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Development and parameterization of an object-oriented model for describing agricultural process steps

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The objective of the „EKoTech“ research project is to identify future fuel saving potentials of agricultural machinery. The results projected to 2030 are compared to 1990. The quantification in current and future scenarios of agriculture is based on model farms and saving potentials by using machine and process models.
The process models presented in this publication determines suboperation times of different field works on individual field contours according to the KTBL time classification scheme. The structure of the simulation model as well as the methodical procedure of data recording and evaluation for plausibility checks of the simulation results are described. Based on recorded GPS positions of the tractors in various field works, a first comparison of measurement and simulation is made and presented.

Keywords
EKoTech, machine operating times, process simulation

In the research project „EKoTech - Efficient Fuel Use of Agricultural Technology“ managed by VDMA Agricultural Engineering in cooperation with partners from industry and science, future potentials for increasing fuel efficiency in agricultural process chains through the use of efficiency-enhancing technology will be determined. The project is supported by funds of the Federal Ministry of Food and Agriculture (BMEL) via the Federal Office for Agriculture and Food (BLE). Further information on structure and procedure in the EKoTech project is given by Nacke (2014), Frerichs et al. (2017), Decker (2017) and Fleck and Hanke (2015).

In this project, industrial partners identify and quantify possible fuel savings that can be achieved by new technological methods. A holistic simulation model depicts these technological innovations, to make conclusions on the total fuel savings of a process chain. The model is based on a coupled simulation approach consisting of machine and process models. The modelling of machines occurs in Hohenheim at the Institute of Agricultural Engineering and the process models are developed at the Institute of Mobile Machines and Commercial Vehicles at the Technische Universität Braunschweig. The Association for Technology and Structures in Agriculture (KTBL) from Darmstadt supports the work.

Depending on the effect, technical and organizational saving potentials are taken into account in the machine and process models or both. A tire pressure control system, for example, is depicted by an adaptation of the driving force coefficient in the machine model and optionally the operating speed in the process model can be adjusted. Both models offer possibilities to consider the saving potentials via parameter variation and to adapt the level of detail to the requirements.

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The process model calculates suboperation times of tractors and equipment. Influencing factors are divided into technical, operational and organizational elements. The possible working speed, for instance, can be described as a technical factor, and the working width of the equipment used on the farm or the field structures as an operational factor. Organizational factors account for the driving strategies within the field (beds or track-to-track). To validate the simulation results of the process models, a comparison with real recorded operating data is necessary. Furthermore, knowledge for further development of the simulation tool is gained.

State of the art

Models for calculating suboperation time in agriculture

The literature contains various approaches for calculating partial working times in arable farming. Total working hours can be estimated by area performance and field area to be processed. The KTBL offers a comprehensive database with information on area performance of a wide variety of tractor-implement combinations (KTBL 2016). This method is very common among farmers and agricultural advisors. Further tables can be found in the literature (Srivastava et al. 2015, ASAE 1999, Uppenkamp and Nacke 2017).

The limits of such approaches are reached when using several machines simultaneously in harvesting processes and the respective operating state depends on other machines. Furthermore, the variety of influencing factors and the number of participating machines make it difficult to determine suboperation times. One approach is to calculate the combine‘s cycle time for filling the grain tank and the tractor‘s turnaround time for transport from the field to the farm. Depending on the duration of each cycle, waiting times for either the combine or the tractor can be derived (Herrmann 1999).

Production processes in factories or supply chains use agent-based simulations to represent and analyze suboperation times of machines. Point of interest in this case are the utilization or waiting times of machines in process chains of a production. For some agricultural process steps, e. g. harvest logistics for maize harvest, this method was successfully implemented and suboperation times of the machines were broken down in detail (Sonnen 2007, Steckel 2014). Similar approaches and simulation models have been presented by Hameed (2013), Oksanen (2007) and Zhou (2015). Currently, Osnabrück University of Applied Sciences is working on a modeling method for evaluating grain harvesting concepts (Peters 2017).

Time recording of suboperations on a farm

The recording of suboperation times in agricultural field works for research purposes can be carried out both manually and in a (partially) automated manner. In manual manner, an observer measures and notes the suboperation times of a machine driven by a machine operator. For example, to identify the turning time of different turning figures in different process steps, this procedure was successfully applied (Engelhardt 2004).

In further research work, automated recordings of data on tractors are carried out, which are evaluated on a computer according to various key values. Mini computers are usually used to record data from CAN bus or a GPS receiver. A subsequent evaluation can, for example, identify and display working times, fuel consumption or engine utilization (Heizinger 2014, Grenier et al. 2014).

In a more mature and user-friendly version, comparable functions are offered as so-called telematic systems or as farm management information systems (FMIS) from different manufacturers. The user does not come into contact with measuring technology and evaluation and data is available in a cloud.

Methodical approach

Overview

In general, changes in complex systems are quantified by practical tests, simulation calculations or in a combination of these. Against the background of the diversity of agricultural farms and production systems adapted to local conditions, the efficiency of technical or logistical measures can not be proven just by practical tests, such as field trials. Cost- and time-limiting factor represents the necessary scope of tests. For partial-factorial experimental designs, as they are often used in complex system studies, the loss of information cannot be estimated with adequate certainty because of complexity of the agricultural system and the inherent interaction of different processes and factors. Therefore, a modeling and simulation approach is used in this research project to map agricultural processes. The calculations within the simulation are parameterized and the plausibility of the results is checked by comparison with measured data of field works.

One task of the simulation is to determine the suboperation times (working, turning, ...) in different process steps. For this purpose, an object-oriented simulation model is developed in which agricultural farms – each typical for a defined region in Germany and Europe – are modelled. The diversity of farms is taken into account by different machine specifications and equipment, field structures, road networks, yields, process flow and process parameters, such as working depths or application rates. For this article, the process models were parameterized with measured data. The model calculations can be used to assess operating profiles of tractor-implement combinations under different operating conditions. On this basis, operational changes can be calculated in different scenarios. The results of the simulation allow to make conclusions and offer a basis for making decisions for real operation.

Figure 1 shows the basic procedure for transferring the measured real data into the simulation model, the calculation of scenarios and the final decision making process. The recorded data is used to parameterize the process model. In a further step, scenarios can be calculated with the parameterized simulation model. Based on the results of the scenarios, a decision can be made, for example, for an expansion of a real farm. The simulation offers time- and cost-efficient possibilities for evaluating the effects of technical measures and scenarios of operational conditions and organisational forms.

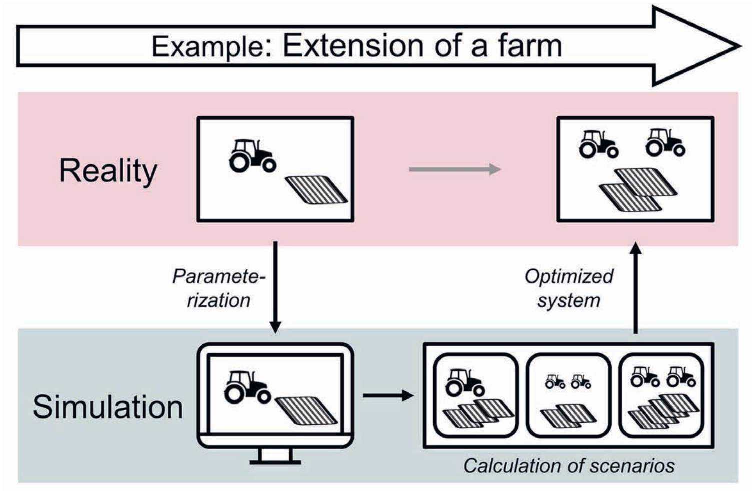

Figure 1: Basic procedure of scenario simulation from real world to virtual world and back to real world

Development of an object-oriented simulation model

A starting point for the development of a simulation model is the development of requirements. The operating conditions, the technical equipment and the process chains are included as input data in the model. Output values are the operating profiles of machine work carried out in KTBL time classification scheme. The aim is to represent field areas as well as farm-field and field-field distances as realistically as possible and to simulate all work on fields based on the existing process chain. In addition to simple tasks, complex multi-machine applications, e. g. processes for grain or hay harvesting, can be simulated. As simplifications, fields with homogeneous soil conditions and homogeneous yields are initially assumed. The machines are classified according to the KTBL classes. However, the model has a modular design, so that variance can also be implemented.

An agent-based simulation approach is used to map agricultural processes. An essential feature of agent-based simulations is to focus on individual active units of a system, which are generally called agents. In the simulation environment, behavior patterns can be defined for these agents. The agents can have specific characteristics, interact with each other or react to their environment

With regard to the simulation model of agricultural processes, the agents are not only machines or machine combinations, but also managers and farm locations. By this way, the workflow of an agricultural farm is interpreted as a multi-agent system. According to this interpretation, it is possible to map the farm system as realistically as possible. The agents are characterized by different characteristics and tasks. The behavior is programmed according to the type of agent. The machines and machine combinations act depending on the process step they perform. The basic actions are based on the KTBL time classification scheme. Using stubble cultivation as an example, these actions include setting up, preparing the machine combination, driving on the road and in the fields, and working in the fields. When working in the field, a difference is made between working and turning at the end of the field.

The simulation model consists of several modules (Figure 2). In addition to a map material, a calendar is also provided in the simulation environment. The work on the fields can be scheduled and shift times can be taken into account. The general procedure within the simulation model is described by Frerichs et al. (2017).

The fields on which the process steps are to be carried out are created in the field generation module (Figure 2). Based on the GPS coordinates of field corner points, an algorithm creates the field within the map material of the simulation environment. First, the field is divided into two areas: headland and main field. In the model, the fields have headlands on all field edges. Headlands are generated depending on a given width along external borders of the field. The main field is located inside the circulating headland. The field can have a complex geometry according to field corner points. To perform a practice-oriented processing of the field, the main field is subdivided into subfields. Subfields have simple contours of 3 or 4 corner points and have a defined main working direction. In addition, they are arranged in a way that processing with a small number of lanes can be performed.

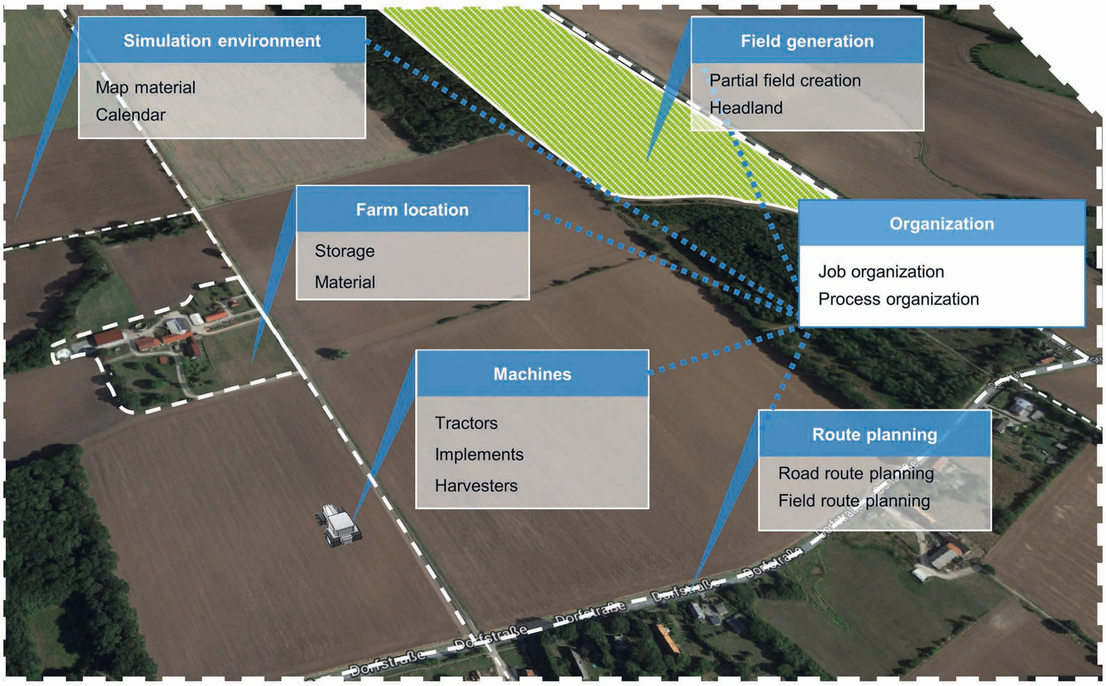

Figure 2: Structure of simulation model with developed and still to be developed modules

During field work on headland, the agent decides for a subfield and calculates startpoint and endpoint of the next lane. The calculation of the path taken by the agent during turning is done in the route planning module (Figure 2). For turning, two basic manoeuvres are available in the simulation. Turning can be carried out by a pure forward movement or by several changes of direction with forward and reverse movement. For turning manoeuvres without a change of direction, the path planning according to Dubins (1957) is used in the model. Depending on a start and finish configuration, which is characterized by a position and an orientation of the vehicle, so-called Dubins paths are calculated using the specified turning radius of the machine combination. They describe a set of shortest paths between two configurations. Paths can consist of both circular and straight lines. Figure 3 shows a selection of Dubins paths using the example of a headland turn. The turning method is selected taking into account surface geometry, headland width and path length.

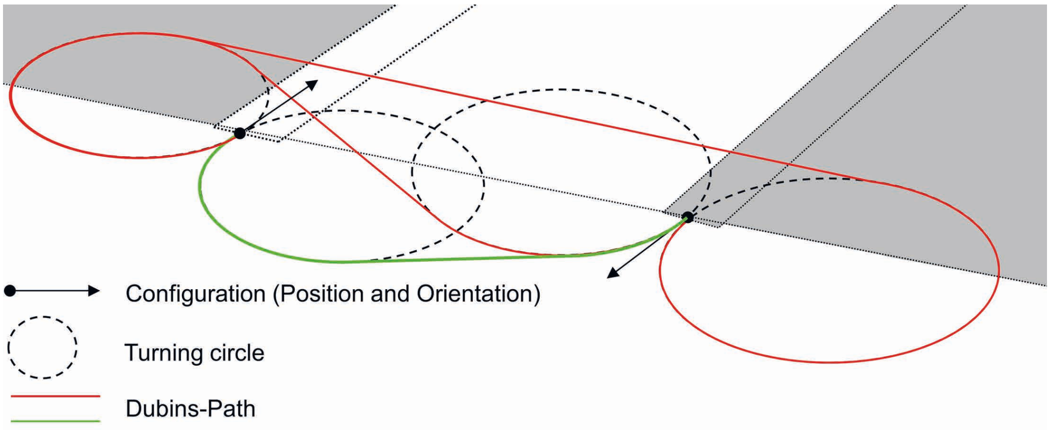

Figure 3: Dubins path with configuration of start- and endpoint using example of a turning manoeuvre in headland

Referring to the Dubins paths, so-called Reeds Shepp curves (Reeds and Shepp 1990) also represent a set of paths between two configurations. Additionally, the vehicle is able to reverse. These paths are used for turning manoeuvres with changes of direction. The additional degree of freedom in direction of movement increases the number of possible turning paths. The selected turning type (Dubins paths or Reed-Shepp curves) depends on the machine combination and the type of process step. Further modules are currently in development and are not described yet. Nevertheless, it is already possible to simulate simple process steps such as soil cultivation, sowing, fertilisation and spraying.

Reference data and evaluation methodology

Requirements and data collection

Reference data is used for plausibility check and parameterization of the described simulation model. In initial test recordings, tractor-implement combinations were recorded while carrying out soil cultivation, sowing, fertilisation and spraying. Technical working widths of implements are in a range of 2.0 m for a plough, 6.0 m for a disc harrow and up to 27 m for a field sprayer. Recording of the data is carried out on several farms by the usual machine operators and not by scientific personnel. This will ensure that practice-relevant results are generated. There are 3 tractors equipped with a variable, simple measuring technique that does not influence the driver. Minimum requirements for the measuring system are derived from the process steps to be recorded and listed below:

- Simple construction and installation of the measuring system on the tractor (estimated time < 20 minutes)
- Accuracy of GPS signal less than 20 cm
- Automated recording of GPS positions when starting tractor
- Low-cost purchase (< 150 €)

Among the requirements, a GPS receiver (NL-402U USB, Navilock) with USB connection and a Raspberry Pi 1 (Model B+, Raspberry Pi Foundation) were selected (Figure 4). The GPS receiver provides EGNOS support (European Geostationary Navigation Overlay Service) to maintain required accuracy and supports the NMEA 0183 standard. The measuring system is supplied with power via the 3 pin socket (DIN 9680) in the tractor cab. It is a closed system, so that no connection to the tractor is necessary besides the power supply.

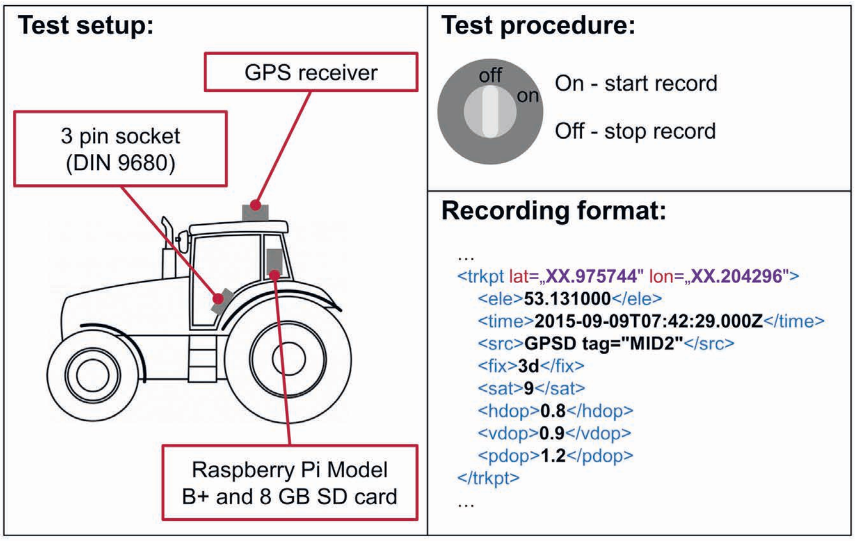

Figure 4: Test setup, test procedure and recording format

Test procedure is performed automatically, i. e. the measuring system does not have to be switched on or off by the operator, thus avoiding operating errors. The mini computer starts up when the engine is switched on, initializes the GPS receiver and starts recording the GPS signal after 60 seconds. Delayed recording ensures that the GPS receiver has received a signal and that recording can thus be started without errors. When the engine is switched off, the mini computer is no longer supplied with power and is switched off.

“Raspbian” is used as the operating system on the Raspberry Pi and “gpxlogger” for recording GPS positions. Recorded data sets are stored as gpx files on a SD card and can be copied to a computer at regular intervals. GPS positions are recorded in an interval of one second and stored as data sets of waypoint format. Recorded gpx files include latitude and longitude (WGS84), altitude in meters, time stamp in the format YYYY:MM:DD-hh:mm:ss and further information on position accuracy.

As a result of the simple approach to recording suboperation times, only time- and location-based data is available for the documentation. In favor of a simple and closed system, no internal tractor data via CAN or ISOBUS interface has been recorded.

The farms are located in the northern parts of the states of Brandenburg and Sachsen-Anhalt and have a farm size between 200 and 300 ha. In addition to the data records, further information about the farm such as used implements and field boundaries are required once. The used tractors and implements and the technical data are shown in Table 1.

Table 1: Selected tractor implement combinations with parameter

Tractors	Implement type	Technical specifications
Tractor 1 (120 kW)	Plough (drawn)	2.0 m
Tractor 2 (150 kW)	Disc harrow (drawn)	6.0 m
Tractor 2 (150 kW)	Cultivator (drawn)	4.6 m
Tractor 3 (150 kW)	Seeder (drawn)	3.0 m, 1,400 l
Tractor 3 (150 kW)	Sprayer (drawn)	27.0 m, 4,000 l

A data set with the recorded waypoints and field boundaries is shown in Figure 5. By using the automatic recording, several fields as well as partial or complete cultivation can be stored in one data set. A complete cultivation represents the total processing of a process step in a field. A partial cultivation describes the partial processing of a field, e. g. only headland cultivation. These different forms of data sets must be standardised in the evaluation process, which has been carried out on the basis of the field boundaries provided by the farmer (Figure 5).

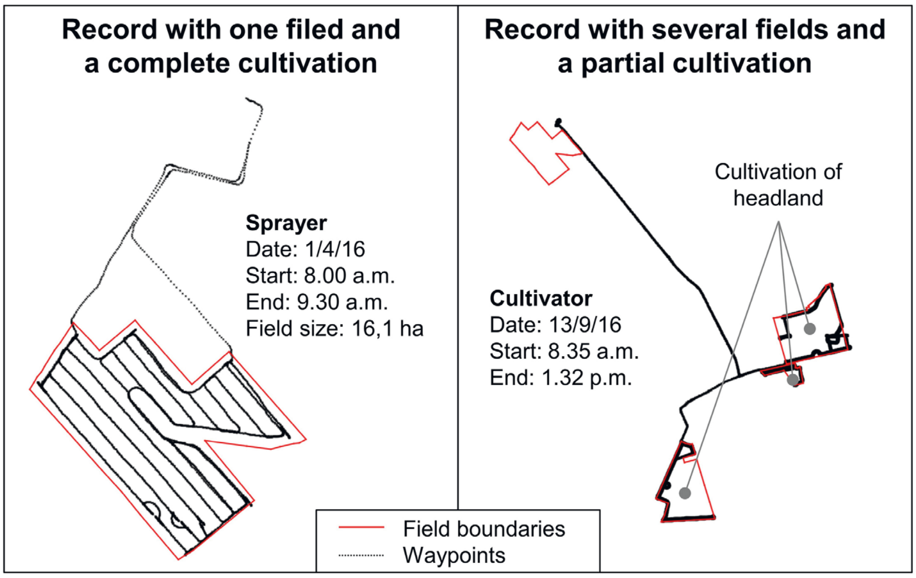

Figure 5: Fields and recorded tracks (waypoints); left: record with cultivation of a field including headland; right: record with cultivation only of headland of 3 fields

The data sets recorded in 2016 and 2017 contain about 433 working hours with 86 jobs. One job represents a complete cultivation of a field with one implement. Results in this paper refer to the process steps soil cultivation, sowing and spraying. After filtering data records, there are altogether 50 jobs. From these jobs, 18 jobs on 15 fields with 109 working hours are randomly selected and analysed. Jobs that do not match to tractor-implement combinations in Table 1 were filtered out (e. g. jobs in grassland).

Challenge in evaluation and evaluation methodology

An algorithm was created for automated analysis of the data records. The programming software “eclipse” with the corresponding Java language is used as development environment. Various libraries are available for this open source software. A graphical interface is created for the user. The procedure for the analysis of data records is divided into five main points, which are to be explained in more detail.

Repair and import of data set

Because of the „hard“ shutdown of the Raspberry Pi when switching off the tractor, the software ends the data recording without closing tags. The file must be completed before importing using a so-called standard GPX parser. Since the GPX format is a standard format, libraries are available for this purpose.

Selection of field to be analyzed

The software includes a graphical user interface with input and output elements as well as interactive map material based on OpenStreetMap (OSM 2004). Waypoints from data set and field boundaries are loaded and displayed on the map material (Figure 5). By selecting a field boundary on the map material, a field can be selected. After defining the field, relevant waypoints are selected in a two-step procedure. In a first phase, all waypoints are evaluated and stored in a buffer if they are within the field boundary. In a second phase, startpoint and endpoint are selected from the buffer and all points of the waypoints between startpoint and endpoint are stored in the buffer. Finally, all waypoints from first time driving on the field to final departure from the field are taken into account. This means that turning manoeuvres outside the field or road transports are also taken into account.

Determining the tractor and working width

Raspberry Pi are permanently assigned to the tractors (Table 1). While generating the raw data, the file names are extended by date and tractor identification. When the data set is loaded for evaluation, one of the stored tractors based on file name is selected and saved. Effective working width is determined semi-automatically by the user. Several side-by-side lanes on a line (orthogonal to the lanes) are selected and the average working width is calculated and stored.

Calculation of relevant parameters for the process step

A calculation of suboperation times and further values, such as the average working speed for the process step, is carried out in the next step. The division of suboperation times is based on the KTBL time classification schema, but differs in further subdivision of road and field time (KTBL 2016):

Road time (R): Times when the tractor is at least 300 seconds outside the field boundary.

- Preparing time and disturbances: Times at farm or on road when tractor is driving at least 30 seconds slower than 2 km/h
- Travel time: Times on road when tractor is driving at least 2 km/h.

Field time (F): Times when tractor is inside or temporarily outside field boundary (see road time).

- Preparing time and disturbances: Times on field when tractor is at least 30 seconds slower than 2 km/h.
- Travel time: Times on field when tractor travels along a line and differs at least 20 % from the average working speed.
- Basic time: Work and turn times with at least 2 km/h.
  - Work time: Times when tractor is working along a line and with an average working speed (permissible deviation ± 20 %).
  - Turn time: Times when tractor does not drive along a line or covers a maximum distance of 40 m along a line.

When defining suboperation times, recorded waypoints of a field are scanned several times by an algorithm. On each pass, a characteristic is set to a waypoint. In the first iteration, waypoints are subdivided by location so that they can be assigned to road or field time. The conditions of the division can be found in the above list of suboperation times. During the next iteration, all waypoints of road time are taken into account and additionally assigned to the properties „preparing time and disturbances (R)“ or „travel time (R)“ . This characteristic is classified on the basis of driving speed. The waypoints therefore have both the characteristics of „road time“ and either „preparing time and disturbances (R)“ or „travel time (R)“. The properties of „preparing time and disturbances (F)“, „travel time (F)“ and „basic time“ are assigned to waypoints of field time in further iterations. Waypoints of „basic time“ are further subdivided into „work time“ and „turn time“.

In addition to determining suboperation times, further key values are calculated. The average working and turning speeds are calculated from distance travelled and duration of respective suboperation. The processed area is calculated by an concave hull algorithm. Area performance or proportion of worked areas can be derived from key values.

Export of data to Excel for further handling

The jobs stored in a database can be converted to the Excel format by using an interface. Each job is exported line by line into a spreadsheet of Excel. Necessary information such as date, implement, working width or suboperation times are stored for each job. Complete data can be analyzed by using Excel. For example, all jobs carried out with plough can be filtered and key values for area output or working width can be compared. Non-plausible information can be found with the help of software and further analysis can be carried out.

Results

With help of reference data collection, suboperation times of process steps were determined. The methodology also enables suboperation times during basic time (turn and work), travel time as well as preparing time and disturbances of jobs to be displayed in the user interface. With additional evaluation of waypoints during basic time, average speeds for turning and working are available. Furthermore, turning manoeuvres can be displayed. Figure 6 shows the evaluation of measured data of a job (job number 4, Figure 7). In addition to a visualization of jobs on a map material, calculated key values are available. GPS points are shown in blue for work time and in black for turn time. A zoomed view of headland with turning manoeuvres is shown. Further colored view settings of GPS points like display of speed or order of processing can be made. Individual suboperations such as work or turn (see enlarged headland area) can be shown or hidden. Key values contain information on duration of operation, tractor-implement combination used, working and turning speeds as well as calculated suboperation times for, among other things, turning and working.

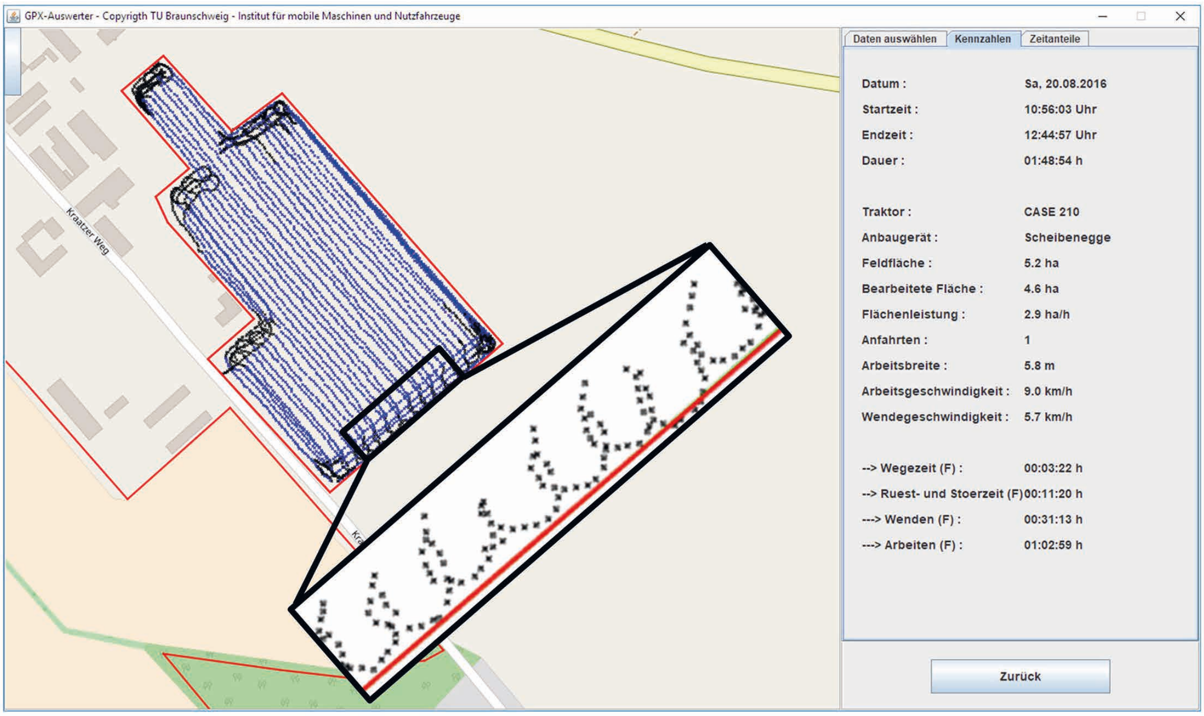

Figure 6: Screenshot of evaluation program with a selected process step of stubble cultivation with a disc harrow; calculated key values and visualization of the suboperations (working (blue) and turning (black, enlarged) in the field)

The illustrated job shows work with a 150 kW tractor and a disc harrow on a 5.2 ha field. Total time was determined to 1 hour, 48 minutes and 54 seconds and the area output was calculated to 2.9 ha/h, with both values in the range specified by KTBL for this working method. Also the turn time share of 33 % of basic time (sum of work and turn time) is plausible.

For the simulation of different work jobs with the described tool, fields with GPS positions of field boundaries were used. Machine and process step characteristics are set as parameters in the process model. Speeds during work and turning procedures are average values from all investigated data sets of the respective process step. Simulation results for work time, turn time and basic time are shown in Table 2 (for job number 4 in Figure 6). Deviations between simulated and measured values are within a range of 3 to 4 % for individual jobs. In the simulation, the share of turn time in basic time remains at around 31 % on the same level as in the reference measurement. Operating sequence and turning figures are similar to those of reference measurement and were defined by the parameter set, regarding working direction, turning radius or turning type. In further project steps, these and the following results are to be verified by validation tests of holistic process chains.

Table 2: Comparison of reference and simulation results of selected job (job number 4)

Suboperation	**Reference results in min**	**Simulation results in min**	**Deviation in %**
Basic time	94.2	91.0	-3.3
Work time	63.0	60.5	-3.9
Turn time	31.2	30.5	-3.2

This simulation calculation was carried out for 18 jobs. For all of 18 jobs, a detailed presentation of shares of turning and working time in basic time is shown in Figure 7. For each job measurement, results are shown in light red/light blue and simulation results in dark red/dark blue. Share of work time in basic time is between 66 and 93 %, predominantly between about 80 and 90 %, with field sizes ranging from 5 to 36 ha. Minimal deviations between simulation and measurement are both positive and negative. Deviations are similar for all tractor-implement combinations. In addition to work and turn times, the number of travels to the field were also evaluated for field sprayer applications. The results are in same order of magnitude in simulation and measurement. As a result, it can be stated that the model can basically be parameterized very precisely with real data.

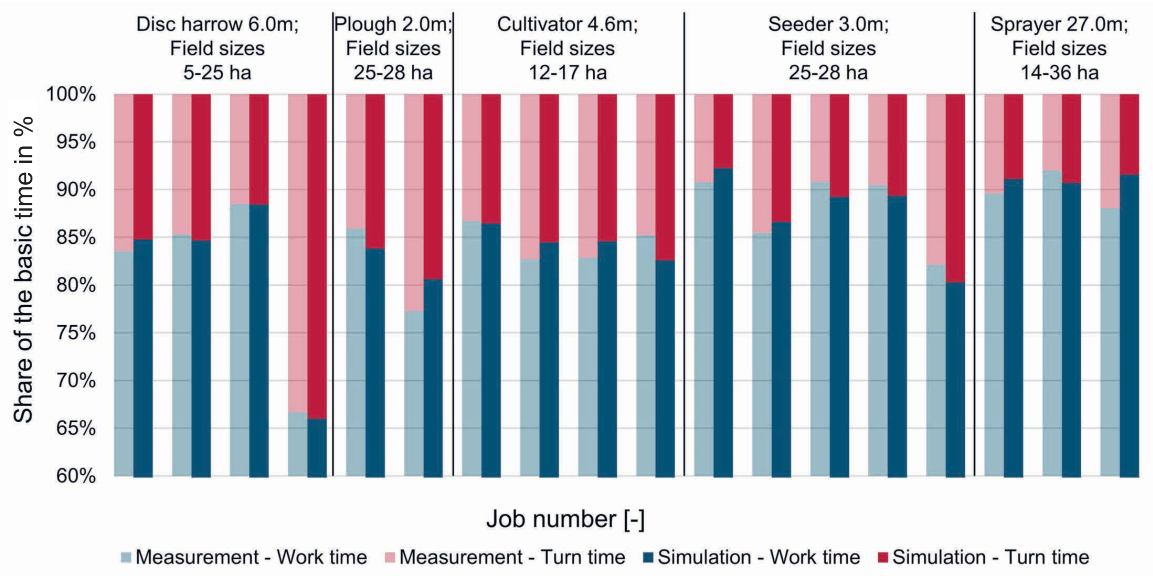

Figure 7: Results from simulation and measurement for different jobs and implements

Total time for processing of all jobs was in reality about 109 hours. In the model, a time of 108 hours was calculated. The processing times per process step can be calculated by adding the basic times of the relevant jobs. In simulation, for example, total time for ploughing is 41 hours. Time components of process steps are shown in Figure 8 with measured times in the left diagram and simulation results in the right diagram. In the simulation, percentage shares of machine use show minimal deviations from measured values.

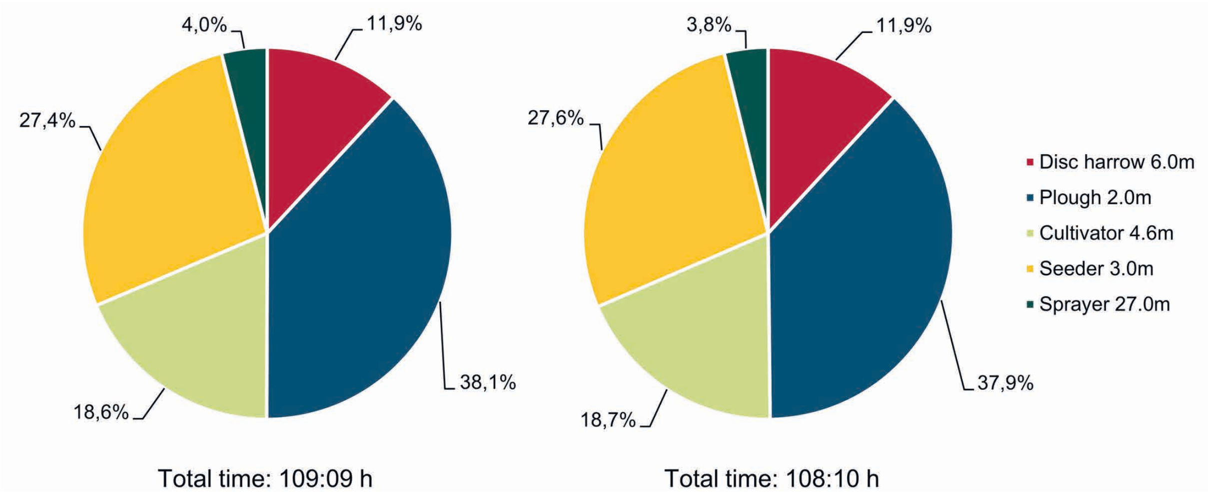

Figure 8: Shares of considered process steps over a total time compared between measurement (left) and simulation (right)

Conclusions

The presented simulation model enables mapping of agricultural process steps and determination of relevant key values of different jobs, e.g. area output or suboperation times. The suitability of the simulation model for determining suboperation times and other key values was shown in the results chapter for process steps with single machines. In addition to these key values, a comparison of a tractor‘s route within a field between measurement and simulation was carried out for each job. A plausibility check of the tractor route in simulation is ensured by this approach.

In further steps, the simulation model will be extended in such a way that complex process steps with a multiple machine application can be mapped. For example, the use of multiple machines occurs in the processes of grain or green crop harvesting with different machines involved simultaneously. After mapping all process steps and validating further reference measurements, operations can be optimized. By use of different optimization strategies, effects of various influences can be presented. The final simulation model can serve as a decision support for manufacturers, consultants, contractors and farmers.

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