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Geometric Assessment of Software-Based Path Planning for Mechanized Seeding Operations

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Abstract.

This study evaluated the impact of different software-based planning routines on the geometry of guidance lines for mechanized seeding operations. A controlled comparative case-study approach was implemented using two agricultural fields in Minas Gerais, Brazil. One irregular field of 33.6 ha and one predominantly rectilinear field of 107.6 ha. Two anonymized tools, Software A and Software B, were applied to identical boundary polygons, with one headland pass and 9 m line spacing. The exported line shapefiles were projected to SIRGAS 2000 / UTM Zone 23S and analyzed using indicators such as line distribution, short-line occurrence, estimated maneuvers, operational continuity, spacing, working angle, and scenario-based operational field capacity. Software B improved the primary path-quality indicators, particularly in the irregular field, where the number of short lines decreased from 15 to 10 and estimated maneuvers decreased from 134 to 130. Operational continuity increased from 88.89% to 92.37%. In the regular field, both tools achieved 100% operational continuity, but Software B reduced line-length variability from 27.59% to 26.05%. Under standardized assumptions of 6 km h^{-1} travel speed and 90 s per headland maneuver, estimated operational field capacity increased from 3.78 to 3.84 6 ha h^{-1} in the irregular field and from 4.78 to 4.80 ha h^{-1} in the regular field. These findings indicate that the planning routine influenced path geometry more substantially than estimated short-term field capacity, with the most pronounced benefits observed under irregular boundary conditions.

Keywords.

precision agriculture; path planning; mechanized seeding; field geometry; operational field capacity.

Introduction

Mechanized crop operations increasingly depend on digital planning, georeferenced data, and automatic guidance. Global Navigation Satellite System (GNSS) receivers and auto-steering systems are now common in seeding, spraying, fertilization, and harvesting because they help maintain pass-to-pass alignment and reduce overlap between adjacent swaths (Santos et al., 2018; Lipinski et al., 2016). Their performance is closely related to the quality of corrections, including real-time kinematic (RTK) and other differential solutions, which may require local base stations, correction networks, or paid correction services (Pagnan et al., 2021; Hofmann-Wellenhof et al., 2008). The adoption of these technologies is part of the broader development of precision agriculture and data-driven decision support (Ortiz et al., 2013; Tey & Brindal, 2012). Nevertheless, accurate positioning is only one component of an efficient operation; the planned traffic pattern also determines how the machine moves within the field.

A guidance system can accurately follow a poorly laid-out path. For this reason, line geometry deserves attention separate from positioning accuracy. Planned paths determine expected travel distance, headland turns, line-length distribution, and the proportion of work performed in uninterrupted passes. These attributes are linked to field efficiency, energy demand, fuel use, and operation time in mechanized agriculture (Bochtis et al., 2012; Rodias et al., 2017). Although previous studies have evaluated guidance and positioning errors during field operations (Santos et al., 2017; Pagnan et al., 2021), fewer studies have focused on the line set produced before operations begin.

Boundary shape is one of the main constraints in this planning problem. Fields with regular borders tend to accommodate parallel lines with similar lengths, whereas irregular limits create residual areas and interrupt otherwise continuous passes. During seeding, these short passes are relevant because the tractor–implement set may not remain in stable operating conditions during long enough before reaching the end of the line, affecting travel-speed stabilization and seed-metering regularity (Garcia et al., 2016; Weirich Neto et al., 2015). Plot geometry has also been associated with efficiency and quality indicators in mechanized seeding (Paixão et al., 2017), supporting evaluation of planned geometry before field execution.

Different software routines may transform the same boundary into different sets of guidance lines. The final output depends on how each routine handles line orientation, boundary offsets, clipping, headland configuration, and residual fragments. These internal decisions are not always visible to the user, particularly when proprietary routines are involved. A direct comparison of exported line geometries is therefore a practical way to evaluate whether two planning workflows produce alternative operational indicators under identical input conditions.

This study compared the exported path geometries generated by two anonymized software tools for mechanized seeding in one irregular field and one predominantly rectilinear field. The objective was to quantify the effects of the planning routine on line distribution, short-line occurrence, estimated maneuvers, operational continuity, spacing, working angle, and a standardized estimate of operational field capacity. Differences between tools were expected to be greater in the irregular field because boundary complexity raises the likelihood of fragmented lines and additional headland turns.

Materials and Methods

A controlled comparative design was implemented. Both planning tools were applied to identical field boundaries, and their exported line sets were evaluated using the same metrics. The first field exhibited an irregular boundary and covered 33.6 ha, while the second field was predominantly rectilinear and encompassed 107.6 ha. Both fields are located in the Cerrado biome of Minas Gerais, Brazil (Fig. 1). As each software package received the same polygon for each field, any differences in the exported paths were attributed to the planning routines rather than to field delimitation.

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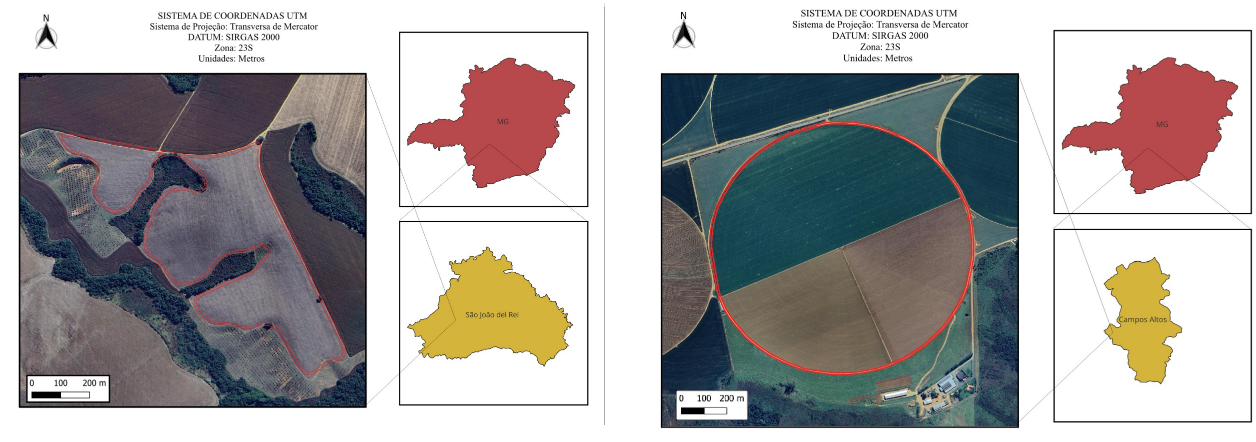


(a) Irregular field **(b) Regular field**

Figure 1. Spatial context of the fields used for geometric path-planning analysis, showing the field boundaries over satellite imagery and their location in Minas Gerais, Brazil, in the SIRGAS 2000 / UTM Zone 23S coordinate reference system

Software tools and geometric optimization

The two planning tools were evaluated as black-box generators of seeding lines. Software A operated within CAD (Autodesk, San Francisco, CA, USA) and generated lines using its standard computer-aided design workflow. Software B, developed with Flutter and Python, produced lines through a proprietary geometric optimization workflow designed to minimize residual fragments, short passes, and line-length irregularity. The comparison excluded assessments of interface design, processing time, terrain elevation, slope, drainage, soil restrictions, and agronomic constraints. As the optimization logic of Software A is proprietary, the study focused exclusively on the georeferenced line outputs exported by each tool.

Input conditions were standardized across both tools. For each field, both planning tools received the same boundary polygon, a single headland pass, and a 9 m spacing between adjacent working lines. These controls isolated the effect of the planning routine from user-defined parameters. Each output was exported as a line shapefile in the World Geodetic System 1984 (WGS 84; EPSG 4326). Metric extraction was conducted using Python following export, rather than within a standalone GIS package.

Data processing and metric extraction

A custom Python script was developed to read and analyze the exported shapefiles. GeoPandas facilitated vector file handling and coordinate transformations, while NumPy supported numerical operations. Prior to distance calculations, all line layers were transformed from WGS 84 (EPSG 4326) to SIRGAS 2000 / Universal Transverse Mercator (UTM) Zone 23S (EPSG 31983). This projected coordinate system enabled all length and spacing estimates to be expressed in meters. The script generated a metric dictionary for each software-field combination and is provided as supplementary project material.

The script initially calculated the length of each projected line feature. Based on these values, it determined the total line count, total planned length, mean line length, standard deviation, coefficient of variation, minimum length, and maximum length. Lines shorter than 50 m were counted separately. This threshold was selected based on field experience with mechanized seeding and serves as an operational screening value rather than a universal agronomic boundary. The estimated maneuver count was defined as the number of lines minus one, representing the minimum number of headland turns in a sequential operation. Operational continuity was calculated as the percentage of lines with a length of at least 50 m.

Spacing was determined from line positions rather than from software-reported attributes. The routine calculated the centroid of each line, used the longest line to represent the dominant travel direction, projected the centroids onto the perpendicular axis, and averaged the distances between adjacent projected coordinates. This value served solely as a quality-control check against the configured 9 m spacing. The working angle was calculated from the longest exported line and normalized to the 0–180° interval. This value describes the orientation present in the exported line set; the internal angle-selection logic was not evaluated due to lack of public documentation.

A scenario-based operational field-capacity estimate was included to express geometric differences in operational terms. This calculation was not based on machine logs and should not be interpreted as measured field performance. Total time was defined as the sum of travel time and headland-turn time. The assumed travel speed was 6 km h^{-1}, and the assumed duration of each headland turn was 90 s. Field capacity was then calculated using the measured areas of the irregular field (33.6 ha) and the regular field (107.6 ha):

$$T_{travel} = \frac{L}{v \times 1000}, \quad T_{maneuver} = \frac{N_m \times t_m}{3600}, \quad T_{total} = T_{travel} + T_{maneuver} \tag{1}$$

$$OFC = \frac{A}{T_{total}}, \quad \Delta OFC = \frac{OFC_B - OFC_A}{OFC_A} \times 100 \tag{2}$$

where L is the planned path length (m), v is the assumed forward speed (6 km h^{-1}), N_m is the estimated number of maneuvers, t_m is the assumed time per maneuver (90 s), and A is the measured field area (ha). Operational field capacity (OFC) is the estimated capacity (ha h^{-1}).

Comparative analysis

Software A and Software B were compared within each field. Absolute and relative differences were calculated for each metric. Because boundary, headland pass, and spacing were fixed prior to line generation, the comparison focused on the effect of the planning workflow on the exported geometry. Inferential statistics were not applied, as there were no replicate runs and each tool produced a single deterministic output per field. The results are therefore descriptive and should be interpreted as a controlled two-field comparison.

Results

All values in this section were derived from the exported line shapefiles. The Python routine converted each line set into descriptive indicators of path geometry, so the results refer to delivered planning outputs rather than to the undisclosed internal code of either tool.

Irregular field

Table 1 summarizes the outputs for the irregular field. Compared to Software A, Software B generated four fewer lines, reducing the total from 135 to 131. The total planned length was also slightly lower (32,988.75 m versus 33,268.55 m), while the mean line length increased from 246.43 m to 251.82 m. The most notable difference was the reduction in the number of lines shorter than 50 m, from 15 to 10. This change was accompanied by a decrease in the estimated number of maneuvers from 134 to 130, an increase in operational continuity from 88.89% to 92.37%, and a lower coefficient of variation (76.01% versus 77.90%).

Table 1. Operational metrics for the irregular field under Software A and Software B

Metric	Software A	Software B	Relative difference (%)
Total number of lines	135	131	−2.96
Total path length (m)	33,268.55	32,988.75	−0.84
Mean line length (m)	246.43	251.82	+2.19
Standard deviation (m)	191.96	191.41	−0.29
Coefficient of variation (%)	77.90	76.01	−2.43
Minimum line length (m)	3.75	6.38	+70.13
Maximum line length (m)	841.38	842.09	+0.08
Short lines (< 50 m)	15	10	−33.33
Estimated maneuvers	134	130	−2.99
Operational continuity (%)	88.89	92.37	+3.92
Mean spacing (m)	8.95	8.85	−1.12
Working angle (°)	115.19	115.49	+0.26

Regular field

Table 2 presents the comparison for the regular field. In this case, both outputs achieved complete operational continuity and did not produce any lines shorter than 50 m. Consequently, differences were concentrated in line number, variability, and orientation metrics. Software B generated 126 lines, one fewer than Software A, and reduced the total planned length from 116,220.06 m to 115,780.42 m. The standard deviation of line length decreased from 252.47 m to 239.41 m, and the coefficient of variation decreased from 27.59% to 26.05%. The final exported orientations differed substantially: 59.00◦ for Software A and 99.12◦ for Software B.

Table 2. Operational metrics for the regular field under Software A and Software B

Metric	Software A	Software B	Relative difference (%)
Total number of lines	127	126	−0.79
Total path length (m)	116,220.06	115,780.42	−0.38
Mean line length (m)	915.12	918.89	+0.41
Standard deviation (m)	252.47	239.41	−5.17
Coefficient of variation (%)	27.59	26.05	−5.58
Minimum line length (m)	202.18	210.73	+4.23
Maximum line length (m)	1,158.82	1,156.16	−0.23
Short lines ($<$ 50 m)	0	0	0.00
Estimated maneuvers	126	125	−0.79
Operational continuity (%)	100.00	100.00	0.00
Mean spacing (m)	8.97	9.00	+0.33
Working angle (°)	59.00	99.12	+68.00

Estimated operational field capacity

Table 3 translates the geometric outputs into a standardized field-capacity scenario. In the irregular field, the combination of a lower planned length and fewer estimated maneuvers reduced the estimated operation time from 8.89 h to 8.75 h. This increased the estimated operational field capacity from 3.78 to 3.84 ha h−1, representing a 1.68% improvement. In the regular field, the estimated time decreased from 22.52 h to 22.42 h, and field capacity increased from 4.78 to 4.80 ha ha h^{-1}.

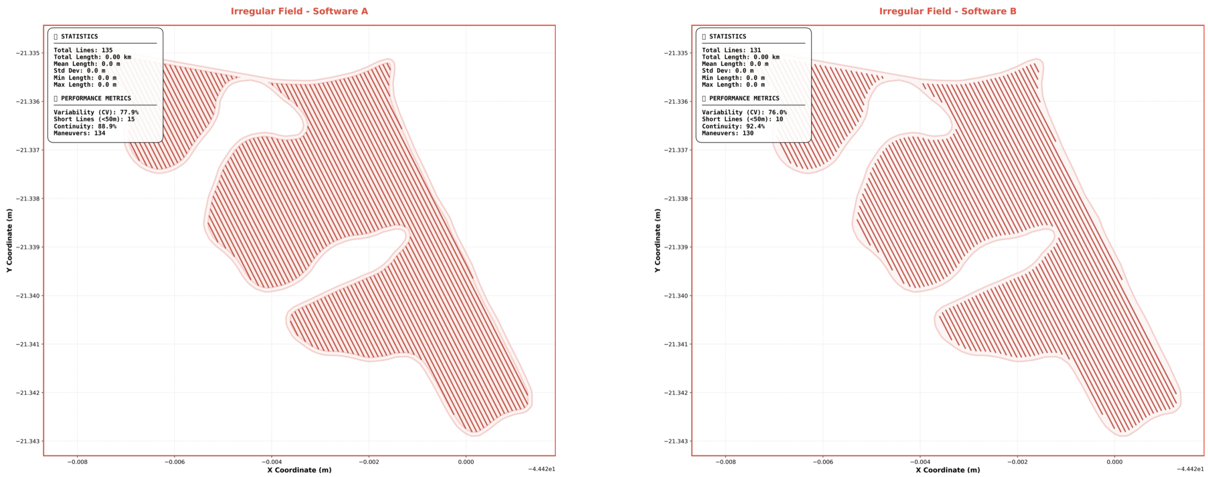
Table 3. Estimated total operation time and operational field capacity under a standardized scenario assuming 6 km h^{-1} forward speed and 90 s per headland maneuver. Field capacity was calculated using the measured field areas: 33.6 ha for the irregular field and 107.6 ha for the regular field

Field	Area (ha)	A T_{total} (h)	B T_{total} (h)	A OFC (ha h^{-1})	B OFC (ha h^{-1})	Δ OFC (%)
Irregular field	33.60	8.89	8.75	3.78	3.84	+1.68
Regular field	107.60	22.52	22.42	4.78	4.80	+0.44

For example, in the irregular field, Software A had $T_{travel} = 33268.55/(6\times1000) = 5.54$ h and $T_{maneuver} = 134 \times 90/3600 = 3.35$ h, resulting in $T_{total} = 8.89$ h. Using the measured irregular-field area of 33.6 ha, the estimated operational field capacity was $33.6/8.89 = 3.78$ ha h^{-1}. For Software B, the same procedure resulted in $T_{total} = 8.75$ h and $OFC = 33.6/8.75 = 3.84$ ha h^{-1}.

Visual comparison of scenarios

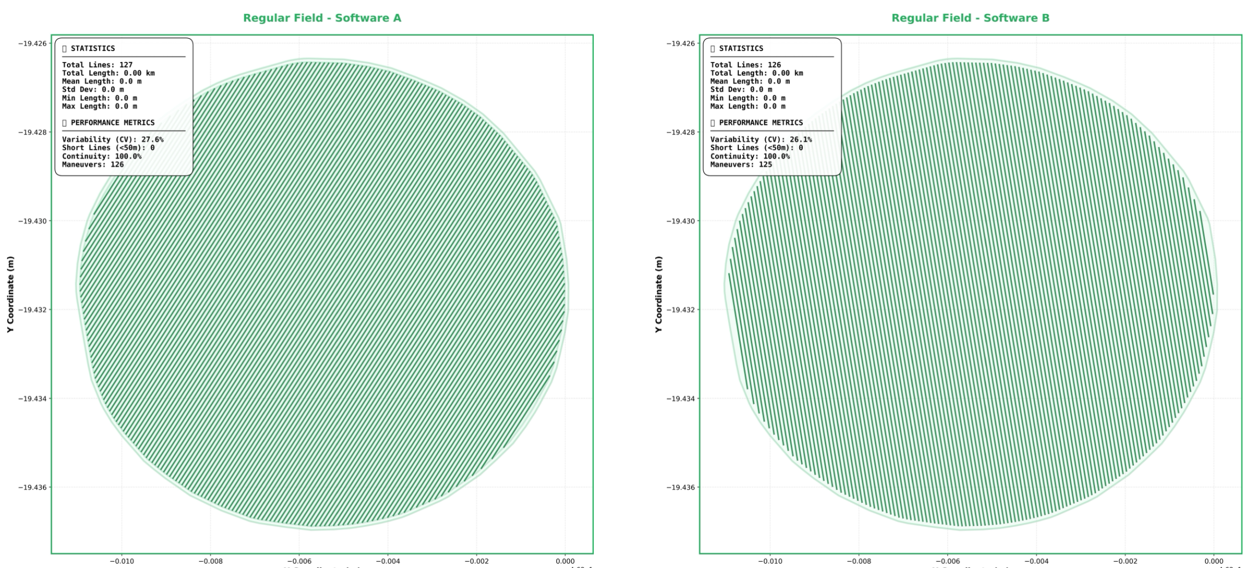
The visual comparison of planned paths supplements the quantitative metrics by illustrating the spatial distribution of lines under each geometric condition. In the irregular field, both software tools maintained similar orientations. However, Software B exhibited less residual fragmentation near the boundaries, which aligns with the observed reduction in short lines and estimated maneuvers (Fig. 2).



(a) Software A **(b) Software B**

Figure 2. Visual comparison of planned paths in the irregular field under Software A and Software B

In the regular field, the maps highlight the difference in the working angle selected by each routine (Fig. 3). This spatial difference helps explain the lower line-length variability observed with Software B, even though both methods achieved complete operational continuity.



(a) Software A **(b) Software B**

Figure 3. Visual comparison of planned paths in the regular field under Software A and Software B

Graphical comparison

Software B consistently reduced line-length variability in both field geometries (Fig. 4). The reduction was more pronounced in the regular field, where the coefficient of variation decreased by 5.58% in relative terms. In the irregular field, the reduction was smaller but still reflected a tendency toward more uniform line distributions.

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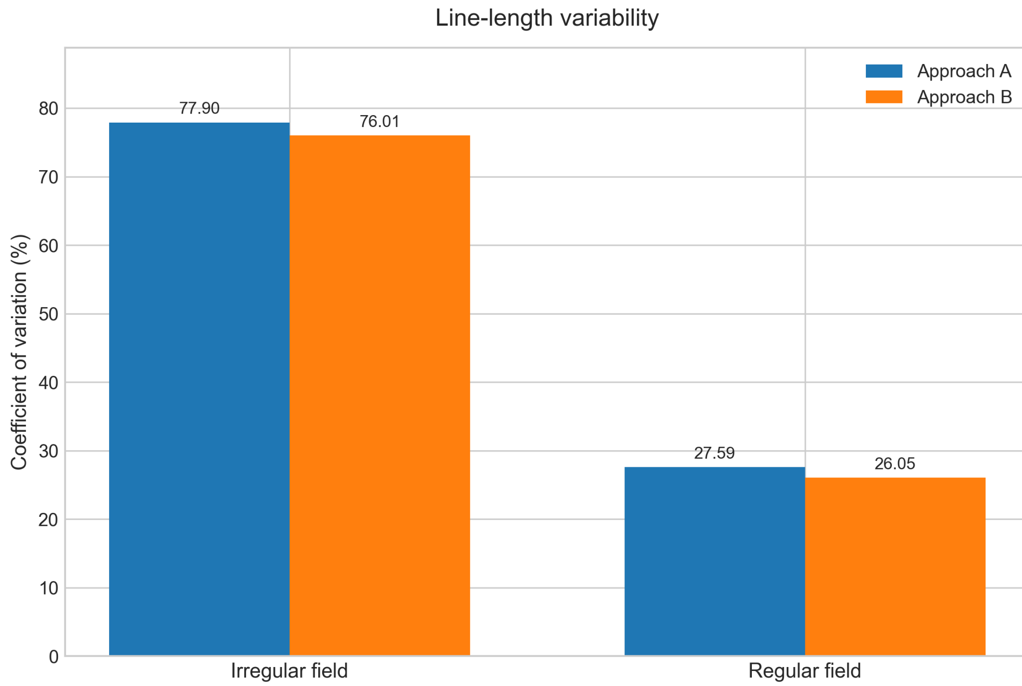

Figure 4. Coefficient of variation of line lengths for both software-based planning routines and field geometries

The reduction in short lines occurred primarily in the irregular field (Fig. 5). Software B reduced the number of segments shorter than 50 m from 15 to 10. In the regular field, neither software tool generated short lines, indicating that the rectilinear boundary facilitated complete operational coverage in this dataset.

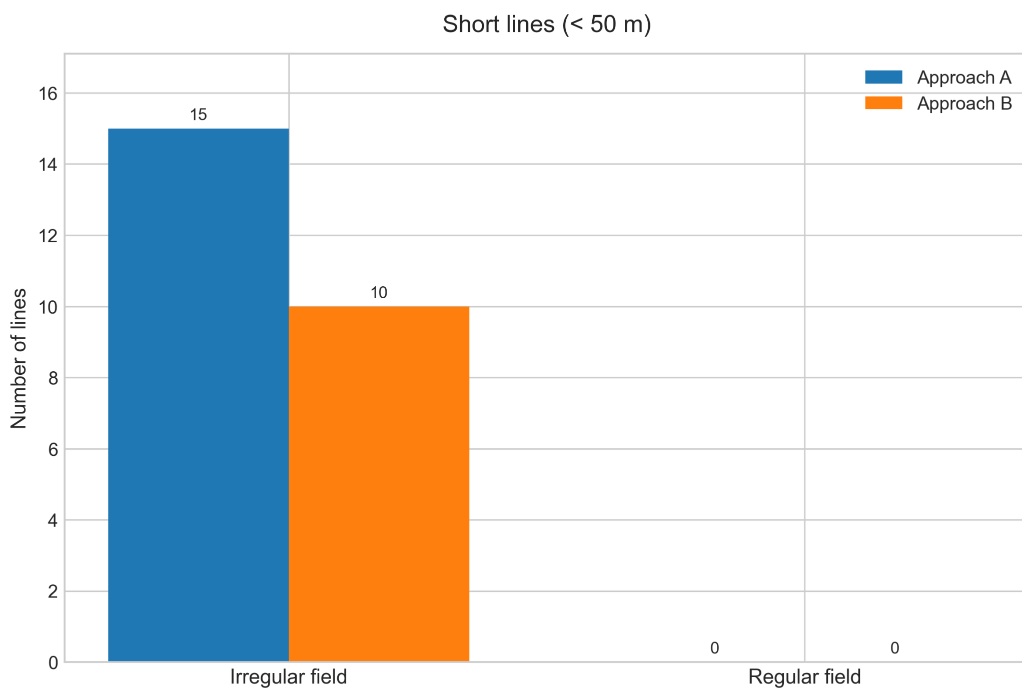

Figure 5. Number of short lines, defined as segments shorter than 50 m

Software B also reduced the estimated number of maneuvers in both scenarios (Fig. 6). Although the absolute differences were modest, each eliminated maneuver represents a potential reduction in a complete headland turn cycle, which may have implications for time, fuel consumption, and localized traffic intensity.

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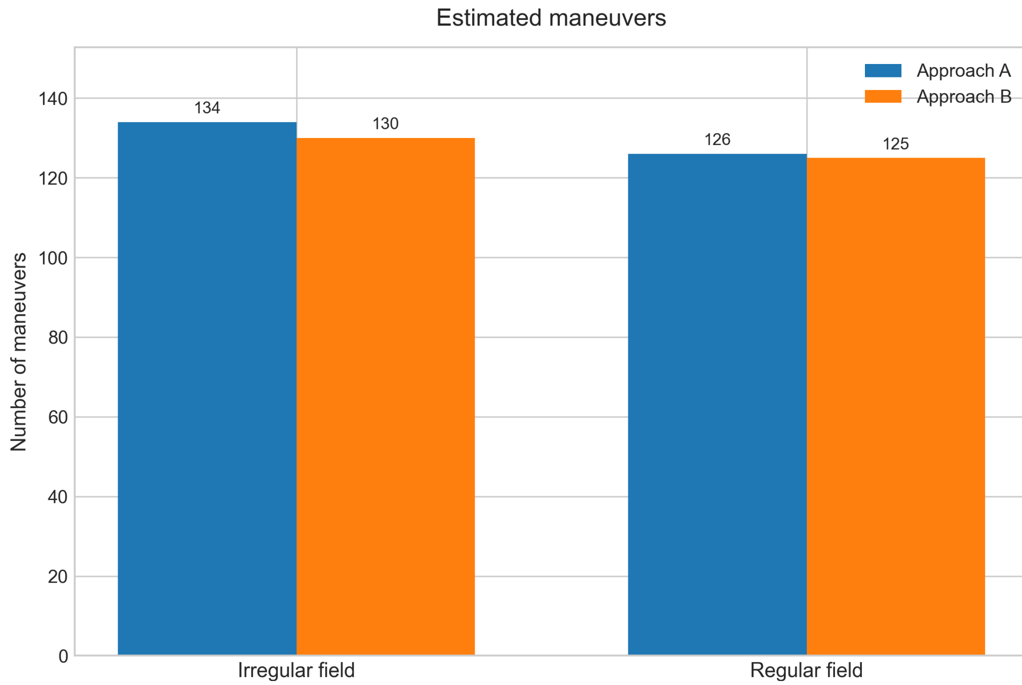

Figure 6. Estimated number of maneuvers required for the sequential execution of the planned paths

Operational continuity improved in the irregular field and remained complete in the regular field (Fig. 7). This metric summarizes the proportion of planned passes that exceed the operational short-line threshold.

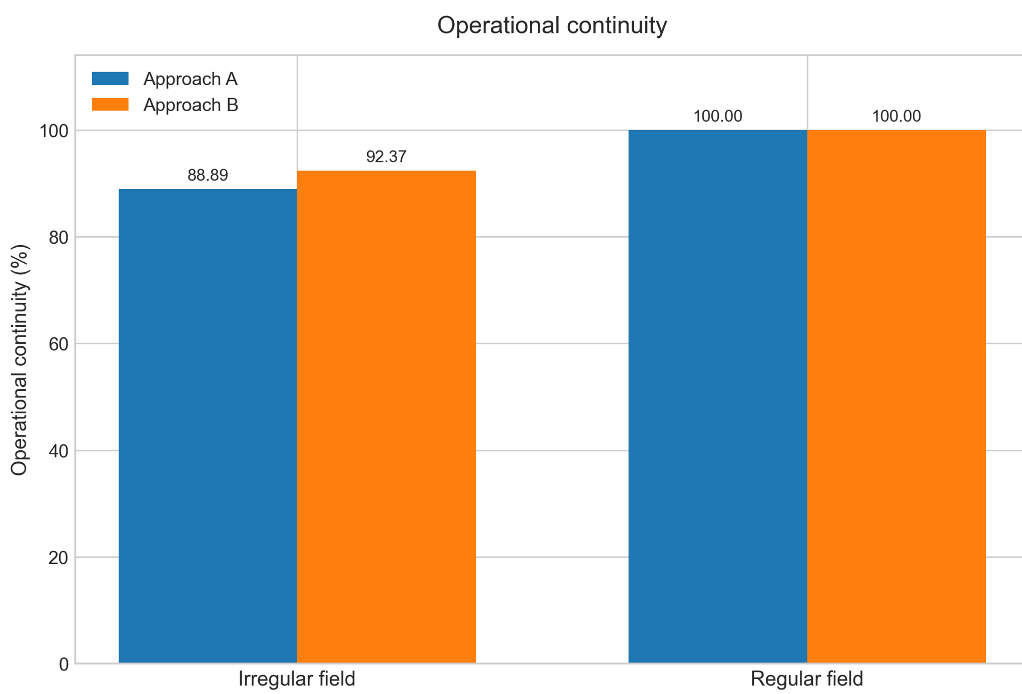

Figure 7. Operational continuity, expressed as the percentage of lines equal to or longer than 50 m

The relative-difference heatmap offers a concise synthesis of all main responses (Fig. 8). The greatest relative improvement was observed in the number of short lines in the irregular field, followed by gains in operational continuity and reductions in estimated maneuvers and line-length variability. In the regular field, the smaller color contrasts indicate that the two routines produced more similar outputs, consistent with the boundary's lower geometric complexity.

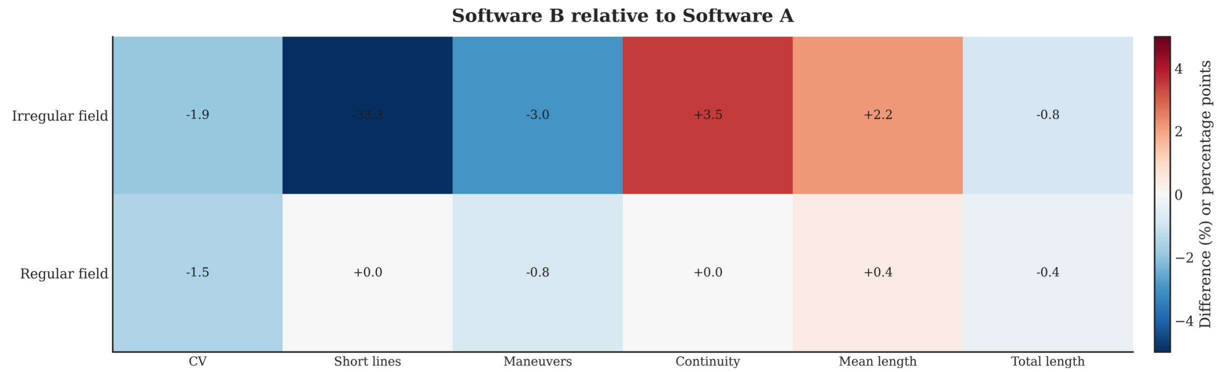

Figure 8. Relative differences between Software B and Software A across the main operational metrics and field geometries. Negative values indicate reductions under Software B, while positive values indicate increases.

Discussion

Planning routine and exported path geometry

The comparison indicates that the two planning workflows did not produce identical line sets, despite using the same boundaries, headland pass, and spacing. In both fields, Software B produced slightly fewer lines and fewer estimated maneuvers than Software A. Although the differences were not large in absolute terms, they were consistent across the main path-quality indicators. This pattern suggests that the geometric rules embedded in the planning routine can influence the final line set delivered to the operator.

The irregular field was more sensitive to the choice of planning routine because its boundary created narrow residual areas and partial passes near field edges. In this context, reducing five short lines and four estimated maneuvers is operationally meaningful within the assumptions of this study. By contrast, the regular field presented a simpler geometry, and both outputs achieved complete continuity.

Short lines and continuity

The reduction in short lines represents the most distinct difference in the irregular field. Software B reduced the number of lines below 50 m from 15 to 10. As the threshold was based on field experience, it should be interpreted as a practical classification value rather than a biological or universal engineering limit. Short passes are generally undesirable in seeding because they may require additional turns and provide insufficient distance for stable travel speed and metering behavior. These interpretations remain provisional because no execution-phase machine data were available.

Operational continuity complemented the short-line count by expressing the same issue as a percentage of executable passes. The increase from 88.89% to 92.37% indicates that a greater proportion of planned passes exceeded the 50 m threshold under Software B. In the regular field, continuity was already complete for both outputs, which limited the potential for improvement on this metric.

Line-length variability

The contrast between field types was more pronounced than the contrast between software tools. Coefficients of variation above 76% in the irregular field and near 26–28% in the regular field indicate that boundary shape was the primary factor influencing line-length dispersion. Nevertheless, Software B reduced the coefficient of variation in both cases, by 2.43% in the irregular field and 5.58% in the regular field. More uniform line lengths may make pass duration more predictable and simplify operational planning. This interpretation aligns with studies relating sowing quality and operational regularity (Arcoverde et al., 2016), but it should be validated with field data before being extended to agronomic performance

Working angle

The regular field showed a pronounced difference in exported working angle: 59.00° for Software A and 99.12° for Software B. Because the angle was calculated from the exported line set, this result describes the final planning output rather than the proprietary angle-search logic. The lower variability and slightly greater mean line length obtained by Software B suggest that its final orientation was better suited to the dominant geometry of this field.

For the irregular field, both tools returned orientations close to 115°. This similarity suggests that the irregular boundary constrained the feasible orientation more strongly than the regular boundary did. More generally, the result reinforces the need to report the working angle in path-planning studies. Without this information, differences in line length, continuity, and maneuver count may be difficult to interpret. The relevance of travel direction is consistent with previous work on guidance and field-operation geometry (Baio, 2012; Oksanen, 2015).

Practical meaning and limitations

The scenario-based capacity calculation gives an operational scale to the geometric differences. In the irregular field, four fewer estimated maneuvers corresponded to approximately six minutes of potential time reduction under the assumed 90 s turn duration. This is a small difference for one field, but repeated operations across several fields could make such reductions relevant. The estimate should nevertheless be interpreted with caution because speed, turn duration, operator behavior, soil conditions, declivity and machine dynamics were not measured.

The study has four main limitations. First, only two fields were evaluated. Second, each software field was tested considering flat fields. Third, the analysis used planned paths rather than executed GNSS tracks. Fourth, Software B contains proprietary optimization logic, which limits the level of algorithmic detail that can be reported. The visual maps help document the exported line patterns, but they do not replace field validation. Future work should include more fields, execution logs, machine-time measurements, and agronomic indicators to test whether the geometric improvements observed here translate into measurable field benefits.

Conclusion

This two-field comparison showed that software choice affected the geometry of planned seeding paths under identical boundary, headland, and spacing inputs. Software B produced fewer lines, fewer short segments, fewer estimated maneuvers, higher operational continuity, and lower line-length variability than Software A in the evaluated outputs. The improvement was more evident in the irregular field, where boundary complexity increased the occurrence of fragmented passes.

The exported working angle varied substantially across tools in the regular field, indicating that orientation should be reported explicitly in path-planning comparisons. Operational continuity also summarized the share of planned lines longer than the 50 m threshold.

The results support the use of geometric metrics for evaluating software-generated seeding paths. However, the findings remain limited to planned line geometries and standardized capacity estimates. Larger datasets and execution-phase machine records are needed to determine whether these planimetric differences yield measurable savings in field time, fuel use, or crop establishment quality.

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