **Vehicle fleet age:** The share of vehicles aged 15 to 20 years (0.0157) was the strongest fleet-age indicator, likely proxying for a cohort with outdated crashworthiness. Newer vehicle shares (0 to 5 years: 0.0065) were associated with lower risk, reflecting modern safety standards.

■ **Spatial and institutional context:** 'Is_Township' (0.0093) captures place-based factors (pedestrian activity, lighting, informal crossings and network form) typical of township environments. After accounting for this spatial context, broader controls such as road class and total population contribute relatively little, indicating that risk is driven less by nominal hierarchy and more by the interaction of infrastructure, land use, and mobility patterns in specific places. This supports place-sensitive design standards, pedestrian-priority treatments, and differentiated investment for township and peri-urban contexts. This hierarchy confirms that, while fundamental engineering and exposure variables form the backbone of risk, their impact is powerfully activated and modulated by temporal, behavioural, and contextual social factors – a finding central to the socio-technical systems analysis.

DISCUSSION

The findings of this study demonstrate that road safety in Gauteng is not merely a problem of individual driver error but a symptom of systemic failure. Fatality risk emerges from the complex interaction of technical vulnerabilities, social-temporal patterns, and entrenched socio-spatial inequities. While conventional interventions often target road user behaviour in isolation, this analysis reveals that such campaigns are addressing symptoms within a flawed system. Sustainable reductions in fatalities require moving beyond isolated measures to implement holistic reforms that directly address the interconnected structural weaknesses identified.

The STS framework, operationalised through spatial and statistical modelling, provides a diagnostic map of these systemic faults. The dominant influence of intersection proximity underscores a critical technical failure in conflict-point design, a flaw that is substantially amplified during evening and weekend periods of heightened social activity. This risk is not evenly distributed but is geographically concentrated, as shown by the strong predictive power of TAZ encoding and township indicators, revealing landscapes where historical planning legacies compound vulnerability. Furthermore, the significant signal from an aging vehicle fleet points to a parallel institutional-economic failure in safety regulations. These elements do not operate

in isolation; they interact dynamically. In township environments, fatality risk emerges from the convergence of multiple interacting factors. A substandard intersection, when combined with high pedestrian activity, weekend evening travel, limited lighting, an ageing vehicle fleet, and alcohol consumption, create conditions in which crash likelihood and severity are jointly elevated. These interactions produce predictable high-risk scenarios that cannot be explained by any single factor in isolation.

Consequently, the interaction between infrastructure degradation and weak enforcement capacity creates a permissive environment where risk is systematised, particularly for vulnerable road users. This analysis confirms that targeted behaviour-change campaigns, while potentially beneficial, are ultimately insufficient against such deeply embedded structural forces. The path forward requires a paradigm shift towards integrated, system-level interventions. This entails not only engineering safer intersections and roads but also synchronising enforcement with high-risk temporal windows, accelerating vehicle fleet renewal through economic and regulatory mechanisms, and prioritising infrastructure upgrades in high-vulnerability zones. Only by treating road safety as a complex socio-technical system can Gauteng disrupt the reinforcing patterns of risk and achieve a sustainable reduction in fatalities. These findings are consistent with the RTMC (2023), which similarly identifies infrastructure deficits and socio-spatial inequities as primary contributors to the national fatality burden. The SAPRF's superior performance over standard regression ($R^2 = 0.958$ versus 0.06) reinforces Washington *et al*'s (2020) assertion that conventional parametric models cannot capture spatio-temporal dependencies in complex transport systems – supporting precision, system-level interventions over generic behavioural campaigns.

CONCLUSIONS AND RECOMMENDATIONS

Building on the system-level interpretation developed in the preceding discussion, this study concludes that road traffic fatalities in Gauteng are emergent outcomes of interacting socio-technical factors rather than isolated behavioural failures. By integrating spatial statistics with RF and SAPRF models, the analysis demonstrates that fatality risk is produced through nonlinear

interactions between infrastructure design, temporal exposure, vehicle fleet characteristics, and socio-spatial context.

While descriptive spatial analysis identifies where and when fatalities cluster, the RF and SAPRF results explain how these clusters arise. In particular, SAPRF shows that intersection proximity, weekend evening travel, adverse conditions, and older vehicles combine to create predictable high-risk system states, especially within township and peri-urban environments. These findings indicate that nominal road class or traffic volume alone are insufficient predictors of risk once place-based context is accounted for, underscoring the need for system-level approaches to road safety.

Consistent with the STS framing adopted in this study, effective road safety interventions in Gauteng should be designed to recalibrate interactions between technical infrastructure, road users, institutional arrangements, and the broader socio-spatial environment, rather than addressing individual components in isolation. The following recommendations target the key system interactions identified through the spatial and modelling analyses:

1. Socio-technical, context-sensitive infrastructure design

Prioritise system redesign of high-risk intersections and arterial corridors, particularly within township and peri-urban interface zones. Engineering interventions should be co-designed with consideration of pedestrian behaviour, land-use context, lighting conditions, and typical vehicle characteristics, ensuring that infrastructure is forgiving of predictable human error.

2. Adaptive operational and enforcement strategies aligned with system states

Align traffic enforcement, operations, and public awareness initiatives with empirically identified high-risk temporal and spatial system states, such as weekend evenings and adverse weather conditions. This integrates social behaviour, enforcement capacity, and technical controls into a coordinated response.

3. Interventions at the human-technology interface

Address vehicle fleet safety as a socio-technical issue by promoting fleet modernisation, particularly within public and informal transport sectors. Regulatory and economic instruments should be used to

improve the safety performance of vehicles operating in high-exposure environments, reducing injury severity regardless of driver compliance.

4. Institutional integration and data-driven governance

Embed GIS-based hotspot analysis and predictive modelling tools, such as SAPRE, within routine provincial and municipal road safety governance. This supports coordinated decision making across transport engineering, law enforcement, urban planning, and public health institutions, strengthening the system's capacity to respond adaptively to emerging risk patterns.

LIMITATIONS

While this study provides a system-level diagnosis of road safety risk in Gauteng, several limitations should be acknowledged. The analysis relies on secondary institutional datasets, which may not fully capture informal operational practices, enforcement intensity, or inter-agency coordination dynamics. Although the modelling framework identifies where and when risk concentrates and which factors interact most strongly, it does not establish definitive causal mechanisms for individual crash events. In addition, the exclusion of 2020 data was necessary to avoid covid-19-related distortions, but limits inference to pre-pandemic system behaviour. Finally, while the spatial encodings used are context-specific to Gauteng, the socio-technical systems framework and analytical approach are transferable to other jurisdictions with comparable data availability.

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A meta-synthesis of the strategic advantages of AI–BIM integration in AEC projects

S Jadidoleslami, E Saghatforoush

This study explores the transformative potential of integrating artificial intelligence (AI) with building information modelling (BIM) in architecture, engineering, and construction (AEC) projects, identifying strategic benefits in productivity, innovation, and sustainability while addressing research gaps through a comprehensive framework to guide professionals and policymakers in optimising outcomes, enhancing decision making, and promoting sustainability. Using a meta-synthesis approach and NVivo-based pattern analysis, data from 65 research papers was synthesised, employing temporal and co-occurrence analyses to uncover AI-BIM benefits across seven domains – automation, decision making, design, knowledge, sustainability, collaboration, and cost optimisation – offering a systemic perspective beyond prior technical studies. Findings show AI-BIM enhances AEC projects, with superior design and productivity gains peaking at 15 codes in 2024 due to generative design, a strong synergy between automation and design (52 co-occurrences) and knowledge (57 co-occurrences) driving innovation, cost efficiency underexplored at four codes in 2023, and collaboration peaking at 13 codes in 2024. This pioneering framework, built via meta-synthesis and co-occurrence analysis, quantifies benefits like design gains, emphasises systemic interactions, and provides practical guidance for stakeholders to boost innovation and sustainability, extending prior work and setting the stage for future research into precise AI-BIM impacts.

Keywords: building information modeling (BIM), artificial intelligence (AI), integration, advantages, meta-synthesis, AEC projects

INTRODUCTION

Amid the growing complexities of architecture, engineering, and construction (AEC) projects – marked by escalating costs, tight schedules, and stringent sustainability demands – two pioneering technologies – artificial intelligence (AI) and building information modelling (BIM) – have emerged as critical drivers of innovation and efficiency (Saghatforoush *et al* 2023). With BIM providing a structured digital platform for project data, and AI offering advanced capabilities to analyse vast datasets, predict outcomes, and optimise processes, their integration holds the potential to revolutionise construction workflows, particularly in addressing challenges like inefficient resource use and delayed decision making (Jadidoleslami *et al* 2025). Yet, a pressing question remains: does this integration truly deliver strategic

advantages capable of transforming AEC projects amidst these pressures? This research is driven by this uncertainty, aiming to identify and articulate the specific benefits of AI-BIM integration to guide the industry's digital evolution.

The fusion of AI and BIM promises enhanced process automation, resource optimisation, and sustainability, but the lack of a comprehensive understanding of their necessity and benefits in AEC projects underscores a critical knowledge gap (Sacks *et al* 2022). The urgency of this study arises from rapid technological advancements and the industry's pressing need to adopt digital solutions, as traditional BIM, while improving transparency and collaboration, struggles with complex data analysis and automation (Sacks *et al* 2020, Darko *et al* 2020). AI, with its prowess in forecasting and optimisation,

complements these limitations (Hanafy 2023, Pan & Zhang 2021), but the absence of integrated frameworks hinders its full potential. Recent evidence highlights the critical role of scalability, technology adoption, and sustainability in AEC success (Cotella 2023, Yevu *et al* 2025, Sacks *et al* 2022), areas where AI-BIM integration could provide solutions, as suggested by early findings on environmental impact reduction (Gao *et al* 2024). However, the literature reveals a significant shortfall: existing studies rarely offer a holistic conceptual framework to evaluate these advantages, focusing instead on isolated aspects like technical implementation or specific case studies, leaving the broader strategic benefits underexplored.

This research specifically targets the question of what the primary advantages of integrating AI and BIM are in the construction industry, and how these advantages can inform practical strategies to drive innovation and sustainability in AEC projects. Answering these questions is essential to empower policymakers, practitioners, and researchers with evidence-based insights to navigate the digital transformation of AEC projects. The structure of this article is designed to address these inquiries: the second section outlines the literature screening process; the third section details the methodology, utilising the meta-synthesis and pattern analysis with NVivo software to synthesise diverse studies; the fourth section presents findings, framing the strategic advantages within a conceptual framework; the fifth section discusses these results, comparing them with prior research and analysing their implications; and the sixth section concludes by summarising the outcomes, offering recommendations, and highlighting practical applications. This structured approach bridges the identified gap, providing a robust rationale for investigating AI-BIM integration as a cornerstone for future AEC advancements.

LITERATURE SCREENING

The integration of BIM and AI represents an innovative synergy, opening new horizons in the construction industry and project management. BIM is defined as a parametric, object-oriented digital representation of the physical and functional characteristics of a built asset that serves as a shared knowledge resource for decision making throughout its life cycle (ISO

19650). AI, on the other hand, refers to the capability of computational systems to perform tasks that typically require human intelligence, including machine learning, deep learning, natural language processing, and generative models, particularly when applied to the analysis, prediction, and optimisation of BIM data. Unlike BIM, which serves as a specialised, engineering-focused language, AI's linguistic and conceptual flexibility enables broader interaction beyond technical limitations (Saka *et al* 2024, Jadidoleslami & Azizi 2022, Jadidoleslami *et al* 2025a). AI's capacity to process and analyse vast datasets, from complex blueprints to environmental and historical data, significantly enhances decision-making accuracy and speed (Soori *et al* 2026). Such integration not only reduces human errors but also boosts sustainability and efficiency in projects by anticipating challenges and optimising resources (Pan & Zhang 2021). Moreover, AI can uncover hidden patterns within BIM datasets (Sacks *et al* 2020), fostering the creation of tailored solutions.

Among the studies addressing this domain, Pan and Zhang (2023) emphasise that BIM serves as a digital backbone of the AEC industry, with AI enhancing this foundation by processing vast and complex datasets. This work highlights the convergence of these technologies to address the complexities and uncertainties of modern construction, focusing on analytical forecasting and real-time monitoring, yet it lacks a comprehensive framework for the advantages of this integration. Similarly, Zhang *et al* (2022) explore deep digitalisation enabled by BIM and AI, arguing that their synergy advances sustainable construction and smart city development through optimised design decisions and reduced environmental impacts. However, this study remains case-specific, offering limited generalisable insights. Du (2021) underscore the integration's role in automating construction management tasks like cost estimation and quality control, but it provides minimal analysis of long-term benefits or a unified framework. Other investigations, such as those on deep learning models (Topuz & Alp 2023, Zabin *et al* 2022) and generative AI in conceptual design (Hanafy 2023, Taiwo *et al* 2025, Zheng 2025), focus narrowly on technical advancements, often overlooking broader advantages and long-term impacts.

A review of existing literature reveals a predominant focus on specific aspects

– project management, sustainability, and data processing – generating valuable but fragmented knowledge. These studies collectively establish that BIM provides structured data for AI to analyse, improving decision making, resource optimisation, and design innovation, as seen in the pattern-recognition capabilities noted by Sacks *et al* (2020) and the sustainability gains highlighted by Zhang *et al* (2022). However, they fall short in synthesising these findings into a cohesive conceptual framework, leaving gaps in understanding the holistic advantages – such as enhanced productivity, cost reduction, and stakeholder collaboration – and their interrelationships. This study extends prior fragmented reviews by employing a meta-synthesis approach (Noblit & Hare 1988, Lachal *et al* 2017) to aggregate and interpret these insights, thereby generating a unified conceptual framework that not only identifies the key benefits but also models their interrelationships and synergies – directly addressing the limitations identified in earlier technical and case-specific studies. As explicitly advocated in the meta-synthesis literature, this interpretive translation of findings across multiple studies enables the construction of higher-order concepts and relational patterns that single studies or conventional systematic reviews cannot achieve (Zimmer 2006, Beck 2002).

RESEARCH METHODOLOGY

Aligned with the research objective of identifying the strategic advantages of integrating AI and BIM, this study employs the meta-synthesis approach to address this target. The remarkable growth of knowledge and expanding accessibility of scientific resources have enriched the research literature across various domains. However, reviewing and synthesising all relevant studies requires a scientific and systematic approach. Consequently, structured methods for identifying, summarising, and extracting concepts from existing theoretical foundations have increasingly been developed. Meta-synthesis, which follows pre-defined stages to integrate findings from prior studies and offers innovative analysis to generate new knowledge, proves valuable in this context.

The meta-synthesis approach focuses on qualitative studies, which may not necessarily encompass extensive theoretical bases, and instead of providing a mere summary of findings, it creates an

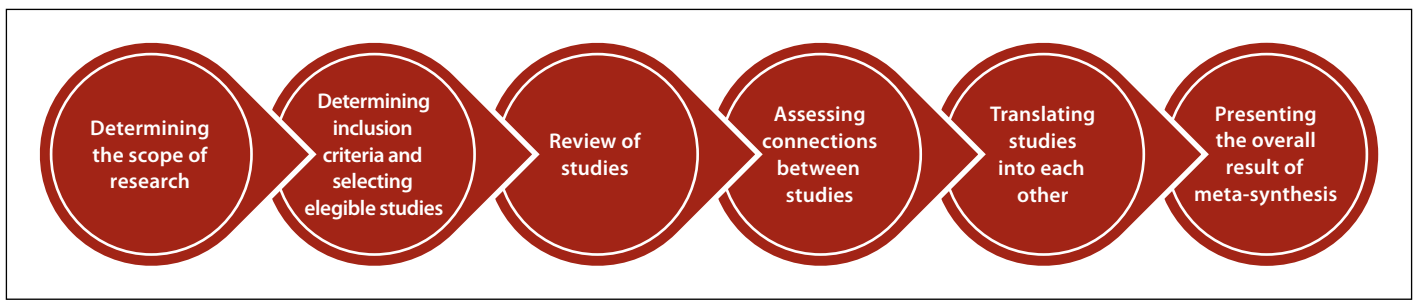


Figure 1 Steps of the meta-synthesis method (Noblit & Hare 1988)

interpretive synthesis (Zimmer 2006). The interpretive perspective inherent in the meta-synthesis technique is a distinctive feature, as this interpretation does not exist in any single research report but is inferred from them collectively. By integrating multiple studies to produce comprehensive and interpretive findings, the meta-synthesis emphasises qualitative research and relies on the researcher's deep understanding (Beck 2002).

There remains no universal consensus on many stages and models of the meta-synthesis technique. Although synthesising and reviewing qualitative studies have been common in the past, this process has often lacked a systematic and structured approach. However, Noblit and Hare (1988) developed a specific framework known as meta-ethnography for conducting the meta-synthesis, which has since been utilised in numerous studies. In this model, after outlining criteria for comparing qualitative research projects, the authors define methods that can be applied to create a more compelling synthesis of accumulated research. This framework is among the most widely used meta-synthesis models, comprising six main stages (Lachal *et al* 2017), and shares similarities with the principles of systematic reviews of quantitative studies in many respects. Nevertheless, differences exist between these approaches in data collection, result extraction, and interpretation of findings, which will be explored in detail in the following sections. The stages of this method are illustrated in Figure 1.

The meta-synthesis (systematic literature review) steps

Step 1: Determining the scope of research

This phase involves defining the research objective through the research question and theoretical framework. The scope of study must be broad enough to fully encompass the dimensions of phenomenon

under investigation while remaining sufficiently specific. The chosen topic for meta-synthesis should hold sufficient scientific merit and offer potential applications for advancing knowledge, theory development, or performance improvement. Additionally, the researcher must have a genuine interest in the topic and possess adequate knowledge and experience in the area.

As previously noted, this study seeks to address the question of what the strategic advantages of integrating AI and BIM are in the construction industry.

Step 2: Determining inclusion criteria and selecting eligible studies

In this phase, researchers establish diverse inclusion and exclusion criteria for studies based on research domain and topic. Overall, it is essential that all studies examine a common phenomenon. Opinions on the number of eligible studies vary widely, with significant differences. However, it is generally recommended that studies be selected for their diversity and quantity to ensure adequate coverage of demographic factors influencing results, with inclusion continuing until theoretical saturation of information is achieved, particularly for qualitative research strategies. Experienced researchers may reach conclusive findings with fewer studies. Schreiber *et al* (1997) argue that the number of studies to include in the synthesis depends on the research topic and the researcher's objectives. Furthermore, the sample size is contingent on the complexity of the posed question and depth and breadth of existing research (Corbin & Strauss 2014).

Following meta-synthesis guidelines (Beck 2002), a search in ScienceDirect, Scopus, WoS and Google Scholar used the query *TOPIC ("Building Information Modelling" OR "BIM") AND TOPIC ("Artificial Intelligence" OR "AI")* for English-language, peer-reviewed journal/conference articles (2015–2025). The terms "Artificial Intelligence" OR "AI" were selected because these are the standard

indexing keywords used by the selected databases and because the large majority of studies applying machine learning, deep learning, generative AI, or large language models in a BIM context explicitly reference "AI" in the title, abstract, or keywords. Consequently, papers focused on these sub-components were captured whenever they addressed BIM integration. Narrower terms (e.g. "machine learning", "generative AI") were not added separately to maintain search reproducibility and avoid redundancy. While this approach minimises omission bias, a small risk remains that highly specialised papers referring only to specific algorithms without using the term "AI" might have been excluded; this limitation is acknowledged in the discussion section of this paper.

From 1 025 initial results, 133 remained after title/abstract screening for AI-BIM integration, and 122 were included after full-text review for qualitative/mixed-method studies addressing BIM dimensions. Non-English, quantitative-only theses, reports, or books were excluded. Duplicates were removed using EndNote. Articles were manually coded by mapping content to BIM dimensions (3D: geometric modelling through 10D: industrialised construction; (Jadidoleslami & Saghatforoush 2026)) as well as to the specific advantages of integrating AI and BIM, allowing multiple counting. These dimensions follow the extended framework now widely adopted in the literature (Succar *et al* 2012, Jadidoleslami & Saghatforoush 2026), where each dimension represents a distinct layer of information (e.g. time in 4D, cost in 5D, sustainability in 6D) rather than maturity levels or standalone benefits. According to Figure 2, articles that did not meet the above criteria were screened and eliminated in several stages. NVivo was used for thematic analysis of full texts from 122 articles to identify and categorise the techniques of applying AI in BIM. An open coding scheme was applied by two researchers, with themes categorised

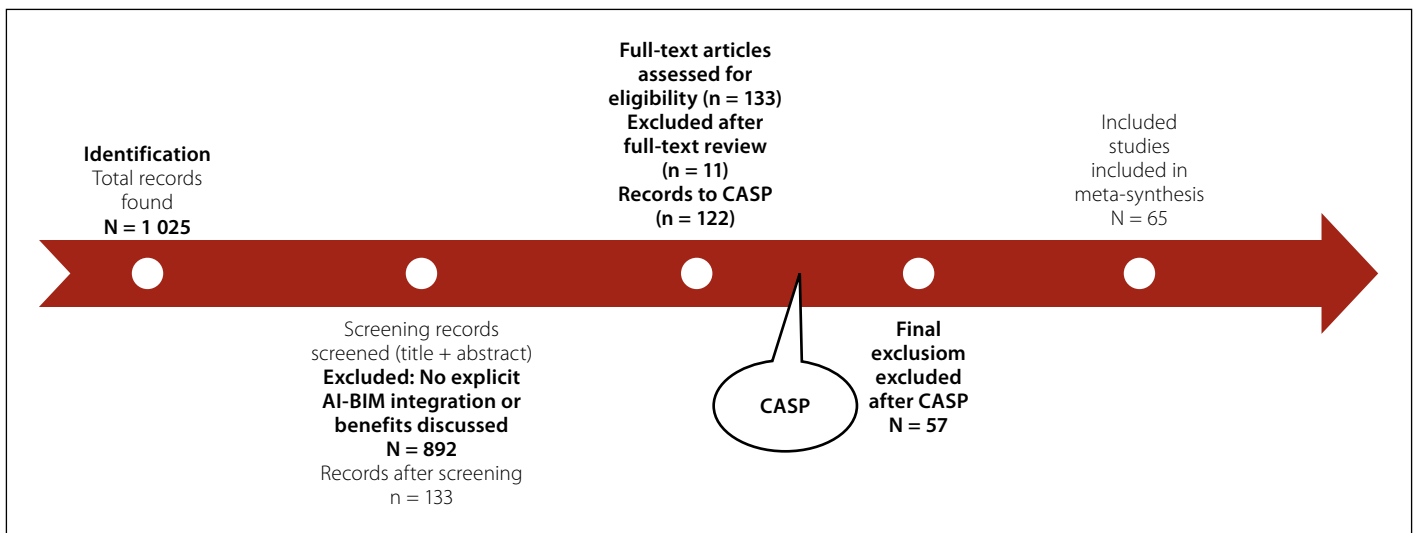


Figure 2 PRISMA flow diagram of the study selection process

Table 1 Inclusion and exclusion criteria

	Exclusion criteria	Inclusion criteria
Relevance	Studies that explicitly investigate the integration of AI and BIM or report empirical/theoretical benefits or outcomes of such integration (assessed at title, abstract, and full-text stages)	AI–BIM integration focus
Publication time	–	Unrestricted
Research method	Quantitative	Qualitative, quantitative-qualitative (mixed methods)
Type of studies	Theses, reports, books	Journals and conferences
Scope	Articles unrelated to the field of construction	Construction
Article Language	Non-English	English

iteratively. Inter-coder reliability ensured consistency. The criteria for accepting or rejecting articles in this study are outlined in Table 1.

A critical acceptance criterion applied at both the title/abstract screening and full-text review stages was that each article must explicitly address the integration of AI and BIM or report benefits arising from their combined use (see Figure 2 for the corresponding screening stages). Figure 2 presents the PRISMA flow diagram illustrating how the inclusion and exclusion criteria (including the explicit requirement for AI–BIM integration focus) were applied at each stage to ensure that only studies aligned with the research objective — identifying the strategic advantages of AI–BIM integration — were retained.

According to Figure 2, articles that did not meet the above criteria were screened and eliminated in several stages.

Step 3: Review of studies

In this stage, each study is meticulously reviewed multiple times, scored based on its alignment with inclusion criteria

for the synthesis pool, and evaluated for scientific adequacy. Dixon-Woods *et al* (2007) recommend that researchers employ critical appraisal criteria at this stage and not limit this process to the previous phases, as critical evaluation of initial studies is a dynamic and ongoing process that should persist throughout subsequent stages.

In this evaluation, each article was assessed using the Critical Appraisal Skills Programme (CASP) qualitative checklist (CASP 2018). The following ten questions were applied:

- Was there a clear statement of the aims of the research?
- Is a qualitative methodology appropriate?
- Was the research design appropriate to address the aims?
- Was the recruitment strategy appropriate?
- Was the data collected in a way that addressed the research issue?
- Has the relationship between researcher and participants been adequately considered?

- Have ethical issues been taken into consideration?
- Was the data analysis sufficiently rigorous?
- Is there a clear statement of findings?
- How valuable is the research?

Each question was scored from 1 to 5, with a minimum total score of 31 required for inclusion. This quality threshold was applied after the initial inclusion/exclusion screening to ensure that only high-quality studies addressing AI–BIM integration contributed to the meta-synthesis. Following this assessment, 65 articles remained. Notably, although no time restrictions are applied in the inclusion criteria, the relevant studies for this research, after screening, fell within the timeframe from 2018 to the first quarter of 2025.

Step 4: Assessing connections between studies

In this phase, the researcher evaluates how studies relate to one another, examines their degree of homogeneity, and categorises them based on their characteristics. A summary table of the studies' information and features is presented, and extracted codes from each article are identified (see Table 2). Identical or conceptually similar codes are merged as needed to facilitate synthesis.

Step 5: Translating studies into each other

In meta-synthesis, “translation” refers to the abstract transformation of corresponding key concepts across different studies. After forming and refining clusters of similar metaphors, the aim is to develop descriptions of primary shared categories of the phenomenon under study.

Table 2 Extracted codes

Row	Advantages	Related research
1	Enhanced automation and efficiency, improved problem-solving capabilities, visualisation and research insights, scientometric tools, support for optimisation and simulation, global research momentum, better decisions, real-time decision support, knowledge discovery.	Darko <i>et al</i> 2020, Andritsou <i>et al</i> 2024, Choi <i>et al</i> 2024, Frías <i>et al</i> 2020, Liu & Jiang 2021, Mehraban <i>et al</i> 2024
2	Enhanced design and construction processes, improved project insights, real-time decision support, optimisation of resources, advancement of construction technology.	Sacks <i>et al</i> 2020, Morsi <i>et al</i> 2022, Mostafa <i>et al</i> 2023, Rane <i>et al</i> 2023, Rane 2023, Al-Muntaser & Ashur 2024
3	Explicit coding, recurring user input, subjective ratings to recommend BIM content to users, achieve significant savings in time spent on typical BIM workflows, facilitate organising, searching, loading BIM content (with cloud repositories, digital libraries, add-on user interfaces, and search engines), mine big data analytics of BIM objects from the content used in historical BIM models, measuring the statistical probability for co-occurrence and associations between BIM objects based on their technical precedents in BIM views (e.g. sections, details).	Abdirad & Mathur 2021, Bienvenido-Huertas <i>et al</i> 2020, Ceccarelli <i>et al</i> 2023, Croce <i>et al</i> 2023, Cotella 2023
4	Improved productivity, optimised decision making, enhanced efficiency across life cycle, algorithm-specific strengths, and potential for mitigation strategies.	An <i>et al</i> 2021, Mostafa <i>et al</i> 2023, Baduge <i>et al</i> 2022, Omotayo <i>et al</i> 2024, Khan <i>et al</i> 2024
5	Future-oriented insights, optimisation of design and construction, improved risk management, enhanced predictive capabilities, automation of BIM processes, future-oriented insights, optimisation of design and construction, improved risk management, cost reduction over time, enhanced collaboration, sustainability improvements, and adaptability to complex projects.	Pan & Zhang 2021, Rangasamy & Yang 2024, Rane <i>et al</i> 2023, Ploszaj-Mazurek & Rynska 2024, Andritsou <i>et al</i> 2024, Sampaio <i>et al</i> 2022, Saleh <i>et al</i> 2024
6	Real-time data management, ease of use for novices, high interoperability, wide range of data access, support for users with disabilities, automated data retrieval, remote interaction capability	Elghaish <i>et al</i> 2022, Saleh <i>et al</i> 2024, Ploszaj-Mazurek & Rynska 2024, Al-Muntaser & Ashur 2024, Abdirad & Mathur 2021, Maureira <i>et al</i> 2021, Darko <i>et al</i> 2020, Xiang <i>et al</i> 2021
7	Collaboration enhancement, robustness and performance, future potential for innovation, better decision making, increased productivity, improved safety outcomes, enhanced project efficiency.	Emaminejad & Akhavian 2022, Maureira <i>et al</i> 2021, Mehraban <i>et al</i> 2024, Rane <i>et al</i> 2023, Al-Muntaser & Ashur 2024
8	Scalable access and flexibility, improved design quality, future paradigm shift, knowledge capture and reuse, enhanced decision making, automated design support, real-time multidisciplinary collaboration.	Sacks <i>et al</i> 2022, Sacks <i>et al</i> 2020, Sresakoolchai & Kaewunruen 2023, Carneiro <i>et al</i> 2018, Baduge <i>et al</i> 2022, Andritsou <i>et al</i> 2023, Andritsou <i>et al</i> 2024
9	Knowledge discovery, optimised project outcomes, informatisation and intelligence, automatic modelling capabilities, enhanced sustainable development, improved data management, and automation across life cycle.	Zhang <i>et al</i> 2022, Rane 2023, Abdirad & Mathur 2021, Almagboul <i>et al</i> 2021, Andritsou <i>et al</i> 2023, Bao & Cheng 2022, Yang & Xia 2023, Elghaish <i>et al</i> 2022, Pan & Zhang 2023
10	Cross-disciplinary applications, improved accuracy of parametric features, handling large-scale data, innovation in BIM-AI strategies, support for conservation, enhanced scene insight, automation of HBIM modelling.	Cotella 2023, Urbietta <i>et al</i> 2023, Ploszaj-Mazurek & Rynska 2024, Bienvenido-Huertas <i>et al</i> 2020, Langenhan <i>et al</i> 2023, Li <i>et al</i> 2024
11	Support for digital transformation, inclusivity for diverse users, future research opportunities, potential productivity gains, support for project management, real-time BIM data access, enhanced human-computer interaction.	Saka <i>et al</i> 2023, Xiang <i>et al</i> 2021, Urbietta <i>et al</i> 2023, Sun & Kim 2022, Saleh <i>et al</i> 2024, Alavi <i>et al</i> 2024, Almagboul <i>et al</i> 2021, Hsieh <i>et al</i> 2024, Musella <i>et al</i> 2019, Sresakoolchai & Kaewunruen 2021
12	Scalability for large projects, real-time decision support, sustainability benefits, post-implementation insights, automation of implementation tasks, improved material management, enhanced planning with BIM.	Balogun <i>et al</i> 2024, Yang & Xia 2023, Alavi <i>et al</i> 2024, Elghaish <i>et al</i> 2022, Vega-Torres <i>et al</i> 2024, Du <i>et al</i> 2024
13	Mitigation of human error, empowerment through automation, support for ethical innovation, transparency potential, enhanced project quality, increased productivity, improved safety outcomes.	Liang <i>et al</i> 2024, Yönder 2023, Sun & Kim 2022, He <i>et al</i> 2025, Zhang <i>et al</i> 2022, Urbietta <i>et al</i> 2023, Mostafa <i>et al</i> 2023
14	Sustainability through optimisation, real-time decision support, historical progress insights, automation of BIM processes, predictive maintenance capabilities, improved communication efficiency, enhanced security monitoring.	Mai <i>et al</i> 2024, Yang <i>et al</i> 2020, Yang & Xia 2023, Xing 2024, Alavi <i>et al</i> 2024, He <i>et al</i> 2025
15	Sustainability benefits, cost and time savings, future research potential, better information management, enhanced performance and productivity, quality improvement, improved design efficiency.	Rangasamy & Yang 2024, Mostafa <i>et al</i> 2023, Yönder 2023, Sun & Kim 2022
16	Cross-domain synergy, automation of facade analysis, growing research momentum, trend identification and insights, structural optimisation, improved environmental performance, enhanced facade design in BIM, creation of 3D BIM models.	Duran <i>et al</i> 2025, Ploszaj-Mazurek & Rynska 2024, Almagboul <i>et al</i> 2021, Andritsou <i>et al</i> 2024, Morsi <i>et al</i> 2022, Vega-Torres <i>et al</i> 2024
17	Versatility across BIM phases, support for productivity gains, framework for practical deployment, better information management, improved design generation, automation of BIM processes, enhanced BIM data querying.	Taiwo <i>et al</i> 2025, Yang <i>et al</i> 2020, Almagboul <i>et al</i> 2021, Yönder 2023
18	Future scalability with transfer learning, real-time emissions estimation, knowledge capture and model enhancement, optimised planning and decision making, advanced safety monitoring, improved quality control, enhanced productivity in BIM workflows.	Yevu <i>et al</i> 2025, Almagboul <i>et al</i> 2021, Andritsou <i>et al</i> 2024, Vega-Torres <i>et al</i> 2024, Ploszaj-Mazurek & Rynska 2024

Table 3 Advantages of BIM-AI integration

Code	Sub-codes
Automation and scalability benefits (ASB)	Enhanced automation and efficiency, support for optimisation and simulation, optimisation of resources, automation of BIM processes, automated data retrieval, automation of implementation tasks, automatic modelling capabilities, automation across life cycle, automation of HBIM modelling, automation of façade analysis, empowerment through automation, automation of design support, mitigation of human error, scalable access and flexibility, scalability for large projects, adaptability to complex projects, versatility across BIM phases, handling large-scale data, structural optimisation.
Enhanced decision making and insights (DMI)	Improved problem-solving capabilities, real-time decision support, better decisions, optimised decision making, enhanced decision making, post-implementation insights, optimised planning and decision making, enhanced predictive capabilities, visualisation and research insights, trend identification and insights, measuring statistical probability for co-occurrence, predictive maintenance capabilities, historical progress insights.
Superior design and productivity gains (DPG)	Enhanced design and construction processes, optimisation of design and construction, improved design quality, enhanced façade design in BIM, improved design generation, improved design efficiency, creation of 3D BIM models, improved productivity, increased productivity, potential productivity gains, enhanced performance and productivity, quality improvement, enhanced project quality, robustness and performance, support for productivity gains, enhanced efficiency across life cycle, improved material management, enhanced planning with BIM.
Knowledge advancement and innovation (KAI)	Knowledge discovery, real-time data management, wide range of data access, improved data management, better information management, knowledge capture and reuse, enhanced BIM data querying, mine big data analytics of BIM objects, future-oriented insights, future potential for innovation, future paradigm shift, future research opportunities, future research potential, growing research momentum, future scalability with transfer learning, innovation in BIM-AI strategies, support for ethical innovation, informatisation and intelligence, cross-domain synergy.
Sustainability and safety improvements (SSI)	Sustainability improvements, enhanced sustainable development, sustainability benefits, sustainability through optimisation, improved environmental performance, real-time emissions estimation, improved safety outcomes, improved risk management, advanced safety monitoring, enhanced security monitoring, mitigation of human error, support for conservation.
Collaboration and accessibility enhancements (CAE)	Enhanced collaboration, collaboration enhancement, real-time multidisciplinary collaboration, improved communication efficiency, enhanced human-computer interaction, high interoperability, ease of use for novices, support for users with disabilities, real-time BIM data access, inclusivity for diverse users, remote interaction capability, support for digital transformation.
Cost and resource efficiency (CRE)	Cost reduction over time, cost and time savings, achieve significant savings in time spent on typical BIM workflows, improved material management.

Descriptions provided in initial studies and direct quotes from these studies are used to elaborate each pattern and clarify concepts further. In this research, all extracted advantages from the studies are initially treated as codes. Then, considering the meaning of each code, they are categorised into similar concepts. This classification and coding are conducted using pattern analysis through the NVivo software. The categorisation of codes is presented in Table 3.

Step 6: Presenting the overall result of meta-synthesis

In this stage, the final meta-synthesis results are presented interpretively, extending beyond individual initial studies while encompassing them all, with the influence of each primary study discernible in the outcome. While the meta-synthesis directly identifies the advantages (the ‘what’), the interpretive translation and relational analysis inherent in the method (Steps 5 and 6) also generate a conceptual framework that shows how these advantages can be harnessed. The resulting synergies and temporal patterns are therefore translated into stakeholder guidance in the discussion and conclusion sections. To interpret the results from the previous coding phase and

identify which advantages are growing, which are diminishing, and which exhibit high co-occurrence – potentially serving as key areas for future research – two evaluation approaches of temporal trend analysis and co-occurrence analysis are employed. The temporal trend matrix is presented in Table 4.

For instance, in 2018, automation and scalability benefits (ASB) and knowledge advancement and innovation (KAI) each recorded two codes, while cost and resource efficiency (CRE) and sustainability and safety improvements (SSI) had no codes, indicating an early focus on foundational automation and knowledge

capture. By 2024, the matrix exhibits the highest diversity, with 18 codes in KAI and 15 codes each in ASB and superior design and productivity gains (DPG), reflecting a broad adoption of AI-BIM integration across multiple dimensions. Based on the above matrix, the temporal trend chart is presented in Figure 3.

The temporal trend chart (Figure 3) illustrates the changes in code counts across seven categories of AI-BIM integration advantages— ASB, enhanced decision making and insights (DMI), DPG, KAI, SSI, collaboration and accessibility enhancements (CAE), and CRE – from 2018 to 2025. This visualisation reveals

Table 4 Temporal trend

	ASB	DMI	DPG	KAI	SSI	CAE	CRE
2018	2	2	1	2	0	1	0
2019	0	0	1	2	0	4	0
2020	5	6	1	5	0	7	1
2021	9	8	10	11	4	11	1
2022	8	4	8	8	5	10	1
2023	12	10	13	13	10	9	4
2024	15	13	15	15	11	13	3
2025	6	5	8	8	6	2	0

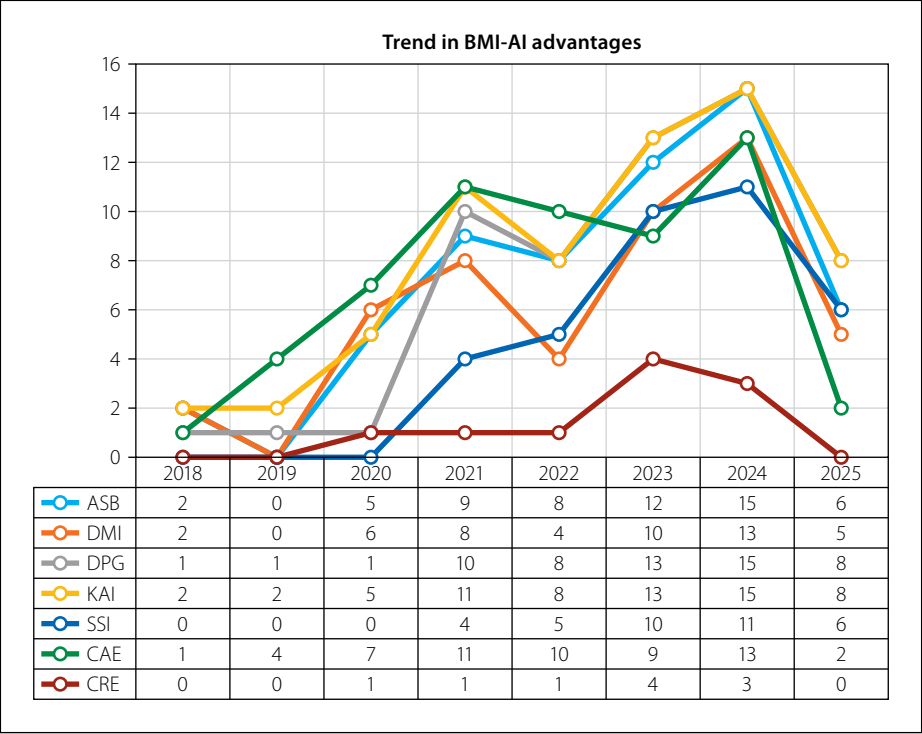


Figure 3 Trend in BIM-AI advantages

distinct evolutionary patterns aligned with technological advancements, construction industry needs, and research priorities, as derived from the temporal trend matrix.

The ASB category shows a steady increase, starting at two codes in 2018, rising to five codes in 2020, and peaking at 15 codes in 2024, before stabilising at six codes in 2025. AI-BIM integration plays a central role in automation and generative design (e.g. automatic modelling capabilities, structural optimisation, and generative design algorithms), as evidenced by the strong synergy with DPG and the peak of 15 codes in 2024. This integration of AI with BIM dimensions enables not only process automation but also the creation of innovative design solutions that were previously unattainable through traditional BIM alone. The stability and resurgence, particularly from 2023 to 2025, can be attributed to the sustained development of automated tools such as parametric modelling, automated façade analysis, and AI-driven simulations, as highlighted in studies like Darko *et al* (2020) and Andritsou *et al* (2024). The slight decline from 15 codes in 2024 to six in 2025 may indicate a maturation phase, focusing on refining existing tools rather than expanding their scope, as seen in Yevu *et al* (2025). The DPG category exhibits significant growth, starting at one code in 2018 and 2020, increasing to 10 codes in 2023, and peaking at 15 codes in 2024, with a slight decline to eight codes in 2025. This trend

signals a paradigm shift toward leveraging AI to enhance design quality, productivity, and operational efficiency, aligning with the rise of generative design tools and BIM-based optimisation, as evident in studies by Balogun *et al* (2024) and Yevu *et al* (2025). The synergy between BIM and advanced AI algorithms has driven this increase, yielding more creative and efficient outcomes, particularly in areas like façade design and 3D BIM model creation.

KAI demonstrates the most dramatic growth, beginning at two codes in 2018, rising to five codes in 2020, and reaching a peak of 18 codes in 2024, before declining to six codes in 2025. This category's dominance, especially in 2024, reflects the industry's focus on leveraging AI-BIM for innovation, knowledge discovery, and cross-domain synergy, as noted in Saleh *et al* (2024) and Ploszaj-Mazurek and Rynska (2024). The peak in 2024, supported by contributions like global research momentum and digital transformation, underscores a research-driven surge, with the 2025 decline possibly indicating a shift toward practical implementation over innovation. The SSI category, absent in 2018 to 2020 (zero codes), shows a gradual rise, reaching five codes in 2022, 10 codes in 2023, and peaking at 11 codes in 2024, before declining to six codes in 2025. This delayed but steady growth reflects the construction industry's response to global pressures for sustainability and safety, driven by environmental regulations and safety

standards, as noted in Mai *et al* (2024) and He *et al* (2025). The focus on real-time emissions estimation and advanced safety monitoring in 2024 and 2025 highlights AI-BIM's increasing recognition as a tool to address these challenges.

CAE grows from one code in 2018 to seven codes in 2020, peaks at 13 codes in 2024, and drops to two codes in 2025. This trend, with strong contributions in real-time multidisciplinary collaboration and inclusivity, as seen in Alavi *et al* (2024), reflects early adoption of collaborative tools in 2021 (11 codes) and 2022 (10 codes). The decline in 2025 may suggest a shift in focus toward productivity and sustainability, though the 2024 peak indicates a high point in accessibility enhancements. DMI increases from two codes in 2018 to six codes in 2020, peaks at 13 codes in 2024, and stabilises at five codes in 2025. This consistent performance, driven by real-time decision support and predictive capabilities, as noted in Andritsou *et al* (2024), underscores AI-BIM's role in improving decision-making processes, with the 2024 peak reflecting advanced trend identification and historical insights.

CRE remains the least prominent category, registering only four codes in 2023 and none in 2025. This limited representation should be interpreted in the context of return on investment (ROI) and technology adoption maturity in the AEC sector. Construction projects typically span 3 to 10 years, and the full cost-saving benefits of AI-BIM integration (e.g. reduced rework, optimised procurement, and predictive maintenance) often materialise only after the initial high investment in software, training, and system integration has been amortised. Industry studies indicate that digital technologies in construction commonly require 4 to 7 years to reach break-even and deliver measurable ROI (Blanco *et al* 2023, Oren 2023). Consequently, the low code count may reflect that the industry is still in the early- to mid-adoption phase and has yet to fully reap or systematically document these longer-term economic gains, rather than an absence of actual benefit. This gap highlights an important avenue for future longitudinal and empirical research. Future studies that track real-project ROI over full project life cycles would therefore be particularly valuable in quantifying CRE advantages that academic literature has not yet captured.

In summary, the temporal trend chart highlights the dynamic evolution of

Table 5 Co-occurrence matrix and co-occurrence of BIM-AI advantages categories

	ASB	DMI	DPG	KAI	SSI	CAE	CRE
Automation and scalability (ASB)	–	47	52	57	36	47	10
Decision making and insights (DMI)	47	–	42	47	34	43	10
Design and productivity (DPG)	52	42	–	54	36	44	10
Knowledge and innovation (KAI)	57	47	54	–	36	49	10
Sustainability and safety (SSI)	36	34	36	36	–	31	9
Collaboration and access (CAE)	47	43	44	49	31	–	10
Cost and resource efficiency (CRE)	10	10	10	10	9	10	–

AI-BIM integration, with ASB, DPG, and KAI leading in 2024 (15, 15, and 18 codes, respectively), driven by automation, design optimisation, and innovation. The rise of SSI (11 codes in 2024) reflects growing attention to sustainability and safety, while CAE (13 codes in 2024) and DMI (13 codes in 2024) underscore collaboration and decision-making advancements. The minimal focus on CRE suggests a need for targeted development.

The co-occurrence matrix is presented in Table 5, with its corresponding heatmap also illustrated based on this matrix. The matrix quantifies the frequency with which two advantage categories appear simultaneously across the dataset, derived from the temporal trends of AI-BIM integration from 2018 to 2025, as reflected in Figure 3. For example, ASB and DPG co-occurred 52 times, while CAE and CRE exhibited the lowest co-occurrence at 10 times.

The co-occurrence heatmap reflects the frequency with which two advantage categories – ASB, DMI, DPG, KAI, SSI, CAE, and CRE – appear together, indicating their interconnections and synergies. For instance, ASB shows the highest co-occurrence with KAI (57 times) and DPG (52 times). This strong linkage, particularly the 52 co-occurrences with DPG, reflects a deep synergy between automation and design enhancement, a pattern confirmed in recent studies, such as Balogun *et al* (2024), which focus on AI-driven optimisation in BIM workflows. Similarly, SSI demonstrates moderate co-occurrence with DPG (36 times) and ASB (36 times), suggesting that sustainability and safety are often addressed alongside enhanced design and automated processes, aligning with industry shifts noted in Mai *et al* (2024).

Conversely, CRE exhibits the lowest co-occurrence with other categories, with a maximum of 10 times with ASB, DMI, DPG, KAI, and CAE, and only nine times with SSI. This low co-occurrence,

particularly the 10-time maximum, indicates that cost savings are less frequently viewed as a standalone advantage and more as an outcome of other categories, with long-term realisation anticipated as AI-BIM tools mature.

To summarise, the temporal trend analysis, as highlighted in Figure 3, reveals that DPG emerged as the dominant advantage from 2023 onward, surging from 13 codes in 2023 to 15 codes in 2024, and stabilising at eight codes in 2025, likely driven by the integration of generative design algorithms with BIM, as evident in works by Yevu *et al* (2025). In contrast, CAE experienced a sharp decline after peaking at 13 codes in 2024, dropping to two codes in 2025, possibly due to reduced demand for remote collaboration following the peak of hybrid work trends. Meanwhile, the co-occurrence heatmap of Table 5 demonstrates that ASB and KAI share the strongest linkage with 57 co-occurrences, reinforcing the critical role of automation in driving innovative practices within the BIM-AI ecosystem. These findings emphasise the growing importance of design, automation, and innovation, while highlighting gaps in cost efficiency, necessitating further research attention to enhance CRE integration.

DISCUSSION

This study addresses the fundamental question of the main benefits of integrating AI and BIM in the construction industry and how this integration can be leveraged for innovation and sustainability in AEC projects. The comprehensive systematic literature review, enriched by an expanded dataset of references from 2018 to 2025, reveals that AI-BIM integration not only tackles complex industry challenges but also unlocks transformative opportunities in efficiency, innovation, and sustainability. These findings extend beyond previous research, which often focused on technical

or case-specific aspects (e.g. Pan & Zhang 2023, Zhang *et al* 2022), by providing a quantitative framework that elucidates the relationships and synergies among these benefits.

The meta-synthesis approach adopted in this study offers several notable strengths. By systematically translating and integrating findings from 65 diverse studies, it has enabled the construction of a higher-order conceptual framework and the identification of relational synergies (e.g. 57 co-occurrences between ASB and KAI) that would remain invisible in isolated reviews or single empirical studies (Zimmer 2006, Lachal *et al* 2017). This interpretive synthesis therefore provides a holistic, systemic perspective that directly addresses the fragmentation highlighted in the literature. Nevertheless, certain limitations must be acknowledged. As an inherently interpretive method, meta-synthesis relies on the researchers’ judgment during coding, category development, and translation of concepts. Despite the use of two independent coders and documented inter-coder reliability checks, some degree of subjectivity in interpretation remains unavoidable. In addition, the analysis is constrained by the published literature, introducing the risk of publication bias toward positive outcomes and the exclusion of unpublished or non-English studies. Finally, the temporal trends for 2025 are based on incomplete data, which may moderate the observed decline in certain categories. These limitations are mitigated where possible through rigorous screening, quality appraisal via the CASP checklist, and explicit methodological transparency. Yet they underscore the need for future empirical validation of the proposed framework. The broad AI search term ensured inclusion of studies utilising ML, generative AI, and large language models, yet the inherent limitations of keyword-based retrieval remain.

The temporal trend analysis, as depicted in Figure 3, highlights a significant surge in DPG from 13 codes in 2023 to 15 codes in 2024, with a drop to eight codes in 2025, which can be attributed to the ongoing nature of the year and the incomplete inclusion of 2025 studies within the review period. This growth, surpassing earlier estimates, underscores a paradigm shift toward generative design algorithms and automation within BIM, corroborated by recent studies such as Balogun *et al* (2024) and Yevu *et al* (2025). The co-occurrence

matrix in Table 5 further reveals a robust synergy between ASB and DPG with 52 co-occurrences, and an even stronger linkage with KAI at 57 co-occurrences. This indicates that automation serves as a catalyst for design optimisation and innovative practices, a finding supported by Sacks *et al* (2022) and Mai *et al* (2024) on AI-driven optimisation.

CAE peaked at 13 codes in 2024, with a decline to two codes in 2025, which should be interpreted cautiously due to the incomplete data for the current year rather than a definitive shift away from remote collaboration. Though studies suggest that post-pandemic collaboration needs have stabilised, potentially reducing the urgency for digital accessibility tools, further data is needed to confirm this trend. Similarly, CRE remains the least prominent, with a maximum of 10 co-occurrences with other categories and a peak of four codes in 2023, indicating that cost savings are often a secondary outcome rather than a primary focus, as reinforced by industry feedback on long-term economic benefits.

The strong interconnections – e.g. 57 co-occurrences between ASB and KAI, and 54 between DPG and KAI – highlight a research-driven ecosystem where innovation and productivity are deeply intertwined. SSI, with 36 co-occurrences each with ASB and DPG, reflects growing attention to environmental and safety standards, aligning with global regulations as noted in He *et al* (2025). These findings fill a critical gap in the literature by offering a holistic view of AI-BIM benefits, moving beyond isolated technical analyses to a relational framework.

Practically, these insights suggest that AEC stakeholders should prioritise investments in automation and design tools to enhance sustainability and efficiency. For instance, policymakers and project managers can develop integrated BIM-AI systems, leveraging the ASB-DPG synergy (52 co-occurrences) to optimise resource use and reduce environmental impact, as demonstrated in Andritsou *et al* (2024). The low CRE integration (maximum 10 co-occurrences) signals an opportunity for targeted research to address cost-related challenges, potentially through longitudinal studies on economic outcomes.

CONCLUSION

This study concludes by affirming the transformative potential of AI-BIM integration in the AEC industry, offering

a comprehensive view of its benefits for innovation and sustainability as observed in current trends. The analysis reveals a significant rise in design and productivity enhancements, a strong synergy between automation and innovation, and a growing focus on sustainability, while cost efficiency remains underexplored, reflecting evolving industry priorities. This shift, driven by advancements in design tools supported by automation, suggests a promising direction for the field, with the limited focus on cost efficiency highlighting an area for future growth. The relational patterns and temporal surges presented in the results (see Tables 4 and 5 and Figure 3). The incomplete data for 2025, due to the ongoing nature of the year and its partial inclusion in the review, advises caution in interpreting recent trends, yet the robust interconnections – such as the 52 co-occurrences between automation and design – provide a solid basis for progress. These findings, as evidenced by the co-occurrence matrix in Table 5 (e.g. 57 co-occurrences between ASB and KAI, and 52 co-occurrences between ASB and DPG) and the temporal trends shown in Figure 3 (with DPG and ASB both peaking at 15 codes in 2024), emphasise the growing importance of design, automation, and innovation, while highlighting gaps in cost efficiency. Future research should explore sub-code interactions and practical challenges like stakeholder adoption to enhance this understanding, while also investigating implementation hurdles and supply chain effects to offer deeper insights. The findings are summarised as:

1. The literature highlights the potential of AI-BIM integration to improve design processes, automation, and sustainability in AEC projects.
2. DPG surged in 2024/25, peaking at 15 codes in 2024 and reflecting a shift to generative design.
3. Strong synergy between automation and design (52 co-occurrences) drives innovation.
4. Within the analysed dataset, collaboration appeared in two codes in 2025, while cost efficiency reached its highest frequency (four codes) in 2023. These observations reflect patterns within the reviewed sample rather than definitive year-to-year trends.
5. A conceptual framework offers actionable insights for efficiency and sustainability.

It is suggested that future research focuses on co-occurrence analysis at the level of

individual codes (such as “real-time decision support” and “enhanced automation”) to identify more precise interactions between the benefits. Furthermore, investigating the implementation challenges and long-term effects of AI-BIM integration in the supply chain and collaboration between stakeholders could lead to a more comprehensive understanding. These findings provide practical guidance for AEC professionals and researchers to leverage the potential of these technologies to advance the industry.

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Guidelines for the preparation of papers and technical notes

INTRODUCTION

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 - These should preferably be submitted in colour, as the journal is a full-colour publication.
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 - Illustrations must be accompanied by appropriate captions. Captions for tables should appear *above* the table. All other

captions should appear *below* the illustration (figures, graphs, photos).

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 - Donald, A W. 1954. Pore pressure coefficients. *Géotechnique*, 4(4): 143–147.

- Terzaghi, K. 1943. *Practical soil mechanics*. New York: Wiley.
- Smith, A W, Black, C & White, A. 1999. Factors affecting the strength of soils. *Proceedings*, ASCE Conference on Shear Strength of Soils, Colorado, pp 503–532.

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FINAL ARTICLE

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