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Cost assessment of robotic technology in maize farming and related logistics

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Germany is facing a growing shortage of skilled labour. The use of autonomous field robots in crop production offers a potential solution to this structural challenge. This study analysed the application of AgBot 2.055W4 in maize cultivation and related logistics on two farms in the Osnabrück district, Lower Saxony. The economic analysis is based on a scenario-based simulation of autonomous field robot operations, complemented by an experimental work time study focusing on logistical processes. Compared with tractor-based operations, the field robot required additional time of 0.05 h/ha within the logistics workflow due to loading onto a low-loader. Increased machinery, diesel, and labour inputs result in additional costs of 13.38 €/ha for field work and 7.56 €/ha for logistics. Assuming uninterrupted autonomous field operation, a potentially productive working time of 0.66 h/ha for other activities can be obtained. If this time is used productively by the operator, a net benefit of 6.29 €/ha compared with tractor-based operations can be realised.

Keywords
Work time study, cost-benefit analysis, power harrowing, maize planting, inter-row crop hoeing

The German economy is expected to face a significant labour shortage in the coming years, which is likely to result in substantial economic costs (Burstedde and Kolev-Schaefer 2024). The Federal Employment Agency's 2023 report on skilled labour shortages highlights this issue as a major challenge, particularly within the agricultural sector (BA 2023). One potential solution to address the shortage of skilled workers in agriculture could be the use of robotic technology. Automated milking robots have been in operation on dairy farms for several years. However, owing to varying field conditions, the use of robotics has not been technically feasible until now.

Over the past five years, the field robot market has experienced rapid growth. Both established agricultural machinery manufacturers, such as Krone and Lemken (https://www.combined-powers.com), and emerging companies, such as Farming Revolution and Naïo Technologies (https://www.naio-technologies.com), have introduced a range of robotic solutions. A key application area is mechanical weed control in vegetable and horticultural farming, with systems such as Orio from Naïo Technologies or Farming GT from the Farming Revolution serving as prime examples (https://www.farming-revolution.com). These robots are designed specifically for this task and typically offer lower hectare performance. For large-scale crops such as maize and wheat, higher performance is needed. Robots such as the AgBot by AgXeed (https://www.agxeed.com) and the VTE developed by Krone and Lemken are specifically designed to meet the demands of large-scale agricultural operations.

Most robotic systems have only recently entered the market, with some still under development. As a result, practical experience and comprehensive scientific analyses are still limited, and the majority of studies have been conducted only within the past few years (Bazargani and Deemyad 2024,

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Lowenberg-DeBoer et al. 2020). The use of field robotics seems to be both technically and economically viable in principle (Lowenberg-DeBoer et al. 2021). Regulatory requirements for onsite supervision of field robots impact profitability, and consequently, the duration of supervision becomes a critical factor (Lowenberg-DeBoer et al. 2022, Maritan et al. 2023). Customised robotic systems can manage irregularly shaped fields more efficiently and deliver higher ecological performance (Al-Amin et al. 2023). The use of robotics also leads to increased economic efficiency when expensive manual labour hours, such as those required in organic sugar beet cultivation, can be replaced (Spykman et al. 2023). Few studies on the German context and logistics have been conducted (Jorissen et al. 2025, Jorissen et al. 2024, Spykman et al. 2023). On the basis of these findings, the following research questions were formulated:

- How are working time and costs structured in the use of field robots, and what proportion is attributable to logistics?
- How does the cost structure change compared with conventional tractor use when the working time gained through autonomous operation is used productively?

This study is based on a series of initial field trials conducted at two commercial farms in the Osnabrück district, Lower Saxony. Both the farms and the experimental activities were integrated into the federal research project Agro-Nordwest. In 2024, the autonomous field robot AgBot 2.055W4, developed by AgXeed, was deployed on both farms to perform operations in maize cultivation, including soil cultivation, sowing, and inter-row hoeing. Each of these operations was carried out using implements with a working width of three metres.

For the economic evaluation, a hypothetical machinery cooperation between the two farms was assumed. The assessment of fieldwork performance is based on modelled AgBot operations using a digital planning tool, as no actual operations were conducted across the entire farm. In contrast, the evaluation of logistical processes rests on an experimental work time study.

Study context: field robot and farm description

This study examined the deployment of the autonomous field robot AgBot 2.055W4, which is part of the commercially available field robot series developed by the Dutch manufacturer AgXeed. Designed for various agricultural applications, such as arable farming, vegetable production, orchard management, and grassland operations, the field robot series includes three configurations: a four-wheel model (2.055W4), a tracked model (5.115T2), and a three-wheel variant (2.055W3). The present analysis focuses on the four-wheel model (2.055W4). A low-loader with an additional tractor is required to transport the AgBot on public roads.

AgBot 2.055W4 features frot and rear three-point hitches, an electric rear power take-off, and ISOBUS compatibility, enabling its use with conventional implements. It is powered by a Deutz diesel engine that drives an onboard generator supplying electricity to electric motors on the wheels and auxiliary drives. Various sensors detect obstacles and reduce speed or stop the robot as needed. Routing and task planning are managed via the AgXeed online portal, where GNSS-based field maps and implement data are uploaded. During operation, the portal records key performance data such as the working hours, fuel consumption, and engine load.

The working time study and cost analysis were conducted for a hypothetical machinery cooperative based on two commercial farms: Langsenkamp Farm (LaFarm) and Westrup-Koch Farm (WK-Farm), both located east of Osnabrück. LaFarm is a smaller operation focused on horse boarding, pig fattening, and forage production on 80 hectares. WK Farmis relatively large, with 767 hectares dedicated to dairy farming, biogas production, and arable as well as forage cropping. The farms, which are 13.6 km apart, are run as full-time agricultural businesses. Both farms participated in the Agro Nordwest project in 2024, which included field trials with the AgBot 2.055W4. In that year, LaFarm cultivated 36 hectares of maize in nine fields, whereas WKFarm cultivated 242 hectares in 52 fields.

The analysis is based on scenario simulation of AgBot operations using the AgXeed portal. No actual field operation was performed on the 61 maize plots. Instead, routes and work times were simulated digitally under ideal operational conditions without considering downtimes or human interventions. In contrast, the evaluation of logistical processes is based on an experimental work time study conducted under practical conditions at the two farms.

To ensure a broader applicability of the findings and to avoid limiting the analysis to a specific manufacturer or model, the term field robot instead of the originally applied designation AgBot is used in the following. This generalisation aims to emphasise the relevance of the results for autonomous field robots in arable farming beyond the specific system studied.

Scenario design and route planning

The study design and route planning were based on the KTBL system for work time classification (KTBL 2022). In contrast to the KTBL methodology, the subsequently defined processes are broken down into a maximum of two levels. The application of the field robot was analysed in two scenarios (Sc1 and Sc2) in maize cultivation on the commercial farms LaFarm and WKFarm (Table 1). The logistics of the field robot were managed using an existing 121-kW tractor and a low-loader. A tractor with a lower engine power would not have been adequate for operating in the hilly landscape of the Osnabrück region. For the fieldwork, a fictional 55-kW tractor was assumed, as it corresponds to the engine power of the field robot (55 kW).

In Sc1, the determined working times and cost structure of the field robot operations were recorded and compared to those of conventional tractor operations. In Sc2, an extended cost-benefit analysis was conducted to determine whether the human labour freed up during autonomous field work was economically utilised on the farm. It was assumed that the operator returns to the farm with the tractor during autonomous operation of the field robot and performs productive farm activities. Each scenario included the following operational processes: field work (FW) and logistics (L), which was subdivided into transport (T) and loading (Lo). In Sc2, farm work (FaW) represents on-farm value creation. The analysis focused on three agricultural operations: power harrowing, maize sowing, and inter-row hoeing. A total of four operations were assumed, with one each for power harrowing and maize sowing, and two for inter-row hoeing. As in the practical trials at Agro-Nordwest, the implements assumed in this analysis have a working width of three metres. In both scenarios, the low-loader waits at the edge of the field until the robot has completed its operation.

Table 1: Work processes and operational resources by scenario and carrier vehicle

<table>
<tr><th></th><th>Operational process</th><th>Operational resource: field robot</th><th>Operational resource: tractor</th></tr>
<tr><td rowspan="2">Total work scenario 1 (TW_Sc1)</td><td>Field work scenario 1 (FW_Sc1)</td><td>Field robot (55 kW)
Implements (power harrow, maize planter, and row-crop hoe)
Diesel
Human labour</td><td>Tractor (55 kW)
Implements (power harrow, maize drill and inter row-crop hoe)
Diesel
Human labour</td></tr>
<tr><td>Logistic scenario 1 (L_Sc1)</td><td>Tractor (121 kW)
Low-loader
Diesel
Human labour</td><td>Tractor (55 kW)
Diesel
Human labour</td></tr>
<tr><td rowspan="3">Total work scenario 2 (TW_Sc2)</td><td>Field work scenario 2 (FW_Sc2)</td><td>Field robot (55 kW)
Implements (power harrow, maize planter, and row-crop hoe)
Diesel</td><td>Tractor (55 kW)
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Diesel
Human labour</td></tr>
<tr><td>Logistic scenario 2 (L_Sc2)</td><td>Tractor (121 kW)
Diesel
Human labour</td><td>Tractor (55 kW)
Diesel
Human labour</td></tr>
<tr><td>Farm work scenario 2 (FaW_Sc2)</td><td>Human labour</td><td></td></tr>
</table>

Route planning was based on the maize fields cultivated in 2024, which were divided into routes of approximately 20 ha each, corresponding to the assumed daily capacity of the field robot. Field proximity was considered to minimise the transport time. Routes were planned via Google Maps, starting and ending at the farm and including all necessary field access points. Only roads suitable for low-loader transport were used. In total, two routes were defined for LaFarm and twelve for WK-Farm. For each route, the following key parameters were recorded: number of fields, number of access points, route sizes (ha), field sizes (ha), and route length (km). In Sc2, return routes to the farm (km) were also measured to estimate the potential for productive farm work during field robot operations.

Methodology of the work time study

The methodology for the field robot work time study was based on the KTBL system for work time classification (KTBL 2022). In contrast to the KTBL approach, total times were recorded for the defined processes, without differentiating between execution times, waiting times, setup times, etc. To record logistics times, each route was driven with an existing 121-kW tractor and a low-loader at a maximum speed of 50 km/h. In Sc1, the logistics time (LT) was calculated as the sum of the transport time (TT) and loading time (LoT). Initially, loading and unloading times were measured twice, starting when the field robot was positioned next to the trailer until it was securely fastened. Secondly, the transport time was recorded. It began when the field robot, equipped with a front-mounted bumper and a rear ballast weight, was positioned on the trailer and the transport unit left the farm, and ended at the field access point. In the work time study, the routes of LaFarm were driven first, followed by those of WKFarm. The transport time between the two farms was recorded twice. Additionally, the tractor's diesel consumption was recorded for each route section.

$$LT\_Sc1 = TT\_Sc1 + LoT\_Sc1 \quad \text{(Eq. 1)}$$

The logistics time in Sc2 was the sum of TT_Sc1 and LoT_Sc1 plus the return transport time to the farm from each field, and the subsequent drive back to the field (RTTFa_Sc2).

$$LT\_Sc2 = TT\_Sc1 + LoT\_Sc1 + RTTFa\_Sc2 \quad \text{(Eq. 2)}$$

The working times for the field robot on the 61 maize fields were calculated in the AgXeed online portal on the basis of the set forward speed and a 3-metre working width for each implement. No systematic experimental data were collected. The limited practical experiences at Agro-Nordwest indicate that the time is largely maintained when no downtime or human intervention occurs. Since these initial analyses with the field robot were based on ideal field operations, neither downtime nor human intervention were taken into account. The starting point was the field access point, and the endpoint was either the loading point on the low-loader or the access point of an adjacent field. Headlands were defined as five lanes around the field and processed after the long lanes were completed. The driving speed of the field robot was uniformly set as follows: 7 km/h for lanes, 5 km/h for headlands, 3 km/h for forwards turns, and 2 km/h for reverse turns. All other settings followed the default values from the portal, adjusted only minimally for field conditions on the basis of practical experience from Agro-Nordwest. The portal was used to calculate travel paths and estimated field work time (FWT) for each field. The average FWT for a route was then calculated, and the total work time (TWT) in Sc1 was determined by adding the logistics time.

$$TWT\_Sc1 = FWT\_Sc1 + LT\_Sc1 \quad \text{(Eq. 3)}$$

For Sc2, the TWT was calculated from FWT_Sc1 and LT_Sc2.

$$TWT\_Sc2 = FWT\_Sc1 + LT\_Sc2 \quad \text{(Eq. 4)}$$

To calculate the economic benefit of the working time freed up by autonomous robot operation in Sc2, the farm work time (FaWT) must first be determined. FaWT_Sc2 was calculated from FWT_Sc1 minus RTTFa_Sc2.

$$FaWT\_Sc2 = FWT\_Sc1 - RTTFa\_Sc2 \quad \text{(Eq. 5)}$$

In the comparison system using the 55-kW tractor, neither specific fieldwork times nor logistics times were recorded. Instead, the same working times as for the field robot operation were assumed. As long as no differences in downtime for the carrier vehicles are considered, these assumptions can be regarded as realistic since nearly identical area performance can be achieved at the same driving speeds.

Methodology of the cost estimation

The cost calculation assumed that the field robot and the three implements were jointly acquired through a machine cooperation and were used solely for maize cultivation. Since the implements are also compatible with conventional tractors, all operations performed by the field robot were assumed to be of equivalent quality to those conducted with a tractor. This assumption had to be made because at the current stage no systematic data on the quality of field operations and downtime related to the field robot was available.

The costs associated with field work and logistics for the field robot (FR), tractors (Tr), implements (Im), and low-loader (LL) were derived from the machine costs (MC), diesel costs (DC), and labour costs (LaC). These costs were calculated on the basis of the recorded working times (WT) from the working time study, estimated diesel consumption (DCo), machine hourly rate (MR), hourly labour rate (LR), and diesel price (DP).

$$MC_{FR;Tr;Im;LL} = WT_{FR;Tr;Im;LL} \times MR_{FR;Tr;Im;LL} \quad \text{(Eq. 6)}$$

$$DC_{FR;Tr} = DCo_{FR;Tr} \times DP \quad \text{(Eq. 7)}$$

$$LaC = WT \times LR \quad \text{(Eq. 8)}$$

In Sc1, the logistics costs (LC) of field robot deployment were calculated as the sum of transport costs (TrC) and loading costs (LoC).

$$LC\_Sc1 = TrC\_Sc1 + LoC\_Sc1 \quad \text{(Eq. 9)}$$

$$LC\_Sc1 = MC_{Tr\_}Sc1 + MC_{LL\_}Sc1 + DC_{Tr\_}Sc1 + LaC\_Sc1 \quad \text{(Eq. 10)}$$

The logistics costs in Sc2 were the sum of TrC_Sc1 and LoC_Sc1 plus the return transport costs from each field back to the farm (RTCFa_Sc2).

$$LC\_Sc2 = TrC\_Sc1 + LoC\_Sc1 + RTCFa\_Sc2 \quad \text{(Eq. 11)}$$

$$LC\_Sc2 = MC_{Tr\_}Sc2 + MC_{LL\_}Sc2 + DC_{Tr\_}Sc2 + LaC\_Sc2 \quad \text{(Eq. 12)}$$

The field work costs in Sc1 (FWC_Sc1) included machine, diesel, and labour costs. In Sc2, labour costs were excluded during the field robot's autonomous operation.

$$FWC\_Sc1 = MC_{FR} + DC_{FR} + LaC \quad \text{(Eq. 13)}$$

$$FWC\_Sc2 = MC_{FR} + DC_{FR} \quad \text{(Eq. 14)}$$

In Sc1, the total costs (TC_Sc1) were calculated as the sum of the field work costs (FWC) and the logistics costs (LC). For Sc2, the total costs (TC_Sc2) were calculated from the field work costs (FWC_Sc2) and logistics costs (LC_Sc2).

$$TC\_Sc1 = FWC\_Sc1 + LC\_Sc1 \quad \text{(Eq. 15)}$$

$$TC\_Sc2 = FWC\_Sc2 + LC\_Sc2 \quad \text{(Eq. 16)}$$

The economic benefit of automation (BA) provided by the field robot, resulting from the reduction in human labour requirements, was only considered in Sc2. It was calculated on the basis of the freed-up working time in Sc2 (FaWT_Sc2) and the hourly value creation from on-farm work (VCFaW).

$$BA = FaWT\_Sc2 \times VCFaW \quad \text{(Eq. 17)}$$

In Sc2, the net costs (NC) of using the field robot were calculated by subtracting the economic benefit of automation (BA) from the total costs in Sc2 (TC_Sc2). Additionally, the net benefit (NB) was used in Sc2 to assess the cost-effectiveness of the autonomous field robot operations compared to conventional tractor use (TC_{Tr}).

$$NC = TC\_Sc2 - BA \quad \text{(Eq. 18)}$$

$$NB = TC_{Tr} - NC \quad \text{(Eq. 19)}$$

Data basis for the cost estimation

As described in the section on scenario design, an investment in a low-loader was necessary to enable the transport of the field robot on public roads. The low-loader was adapted to the field robot with its implements and was pulled by the available 121-kW tractor. In the cost calculation, the low-loader was considered solely for transporting the field robot between the maize fields and the two farms. The annual deployment of the field robot, 55-kW tractor, and implements was set at 278 hectares of maize cultivation. For the inter-row hoe, two operations were assumed, resulting in a total treated area of 556 hectares. Due to implement changes, the carrier vehicles pass through the fields four times, which corresponds to an area of 1,112 hectares.

The purchase prices for the field robot, the low-loader, and the implements were based on list prices (excluding VATs and discounts) obtained from various manufacturers (Table 2).

Table 2: List of Machines for cost calculation

Machinery	Type designation	Data source
Field robot	AgBot 2.055W4 (including all features)	List price according to AgXeed B.V., email on 2 Sept 2024
Low-loader	Müller-Mitteltal T3 30.0 Profi	List price according to Müller-Mitteltal, email on 5 Oct 2024
Power harrow	Amazone KG 3001 with wedge ring roller, 3 m working width	List price according to Amazone, email on 23 Aug 2024
Maize planter	Amazone Precea 3.000, 4 rows: 4x75 cm	List price according to Amazone, email on 23 Aug 2024
Inter-row hoe	Schmotzer Kombi-PP, including camera control, 4 rows	List price according to Schmotzer Hacktechnik, email on 15 Jan 2024

The additional parameters for calculating machine costs, including the service life, interest rate, and repair cost ratio, were sourced from the online tool MaKost provided by the Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL 2025a). These data has been consistently applied to all carrier vehicles, the low-loader, and the implements. As there are currently insufficient experience data for the field robot, the same values as for the tractor were applied (Table 3).

Table 3: Economic parameters for cost calculation

Parameter	Value
Residual value of the field robot, tractor, implements, and low-loader	20.0% of the purchase price
Repair cost ration of the field robot, tractor und low-loader	4.0% of the purchase price
Repair cost ratio of the implements	2.5% of the purchase price
Interest rate	3.0%
Service life of the machines	12 years
Diesel price	1.15 €/l
Hourly labour rate/hourly value creation from on-farm work	21,50 €/h

For the calculation of machine and labour costs during field work, the recorded working times from the AgXeed portal were used. Diesel consumption can only be retrieved from the portal after the field robot has completed its operation. Thus, the diesel consumption for both the field robot and the tractor, each with the three implements, was estimated using the KTBL online tool Feldarbeitsrechner (KTBL 2025b). Comparable machines, equipment, working widths, and soil conditions were considered to provide a realistic estimate of diesel consumption. The diesel price and hourly labour rate for field and logistics work were also based on KTBL data (KTBL 2025b). The hourly value creation rate from on-farm work corresponds to the labour rate for field and logistics work. On the basis of the requested list prices for the machinery and implements used, as well as the standard calculation data, the average annual machinery costs were determined (Table 4).

Table 4: Average annual machinery costs for the field robot, tractor, implements, and low-loader

Field robot/Tractor/Implement/Low-Loader	Average machinery costs in €/a
Field robot	25,293
Tractor (55 kW)	10,393
Tractor (121 kW)	18,340
Low-loader	5,245
Power harrow	2,682
Maize planter	3,197
Inter-row hoe	4,508

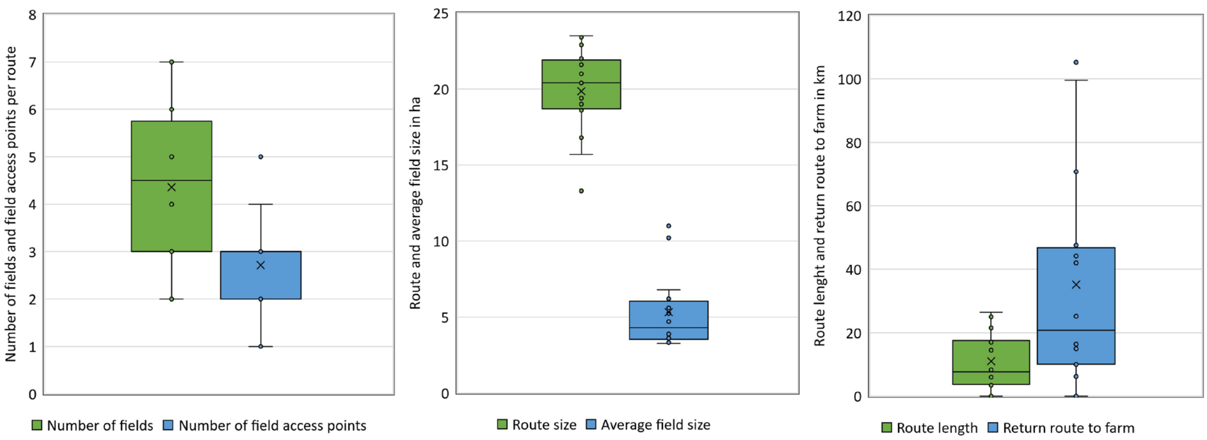
Evaluation methodology

For the box plot analysis, the mean was used for interpretation. Although less stable than the median in the presence of outliers, the small dataset of 14 values justifies considering all the data points. No measurement errors or inconsistencies were found during route composition or working time measurement, so all the values were valid for analysis. Additionally, working time and cost analyses calculate the percentage shares of each category in the total value, which is not possible with the median. The mean was used to determine the central tendency and interpret outliers, whereas the standard deviation (SD) and coefficient of variation (CV) measure dispersion. To analyse the distribution, the coefficient of skewness (skew) was calculated. In standard reference literature, no threshold values are defined for the degree of skewness (Hedderich and Sachs 2016, Mosler and Schmid 2008). For the classification of the results, the following threshold values are established: values within ±0.5

indicate symmetry, values up to ±1.0 suggest slight skew, and values greater than ±1.0 indicate a pronounced skew.

Results of the route composition

As outlined in the section on scenario design, the 61 maize plots (totalling 278 hectares) were organised into 14 routes, with two assigned to LaFarm and twelve to WKFarm (Table A1 in the Appendix). The average route in machine cooperation covers 4.4 fields with 2.7 field access points. The average route size is 19.9 ha, and the mean field size is 5.3 ha (Figure 1, Figure 2 and Figure 3). The average route length is 11.0 km, and the return route to the farm is 35.2 km. The return route to the farm is therefore several times longer than the route length, since the farmer drives back to the farm in Sc2 with the tractor during the autonomous operation of the field robot and performs on-farm tasks. Comparing the two farms, LaFarm tends to have a smaller scale: number of fields = 4.5, field access points = 3.5, route size = 18.4 ha, field size = 4.0 ha, route length = 15.8 km and return route to the farm = 20.1 km. In contrast, WKFarm shows a larger scale: number of fields = 4.3, field access points = 2.6, route size = 20.1 ha, field size = 5.5 ha, route length = 10.3 km and return route to the farm = 37.7 km.



Route composition of the machine cooperation

Figure 1: Number of fields and field access points

Figure 2: Route and field sizes

Figure 3: Route length and return route to the farm

The lowest coefficient of variation of 15.1% is found in the route size, with a standard deviation of 3.0 ha. The identified outlier of 13.3 ha on route 2 of LaFarm has little impact on the results. Comparatively high variations are observed in the return route to the farm (99.8%/35.2 km) and the route length (83.0%/9.2 km). The high variation in the return route to the farm is due to an outlier in route 9 of WKFarm (105.3 km). Additionally, high values for routes 10 and 11 (70.8 km and 99.6 km) and low values for routes 1 and 2 (both 0.0 km) of WKFarm further increase the variation. At WKFarm, the route lengths were effectively zero because the fields bordered directly on the farm, eliminating the need for low-loader transport.

Among the analysed measures of dispersion, the number of fields (39.9%/1.7), number of field access points (48.9%/1.3), and field size (47.3%/2.5 ha) show moderate relative and absolute variations. Two outliers, each with five field access points, on routes 9 and 10 of WKFarm slightly affect the dispersion measures. In contrast, the outliers in routes 1 (10.2 ha) and 5 (11.0 ha) of WKFarm have a considerable effect on the two dispersion measures.

The field size and return route to the farm are clearly skewed, with coefficients of 1.48 and 1.04, respectively. The right skew in field size is caused by two outliers (10.2 ha and 11.0 ha) in routes 1 and 5 of WKFarm. The right skew in the return route to the farm was due to the values in routes 9 to 11 of WKFarm. The route size showed a slight left skew (-0.82), attributed to a low value of 13.3 ha in route 2 of LaFarm. The number of fields, field access points, and route length showed an almost symmetric distribution with coefficients < 0.5.

Results of the working time study

For each of the 14 routes defined in the scenario design, work time requirements were determined in hours per hectare (h/ha), forming the basis for the subsequent analysis (Table A2 in the Appendix). In Sc1, the total working time for the field robot operation is on average 0.77 h/ha. The largest share of the total working time is the field work time, which, at 91.1%, corresponds to an average of 0.70 h/ha. The logistics time is 0.07 h/ha, which is 9.1% of the total working time. The largest share of the logistics time is the loading time, at 64.0% or 0.05 h/ha. Consequently, the transport time was 0.02 h/ha representing 36.0% of the logistics time (Figure 4). On average, slightly higher times are recorded for LaFarm: TWT_Sc1 = 0.86 h/ha, FWT_Sc1 = 0.73 h/ha, LT_Sc1 = 0.13 h/ha, TT_Sc1 = 0.06 h/ha, and LoT_Sc1 = 0.08 h/ha. In comparison, WKFarm presents moderately lower average times: TWT_Sc1 = 0.76 h/ha, FWT_Sc1 = 0.70 h/ha, LT_Sc1 = 0.06 h/ha, TT_Sc1 = 0.02 h/ha, and LoT_Sc1 = 0.04 h/ha.

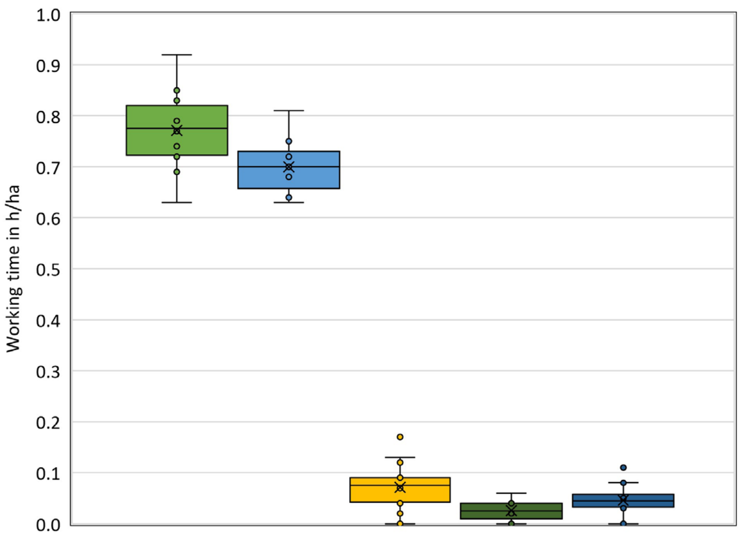


Figure 4: Structure of working times in scenario 1 (Sc1), including the total working time (TWT), field work time (FWT), logistics time (LT), transport time (TT), and loading time (LoT)

In Sc2, the average return transport time to the farm is 0.04 h/ha (Figure 5), resulting in an increased logistics time of 0.11 h/ha and a total working time of 0.81 h/ha. Consequently, the share of logistics time in total working time increases to 13.5%, whereas the share of field work time decreases to 86.5%. On the basis of the return transport time to the farm during the field robot's autonomous operation, an average on-farm working time of 0.66 h/ha is calculated, which can be productively utilised.

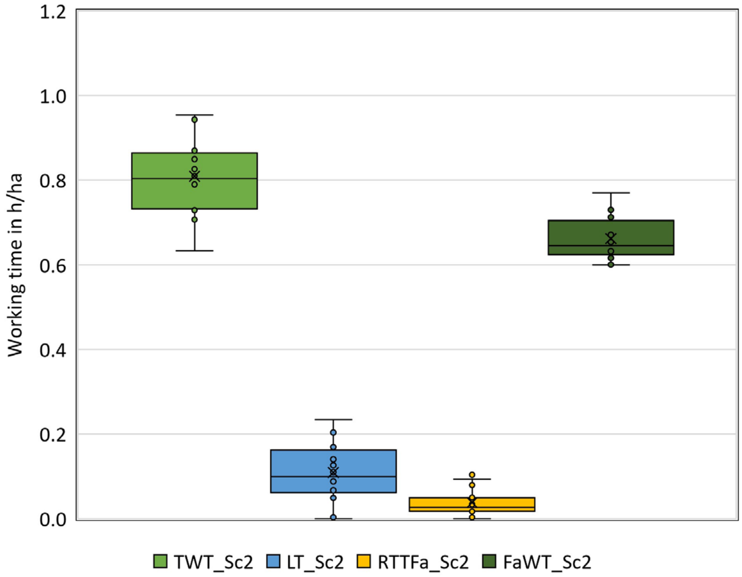


Figure 5: Structure of working times in scenario 2 (Sc2), including the total working time (TWT), logistics time (LT), return transport time to farm (RTTFa), and farm working time (FaWT)

The lowest coefficient of variation is observed in FWT_Sc1 (7.1%), with similar low variations in parameters related to field work, such as FaWT_Sc2 (8.0%), TWT_Sc1 (9.7%), and TWT_Sc2 (12.1%). The standard deviations are similarly homogeneous: 0.05 h/ha (FWT_Sc1 and FaWT_Sc2), 0.07 h/ha (TWT_Sc1), and 0.10 h/ha (TWT_Sc2). While logistics-related parameters exhibited greater relative variation, their standard deviations are marginally lower: RTTFa_Sc2 (87.7%/0.03 h/ha), TT_Sc1 (77.3%/0.02 h/ha), LT_Sc1 (68.8%/0.05 h/ha), LT_Sc2 (68.7%/0.08 h/ha), and LoT_Sc1 (67.9%/0.03 h/ha). The high variation in RTTFa_Sc2 is caused by low values for routes 1 and 2 (each 0.00 h/ha) and high values for routes 9 and 10 (0.10 h/ha and 0.09 h/ha) at WKFarm. For TT_Sc1, the high variation is also due to the high value for route 2 (0.06 h/ha) of LaFarm.

The calculated skewness coefficients show slight right skew for RTTFa_Sc2 (0.91), FaWT_Sc2 (0.70), and FWT_Sc1 (0.53). The high value of RTTFa_Sc2 results from an outlier on route 9 (0.10 h/ha) at WKFarm, which is further amplified by high values on WKFarm routes 10 and 11 (0.09 h/ha and 0.08 h/ha, respectively). The remaining parameters TWT_Sc1, TWT_Sc2, LT_Sc1, LT_Sc2, RTTFa_Sc1, and LoT_Sc1 had symmetrical distributions, with coefficients ranging from 0.15 to 0.32.

Results of the cost estimation: scenario 1

Based on the working time studies and annual machinery costs, machine hourly rates are calculated first, followed by the hectare costs of fiesc2ld robot and tractor operations. The annual utilisation rate is 779 h/a for both the field robot and the 55-kW tractor, 195 h/a for the power harrow and maize planter, 390 h/a for the inter-row hoe, and 78 h/a for the low-loader. This results in hourly rates of 32.45 €/h (field robot), 13.33 €/h (55-kW tractor), 22.02 €/h (121 kW tractor), 67.14 €/h (low-loader), 13.76 €/h (power harrow), 16.40 €/h (maize planter), and 11.57 €/h (inter-row hoe).

In Sc1, cost estimations were performed for each of the 14 routes using the calculated working times, enabling a comparison of fieldwork and logistics costs for the field robot and the tractor (Table A3, Table A4 and Table A5 in the Appendix). On average, total costs for field robot operations amount to 71.93 €/ha for power harrowing, 64.71 €/ha for maize sowing, and 59.87 €/ha for inter-row hoeing (Figure 6). For tractor operations, they are lower at 50.98 €/ha (power harrowing), 43.76 €/ha (sowing), and 38.92 €/ha (inter-row hoeing). The share of field work costs in field robot operations ranges from 85.7% to 88.1%, whereas it ranges from 97.4% to 98.0% for tractor operations. The outliers in total costs for field robot sowing and hoeing (80.42 €/ha and 75.24 €/ha, respectively) are attributable to Route 2 of LaFarm. The same route also explains the logistic cost outliers, 20.30 €/ha during field robot operations.

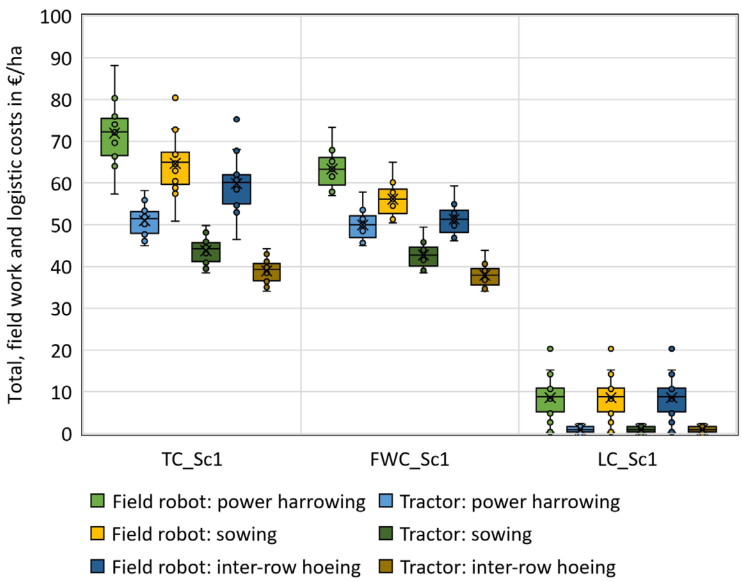


Figure 6: Cost components in scenario 1 (Sc1), comprising total costs (TC), field work costs (FWC), and logistics costs (LC), differentiated by field robot and tractor operation

The average field work costs for field robot operations are 63.34 €/ha (power harrowing), 56.11 €/ha (maize sowing), and 51.28 €/ha (inter-row hoeing). For tractor operations, they amount to 49.96 €/ha, 42.73 €/ha, and 37.90 €/ha, respectively. The higher field robot costs result from its average machine costs of 22.72 €/ha, compared with 9.33 €/ha for the 55-kW tractor (Figure 7). The implement-related machine costs range from 8.10 €/ha to 11.48 €/ha and apply to both carrier vehicles equally. Thus, machine costs account for 51.1% to 60.9% of field work costs in field robot operations and 38.0% to 48.7% in tractor operations. Assuming identical diesel consumption per implement, the diesel costs are highest for power harrowing (15.94 €/ha) and lowest for inter-row hoeing (5.42 €/ha). The labour time assumptions are the same for both carrier vehicles, resulting in uniform labour costs of 15.05 €/ha across all the implements.

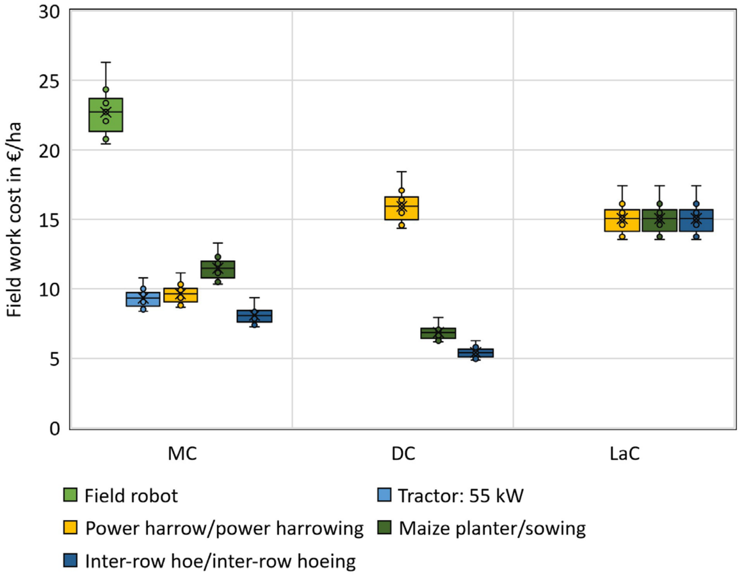


Figure 7: Machinery costs (MC), diesel costs (DC), and labour costs (LaC) incurred during field work in scenario 1 (Sc1)

The logistics costs for the field robot operation average 8.59 €/ha, compared with 1.03 €/ha for the tractor operation (Figure 8). Thus, logistics costs range from 11.9% to 14.3% for the field robot, whereas they account for only 2.0% to 2.6% in the case of the tractor. The higher costs in the field robot operation are due to the use of a low-loader and a 121-kW towing tractor, with average machinery costs of 4.99 €/ha and 1.64 €/ha, respectively. In contrast, the reference system requires only a 55-kW tractor and does not require a low-loader, resulting in lower machinery costs (0.34 €/ha). Additionally, the fuel and labour costs for the 121-kW tractor are 0.35 €/ha and 1.60 €/ha, respectively, whereas they were 0.13 €/ha and 0.55 €/ha for the 55-kW tractor.

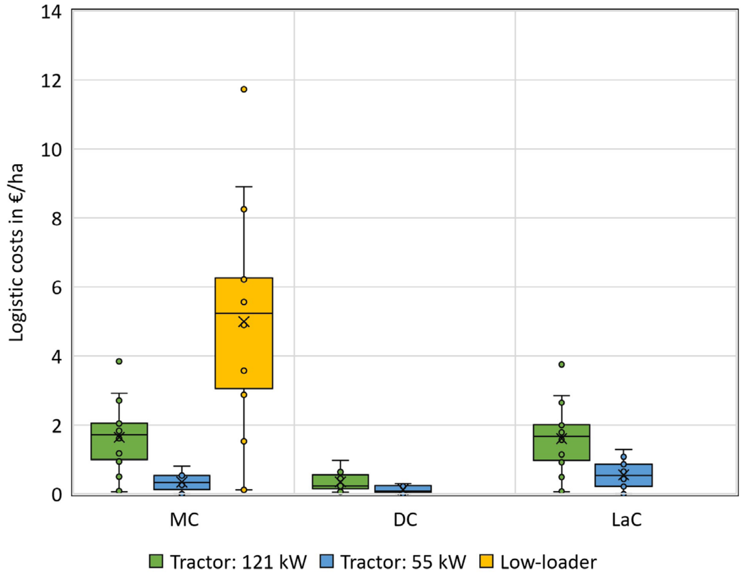


Figure 8: Machinery costs (MC), diesel costs (DC), and labour costs (LaC) incurred during logistics in scenario 1 (Sc1)

The standard deviations of the total costs for field robot operations range between 7.25 €/ha and 7.81 €/ha, depending on the work process. The standard deviations for tractor operations are lower, ranging from 2.94 €/ha to 3.78 €/ha. These differences can be attributed to the variation in logistics costs: for field robot operations, the standard deviation in logistics costs is 5.74 €/ha, whereas for tractor operations, it is 0.79 €/ha. Fieldwork costs show a standard deviation between 3.63 €/ha and 4.49 €/ha for field robot operations and between 2.69 €/ha and 3.54 €/ha for tractor operations. The high variation in logistics costs is due to the machine costs of the low-loader, which have a standard deviation of 3.33 €/ha and include an outlier of 11.73 €/ha on Route 2 of LaFarm. Similarly, high variation in logistics costs is also observed in the 121-kW tractor's machine and labour costs (1.08 €/ha and 1.06 €/ha), driven by outliers (3.85 €/ha and 3.76 €/ha) on Route 2 of LaFarm.

The distributions of the total costs are symmetrical, with skewness coefficients ranging from 0.28 to 0.36 for field robot operations and from 0.09 to 0.17 for tractor operations. The field work costs and their components (machine, diesel, and labour) consistently showed a slight right skew of 0.53, caused by high values from Route 4 of WKFarm, which are not classified as outliers. Regardless of the implement, logistics costs show skewness coefficients of 0.33 (field robot) and 0.26 (tractor). A slightly stronger right skew is observed for the 121 kW tractor's diesel costs (0.90), driven by a high value of 0.97 €/ha on Route 2 at LaFarm, which is not considered an outlier.

Results of the cost estimation: scenario 2

For all 14 routes, the cost analysis was extended to quantify the net economic benefit of automation, focusing on labour savings from the use of the autonomous field robot (Table A6 in the Appendix). In Sc2, return transport to the farm increases logistics costs to an average of 10.63 €/ha (Figure 9). By excluding labour costs for field robot operations in Sc2, the field work costs are 48.29 €/ha for power harrowing, 41.06 €/ha for maize sowing, and 36.23 €/ha for inter-row hoeing. The total costs of the three operations, considering increased logistics costs and decreased labour costs, range from 46.86 €/ha to 58.92 €/ha. The benefit from autonomous field work remains constant across all operations, averaging 14.23 €/ha. Consequently, the average net costs for field robot operations range between 32.63 €/ha and 44.69 €/ha. Compared with tractor operations, the net benefit shows that field robot operations result in an average economic advantage of 6.29 €/ha.

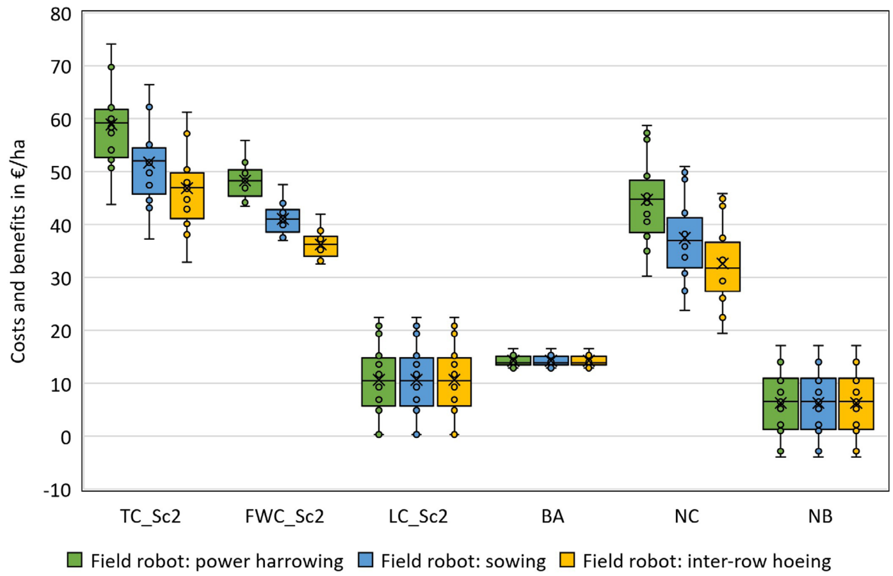


Figure 9: Costs and benefits in scenario 2 (Sc2), comprising total costs (TC), field work costs (FWC), logistics costs (LC), benefit of automation (BA), net costs of automation (NC), and net benefit of automation (NB) for the field robot operation

Compared with Sc1, Sc2 shows higher standard deviations in total costs (8.00–8.45 €/ha) and logistics costs (7.09 €/ha), whereas the field work costs vary less (2.57–3.42 €/ha). Owing to the low variability in farm work time, the benefit from automation has the lowest standard deviation (1.14 €/ha). With a net benefit standard deviation of 6.79 €/ha, field robot operations still yield an average economic advantage over tractor operations. The skewness coefficients of TCSc2, LCSc2, NC, and NB range from -0.05 to 0.27, indicating symmetrical distributions. Slight right skewness is found for FWCSc2 (0.53) and BA (0.70), driven by high values on Route 4 of WKFarm, which do not qualify as outliers.

Transferability of the results

LaFarm, with 80 ha of agricultural land, represents an average-sized farm, whereas WKFarm, with 767 ha, reflects large-scale operations. The national average is 75 ha, reaching 283 ha in Mecklenburg-Western Pomerania. Approximately 84.7 % of German farms manage ≤100 ha, accounting for 36.1 % of total farmland (DBV 2024). Economies of scale may significantly influence the adoption of robotics (Khanna et al. 2024, Lowenberg-DeBoer et al. 2022, Lowenberg-DeBoer et al. 2021). The data must therefore be evaluated to assess whether field robot usage within machinery cooperatives can be transferred to other regions and remain cost-efficient under current conditions.

As outlined in the section on scenario design, a 55-kW tractor was assumed for comparison with the 55-kW field robot. In practical farm operations on both LaFarm and WKFarm, tractors with higher engine power are typically used. Furthermore, certain operations such as inter-row hoeing were either not performed on conventionally managed farms outside the Agro Nordwest project or were carried out using implements with larger working widths. As a result, a more realistic reference system for the field robot could have involved a tractor with higher engine power and wider implements. Under these conditions, the tracked AgBot 5.115T2 with 115 kW engine power would have constituted a more suitable reference system. However, this model was not included in the Agro-Nordwest project or the corresponding logistics trials.

For hypothetical field operations of the 55-kW field robot using a 121-kW tractor with wider implements, an analysis of the previously calculated hourly cost rates suggests the following: the difference in field work costs between field robot and tractor would likely have been slightly smaller, logistics costs would have remained nearly the same, and the net economic benefit of automation would have been slightly lower.

Insights from the cost estimate

The calculated machine hourly rate of the field robot is 32.45 €/h, notably higher than that of the 55-kW tractor at 13.33 €/h. The hourly rates for the power harrow, maize planter, and inter-row hoe are 13.76 €/h, 16.40 €/h, and 11.57 €/h, respectively. In comparison, machinery rings in Germany charge tractor rates between 12.18 €/h and 16.00 €/h (LWKNRW 2025, MROM 2025, MRSB 2024, MRT 2025, MRWL 2024). Implement rates vary widely, ranging from 20.81 to 45.05 €/h for the power harrow, 31.82 to 66.01 €/h for the maize planter, and 19.37 to 45.92 €/h for the inter-row hoe, often due to equipment differences and individual agreements. The lower hourly rates in this study likely result from high annual usage within the machinery cooperative. For reference, the KTBL values are 250 ha/a for the power harrow, 62 ha/a for the maize planter, and 75 ha/a for the inter-row hoe (KTBL 2025a).

Machine costs account on average for 57.4% of field work costs with field robot operation, compared to 44.2% with tractor operation, highlighting a greater cost dependency and potential influence on economic viability. As field robots remain a relatively innovative technology, future learning effects in production and distribution, along with technological advancements, are expected to generate economies of scale and reduce costs (Lowenberg-DeBoer et al. 2022, McGee 2014, Rodríguez-Villalobos and García-Martínez 2018). The logistics costs for field robot operations are also higher, amounting to 8.59 €/ha, in contrast to 1.03 €/ha for tractor operations. This difference is attributable primarily to the use of a low-loader and a more powerful 121-kW tractor, which results in increased machine, diesel, and labour costs. Comparable studies on the Dino robot (Naïo Technologies) report similar logistics costs of 10.09 €/ha (Jorissen et al. 2025, Jorissen et al. 2024).

The average benefit of autonomous field work is 14.23 €/ha, resulting in a net benefit of 6.29 €/ha over tractor use. Comparable studies show that autonomous field robots are economically advantageous only when human supervision time remains low. Mandatory 100% monitoring makes its use unattractive for small farms. A lower level of monitoring is optimal, allowing a quick response to disturbances, depending on the size of the farm, the reliability of the technology, the need for intervention, and the location of the monitor (Lowenberg-DeBoer et al. 2022, Maritan et al. 2023). In this study involving the field robot within the machinery cooperation, an idealised state is assumed, where the farmer remained on the farm during autonomous field operations. A standardised hourly rate for agricultural labour (21.50 €/h) is applied, and the robot workload is allocated across 278 hectares of maize cultivation, without accounting for potential disruptions.

The analysis of the variation and symmetry of the cost and benefit parameters reveals homogeneous distributions for both the field robot and the tractor during field work, with only a few outliers detected. In contrast, greater dispersion and slightly more outliers are observed in the field robot's logistics costs, mainly due to variations in loading times and route composition.

Insights from the working time study

Assuming uniform travel speeds, the estimated field work times ranged from 0.63 to 0.81 h/ha, depending on the field size. Under similar assumptions, the KTBL calculates 0.79–1.00 h/ha for power harrowing, 0.68–0.80 h/ha for maize planting, and 0.93–1.11 h/ha for inter-row hoeing (KTBL 2025b). These differences suggest that KTBL applies implement-specific speed assumptions, especially for inter-row hoeing. In contrast to field work, logistics parameters showed more outliers and greater variation, indicating structural differences or planning deficiencies. For the field robot, the logistics time ranges from 0.00 to 0.17 h/ha, with loading times contributing up to 0.11 h/ha. The return transport times ranged from 0.00 to 0.10 h/ha. According to the KTBL calculation, transport times for the tractor are estimated at 0.05 h/ha (KTBL 2025b).

The average calculated farm working time of 0.66 h/ha depends on the autonomous field work time and the return transport time to the farm. Additionally, field size is a crucial factor in determining the total farm working time. With an average field size of 5.3 ha in the machinery cooperative, this results in a potential working time of 3.5 hours. However, whether this working time can be effectively utilised for value-adding activities must be assessed (Maritan et al. 2023).

Insights from the route composition

The measured working times and the resulting costs and benefits reflect the composition of the routes within the maize fields of the machinery cooperation. The collected route parameters show substantial variation and asymmetry. Long route lengths (0–26 km) and return routes to the farm (0–105 km) during the field robot's autonomous field work led to major differences in logistics-related times and costs. The number of fields and access points per route directly affect loading times and costs, influencing overall logistics. In contrast, the field robot's field work times and costs are only slightly affected by route parameters; here, annual utilisation is more decisive (Lowenberg-DeBoer et al. 2022; Lowenberg-DeBoer et al. 2021; Maritan et al. 2023).

Conclusions

This study demonstrates that the use of an autonomous field robot must be assessed in terms of both economic and labour time factors. While field work processes have proven stable and efficient, logistics-related times and costs have shown notable variation due to differences in route structures, loading efforts, and transport. Thus, logistical conditions and farm organisation strongly influence economic viability, whereas field work costs remain stable. Although field work costs show minimal variation, their high absolute level is a decisive factor, as the higher machinery costs of the field robot compared to a conventional tractor have a major impact on profitability. If future learning curve effects do not lead to a significant reduction in the investment costs of field robots compared to standard tractors, a higher degree of autonomy will be necessary to considerably increase hectare productivity to ensure sufficient cost recovery.

The field work results are based on modelled field robot operations via the AgXeed platform, as no actual operations were conducted on the 61 maize plots. Ideal conditions without downtimes were assumed, leading to an average net benefit of 6.29 €/ha. This gain reflects labour relief through automation and the reallocation of time to other productive tasks. However, the actual value depends on the availability of alternatives on the farm, the downtimes of the field robot, and the level of human intervention required. Future studies should conduct experimental time measurements during actual field operations to capture robot-specific factors such as path planning, field setup, and operational downtimes.

The analysis also underlines the importance of economies of scale and route design. Large-scale farms such as WKFarm offer more favourable conditions for autonomous technologies due to greater land resources. However, the comparison with LaFarm shows that even mid-sized farms can realise their potential through machinery cooperatives and effective management. Hybrid models—such as cooperative ownership—may therefore offer a realistic path towards broader adoption.

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