Concepts for Highly Automated Green Windows in the ISOBUS Architecture

Lukas Pindl, * **Nikolaos Margaritis,** ** **Maximilian Werner,** *
Samuel Brodie, * **Volker Stöcklin,** ** **Timo Oksanen** *

* *Technical University of Munich, Germany; Professorship of Agrimechatronics; e-mail: {lukas.pindl,ml.werner,timo.oksanen}@tum.de; Munich Institute of Robotics and Machine Intelligence (MIRMI)*
** *RAUCH Landmaschinenfabrik GmbH, Germany; e-mail: {nmargaritis,vstoecklin}@rauch.de*

Abstract: This whitepaper presents and analyzes five concepts for implementing highly automated Green Windows within an ISOBUS-based agricultural workflow. The concepts differ in how computation, data exchange, and sensing are distributed among the Farm Management Information System (FMIS), Task Controller (TC), and onboard or external sensors. Key factors influencing concept suitability include the location of algorithm execution, the handling and storage of Green Window positions, interoperability of data formats, and the choice of sensing system. The concepts collectively illustrate a range of options balancing automation, standardization requirements, operational flexibility, and integration effort, enabling stakeholders to select an approach that aligns with their technical infrastructure and management objectives.

Keywords: Precision farming, ISO 11783, Task Controller, FMIS, nitrogen use efficiency

1. INTRODUCTION

1.1 Fundamentals of Green Windows

As nitrogen prices increase, many farmers are trying to optimize their usage of this vital fertilizer. One approach to do this, are Green Windows [1] . They are small plots within a normal field, in which the applied nitrogen amount is varied by hand. During the season the growth is continuously monitored and compared. In [1], this was done by an expert. They decided which was the plot with the lowest amount of fertilizer, that was not visually different from higher fertilization plots. From this information, the optimal nitrogen rate for the rest of the field was derived for the next application. This allowed the researchers to lower the given nitrogen amount by 69% while increasing yield by 13%.

While Green Windows-like concepts have been standard practice in research institutes of nutrient management for decades, this has not been adapted to everyday farming beyond so call null-plots. The fundamental idea of Green Windows concept is that farmers place these Green Windows for every single field plot, or even several per field plot if the spatial variability of the soil and other properties requires that. Similarly, in case of several homogeneous small plots grown virtually as one larger plot, Green Windows might be necessary only in representative one.

To make this procedure more interesting for farmers, automation would be beneficial. The application of fertilizer within the windows should be possible with machinery and for the comparison of different plots, sensors could be employed. This allows automatic analysis and generation of comparison plots as in fig. 1. Standardizing the setup within the existing framework of ISO 11783 ("ISOBUS"), could enable farmers to use this approach with various spreaders, sensors and managment systems.

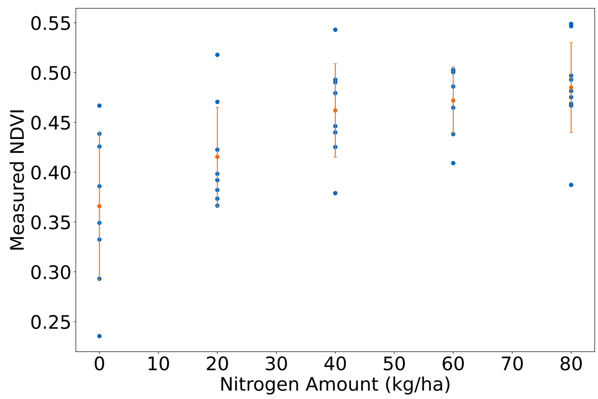

Fig. 1. The effect of additional nitrogen fertilization can be measured, for example using the Normalized Difference Vegetation Index (NDVI). This data comes from a TUM test field.

1.2 Basic Procedure for Green Windows

Over the crop season, the green window approach works in multiple stages.

During seeding, tramlines are added and their position is saved.

Then the green windows are planned. They should be placed next to tramlines and towards the edge of the field for accessibility. However they should be representative for the field, so should not be done in the headlands. To get the best data, the plots should not cover varied soil and have similar yield potential on all plots. If a field is especially large and has different areas with heterogeneous soil types, multiple clusters of green windows can be placed. The fertilization steps need to be defined for each plot. Typical amounts may go from 0% to 200% of the base rate for the rest of the field.

For the first fertilizer application, the plots are fertilized according to these defined steps. Since there was no difference in fertilization until then, no sensing needs to take place.

Starting with the second application and for all further ones, the green windows are first scanned with the sensor. From these sensor values, an optimal fertilization rate for the rest of the field is calculated. Then the fertilizer is spread over the whole field based on the updated prescription maps.

For each fertilizer application, it is possible to give a measured value for the mineralized nitrogen (Nmin) in the ground. These can be used by the GW algorithm to adjust the optimal application rate. While Nmin collection for each field can be a tedious task, [2] shows, that a mixed sample from 0-90cm depth is sufficient, and relatively few samples per field need to be taken. To save costs, the samples do not necessarily need to be brought to a laboratory, but simple test strips can be used and analyzed via smartphone [3].

1.3 Capabilities and Limitations of the Task Controller

As the scope of this paper is to provide concepts for "Highly Automated" version of Green Windows, it needs to be integrated to field machinery. The standard tooling for precision farming, or site-specific farming, is based on ISO 11783 components and ISOBUS system. ISOBUS offers components for the user interface to control the implement, called Virtual Terminal (VT), but that does not provide an automation toolset. In ISOBUS, the main component handling precision farming data is the Task Controller (TC), which is defined in ISO 11783-10 (2015). The Task Controller has several features, out of which here relevant are TC-GEO (variable rate control) and TC-SC (automatic section control). Both of them require that both the terminal (TC server, usually integrated into the tractor cabin) and the implement are certified for that. Also, the Task Controller must receive a localization signal from GNSS with sufficient accuracy to operate automatically (both variable rate and automatic section control). The required accuracy level depends on the application, but typically, the desired accuracy is 1 dm.

The current Task Controller standard was defined for implements, which were developed in early stages of precision farming mechatronics. The original ISO Task Controller concept was developed in 2003. That time, typical machinery were a) two-disc fertilizer spreaders with rate control and automatic weighing system, b) sprayers with single pressure control over the whole boom, divided into 3-7 sections, c) seeders and planters with adjustable dosing unit equal for all coulters, and d) large air cart systems. The Task Controller standard has been expanded in later editions to cover more precise mechatronics, like the number of sections has emerged from 3-7 into 50-100, or in planters, each row unit can be controlled separately. This has caused different generations of certified products on the market.

Currently, the Task Controller concept is limited to one main procedure: 1) The farmer, farm manager or farm consultant is creating application (dosing) maps with office software (generally called Farm Management Information System, FMIS), 2) the application map is transferred into the tractor (Task Controller, TC server) in the standardized ISO-XML data format with proprietary means, 3) the machine is operated in the field with this pre-made prescription, 4) the document is exported from the Task Controller back to the transferrable media using ISO-XML, 5) the data is automatically removed from the Task Controller memory (standard requirement) and 6) data is imported to the FMIS. This procedure is mainstream of precision farming, or site-specific farming, since the 1990s [4].

In the most recent standard version, which is not yet available in any AEF certified products (only in the future in TC Generation 2), the concept "peer control" was introduced. This was created for emerging systems in the early 2000s, which were based on machine-mounted plant sensors that directly command application rates (e.g. fertilizer) without the need for any map. However, this concept, on the other hand, does not address any FMIS-related data, but is solely based on the sensor [5].

A highly automated Green Windows concept would require a different a) memory concept and b) algorithmic concept to be integrated. Currently, the data lifetime in the memory of the Task Controller is limited to one task and one data transfer: after exporting the data, it no longer exists onboard the vehicle. This is also a logical constraint, as next time the fertilization or spraying can be done with another machine combination (different tractor, different sprayer, or both), and it is better to keep data centralized in the FMIS. However, as this Green Windows concept requires first scanning the field (Green Windows area) and then running the algorithm and making the map, this does not fit directly into the intended workflow of the 2003 standard. The other limitation is the missing possibility to hand over any mathematical formula from the FMIS to the Task Controller, to be performed or evaluated in the embedded system by any means. The Green Windows concept requires that this algorithm must be computed while the machine is in the field, and also rapidly, so that the work is not paused for more than a few dozen seconds.

1.4 Plant Sensors

One technique to decide where to put more or less fertilizer is using vegetation indices to identify areas of higher or lower potential yield on the field. These indices typically use optical sensors to estimate the health and growth state of plants [6, 7]. The NDVI, for example, is commonly computed from multispectral camera images mounted on satellites or drones [8, 9]. For drones, many independent images are typically taken with a GPS position and then later stitched together using, e.g., Open Drone Map [10]. There also exist sensors that can be mounted to ground vehicles to accurately map plant growth in the field independent of the weather [11]. They also tend to have slightly better accuracy than proximal sensing, like satellites [12].

Using vegetation sensors on ground vehicles to optimize nitrogen use efficiency (NUE) has been discussed for some

 ISBN:978-3-911430-08-1

time. [13] already presented a strategy using the REIP index, based on ideas from [5].

1.5 Required Fertilizer Spreading Technology

Tractor based fertilization systems have evolved over decades. The popular type for distributing granular fertilizer is based on rotating discs with vanes, where granules are dosed on the disc, and the disc creates the velocity for granules to escape, which results in randomly distributed trajectories to spread them around the spreader. Typical working widths of these machines are nowadays in Europe between 15 to 36 m, depending on the granular fertilizer type used. The distribution pattern of these machines is trapezoidal and needs to be overlapped with the other parallel swath to form a uniform result. Realistically, the smallest controllable area with this technology is around 50mx30m at a 28m working width according to Stöcklin and Zimmer [14]. Therefore, this machine type is not feasible for the Green Windows concept.

The other type of fertilizer spreader is based on a mechanical boom, and granules are transported pneumatically from the dosing unit via hoses to nozzles mounted on the boom. Typical working width of each nozzle is 0.5-2 meters, depending on the design. Traditional boom spreaders have had a single centralized dosing unit and one fan producing airflow for pneumatic transportation. However, with modern mechatronics, it is possible to introduce several dosing units, even one per nozzle. For instance, RAUCH Landmaschinenfabrik GmbH has developed such fertilizer spreaders, with the product name AERO, both trailed and fully mounted. With this kind of machine, it is possible to create Green Windows automatically, as the smallest imaginable Green Windows would be equivalent to 1 nozzle width (e.g. 0.5-2 m) and in driving direction speed dependent. However, to create a large enough consistent area due to overlap requires a set of more than one nozzle to be adjusted.

Similar to the boom-type fertilizer spreaders, field sprayers can also be used for nutrient delivery to the field. Thus, any boom sprayer with section control can also create Green Windows if the liquids are desirable.

In addition, Green Windows can also be established while seeding, using a combined seed drill or planter, with at least one additional tank for fertilizer (either granular or liquid). With seed drills and planters, the advantage is very precise lateral accuracy, as the granules are placed and guided into the ground instead of aerial projectiles randomly distributed. Longitudinal accuracy is speed dependent.

Thus, Green Windows requires either: a) boom spreader (e.g. RAUCH AERO), b) boom sprayer or c) combined seed drill (seed+fertilizer).

1.6 FMIS State of Technology

FMIS systems allow users to plan farm work, typically on a PC or tablet. The planned work can then be exported as ISO 11783 TASKDATA format for interoperability with ISOBUS-certified TCs, regardless of brand. ISO 11783-10 defines the process of exporting and importing using USB, however proprietary methods of sharing TASKDATA between the FMIS and TC over mobile networks are also common.

For site-specific applications and prescription maps, ISO 11783-10 specifies that the geometry is represented using either gridcells or polygons; both are used to link spatial locations to TreatmentZones and/or their associated setpoint values.

In ISO 11783-10, a gridcell is a rectangular, fixed-size area formed by overlaying a grid on a partfield, with cell positions defined relative to the grid origin. A polygon is defined as an area with one exterior boundary and zero or more interior boundaries ("holes"). Polygons may be used (singly or in groups) to define TreatmentZones, especially when zones are irregularly shaped. Polygons are encoded via the XML elements Polygon (PLN), LineString (LSG), and Point (PNT).

In site-specific control, the TC determines the current position, then determines in which gridcell or polygon it is in from the prescription map. Then the TC uses either the zone code (Type 1) or direct values (Type 2) to send updated setpoints to the implement.

Gridcell representations are typically advantageous for prescription maps covering large areas because they support dense, cell-by-cell variation over the field. However, the fixed resolution makes grids inefficient for small subplots or narrow features: to delineate a small plot precisely, the cell size must be reduced globally, which increases the number of cells and introduces "blocky" boundaries that cannot match irregular edges. In contrast, polygon geometries in ISO 11783-10 directly encode precise boundaries and are therefore well suited to defining small, irregular management plots with high geometric fidelity. Yet polygons become less practical for representing continuously varying rates across a large field, because achieving fine-grained variation would require a large number of polygons, increasing computational burden compared with a regular grid representation.

One potential solution would be to encode the GWs as polygons and the remainder of the field as gridcells. This would allow for the precise placement of the GWs while still allowing continuously varying rates in the rest of the field. However, mixed use of gridcells and polygons is not supported by the majority of TCs on the market today.

2. MORPHOLOGICAL ANALYSIS

2.1 Motivation

To introduce automation with ISOBUS to the Green Window (GW) approach, a series of options for individual aspects and components have been evaluated. The morphological analysis covers seven central aspects with their pros and cons as a basis for developing concepts.

2.2 Entry of N-min values

The current N-min value of the soil required for the GW algorithm is measured and must be entered into the system. It can be entered manually via the VT or sent wirelessly, e.g., via Bluetooth. This requires the entered data to be sent via the ISOBUS to be then used by the device responsible for logging (generally the TC) and to the device responsible for calculations. When the data is measured by a mounted sensor, it is also sent over ISOBUS. For all these options that send the N-min data on the ISOBUS, it is necessary to

 ISBN:978-3-911430-08-1

Table 1. Pros and cons of providing the N-min values to the system

	Pro	Con
manual to VT	- low implementation effort - high compatibility	poor user experience
wireless	convenient	requires wireless support
mounted	highest convenience	- reachability of crops - sensor availability
to FMIS	high convenience	

define a DDI for the N-min value. The measurements can also be entered directly into the FMIS.

Entering via the VT requires little implementation effort and provides high compatibility. However, entering via the VT offers a poor user experience, especially for a lot of data values, as this requires high effort. The data could be logged using standard TC logging by sending a to-be-defined N-min DDI at the time of measurement. The position of the sample is also logged by the TC. Therefore, the logged position and measured values can be matched via the timestamps. As the data is logged via ISOXML, the data can be transferred to other systems, such as an FMIS. Other on-board systems can also listen to the DDIs and acquire the data. Wireless transfer, for example, from a handheld device (smartphone, sensor) is highly convenient for the user, especially when considering many data values. However, wireless capability must be supported by the receiving end. A tractor-mounted sensor offers the highest convenience for the user, as one must only drive over the relevant spots. The measuring and logging are managed automatically. This, however, requires the ability to drive over the spots, which might not be possible for all crops at all stages of growth. Furthermore, only a few sensors for mounting are available. Similarly to entering the data into the VT by hand, it is also possible to enter the data by hand into the FMIS. This also offers higher convenience due to better user input capabilities. table 1 summarizes the pros and cons of each option.

2.3 GW Algorithm Calculation

The GW algorithm can be executed by different participants. These are the TC, a sensor measuring the central GW parameter (e.g. NDVI), or the FMIS.

Running the GW algorithm on the TC requires standardization, but the data transfer to the ISOBUS is straightforward. Using a sensor that acts as a WSM to handle the entire GW approach requires little to no data transfer to the ISOBUS, as the measurements are already available internally. The limited computational resources of the TC or a WSM must be considered, depending on the algorithm's requirements and potential real-time constraints. When using the FMIS to calculate the GW algorithm, generally, more computational resources are available, allowing for more complex models. Additionally, it is easier to implement. Data transfer to and from the responsible participant requires consideration. table 2 summarizes the pros and cons of each option.

2.4 Data Format of GW Position

The location of the GWs on the field must be stored in a data format. Similar to the existing options for storing application

Table 2. Pros and cons of which participant executes the GW algorithm

	Pro	Con
TC	easy data transfer to ISOBUS	- standardization - limited computational resources
sensor/WSM	little/no data transfer	limited computational resources
FMIS	- more computational resources - easier implementation	

Table 3. Pros and cons of the GW locations data format

	Pro	Con
polygon	- little data storage - high accuracy	few supporting terminals
grid	supported by all terminals	- higher data size - discretization
parameters	- low data size - high accuracy	standardized algorithm

maps, the GWs can be stored using polygons or as a grid. GWs can not only be placed manually on the map, but also generated using an algorithm. By storing the parameters for that algorithm, the GWs are fully specified.

Storing the location as a polygon requires very little data storage and provides very high accuracy. However, most terminals do not support polygons. Storing the GWs as a grid causes a higher data size, and the defined GWs might not perfectly align to the desired position and tramlines due to the discretization. However, grids are supported by all terminals. When storing the parameters for the algorithm that places the GWs, again, a small data size can be achieved while ensuring high accuracy. However, this requires sharing the algorithm. It must be mentioned that the accuracy of this option can only be preserved when the GW locations defined by the parameters are not internally converted to a grid. table 3 summarizes the pros and cons of each option.

2.5 User Definition of GW Location

To define the location of the GWs, the user either places the GWs manually on a map or defines their location parametrically relative to the tramline. One option is to do that via the VT provided by the TC or the responsible WSM, such as a sensor. It is also possible to define the location via an app or in the FMIS.

Entering via the VT is possible when already at the field and offers high compatibility. However, this offers a bad user experience due to poor user input options. When not using the in-cab VT terminal, another device is needed. The poor user experience can be partially mitigated by generating the GWs automatically. That way, the user is only required to enter the parameters. This, however, does not address the situation when the user desires to manually adjust the generated proposed GW positions. When the VT is provided by the TC, its behavior must be standardized. An app is more convenient for the user than the VT. However, this requires the TC or WSM to provide an interface (e.g. wireless) to the mobile device. Entering the locations in the FMIS is very convenient, as the user input is usually better, and

ISBN:978-3-911430-08-1

Table 4. Pros and cons of user input for defining the GW locations

	Pro	Con
VT	- high compatibility - definition at field	suboptimal user experience
App	high convenience	requires wireless support
FMIS	- tramline definition - high convenience	requires planning in advance

Table 5. Pros and cons of the option where the GW locations are stored

	Pro	Con
TC & WSM	- readily available - ease of use	- TC: standardization - same machine for all operations
USB stick (ISOXML)	- flexibility - data accessable	adjustment to ISOXML standard
FMIS	- easy implementation - most available storage - backup - flexibility	

the tramlines are already defined there. The location can be defined by entering parameters or manually. Similarly, manual adjustments are easily possible. However, generally, the FMIS is accessed at the farm, and thus, the planning must be done in advance, contrary to the other options. table 4 summarizes the pros and cons of each option.

2.6 Memory of GW Location

Once defined, the GW local data must be stored in memory. It can either be stored in the internal memory of the TC or the internal memory of a WSM (e.g.sensor). When writing the GW location to the ISOXML file, it can be stored on a standard USB stick. It is also possible to store the GW locations in the FMIS.

When opting for the internal memory of the TC or the WSM/sensor, the data is always readily available and, therefore, provides ease of use for the operator. However, storing the data in the TC requires standardization. Additionally, it requires that all GW applications on that field must be performed using the same tractor as the data is bound to that tractor. Similarly, when storing the data in the WSM/sensor, the same sensor must be used. In practice, this requires using the same implement/tractor, depending on where the sensor is mounted. Storing the data in the ISOXML file on the USB stick might require adjustments to the ISOXML standard. However, this option provides flexibility as machines can be switched, and the data is easily accessible. Storing the data in the FMIS allows for easy implementation. It also provides the most available storage and allows easy backup. This option provides flexibility as an FMIS is independent of the used machines and, therefore, machines can be switched. However, without standardization, it is hard to transfer data from one system to another. table 5 summarizes the pros and cons of each option.

2.7 User Location for Triggering the Algorithm

The user can execute the GW algorithm at different locations. It can be triggered while standing at the field or at the farm.

Table 6. Pros and cons of the user location for starting the GW algorithm

	Pro	Con
at farm	preparation	
at field	time saving	unknown fertilizer amount may cause extra trips

This is relevant, as the fertilizer is already loaded when calculating the amount at the field. In case the calculation shows that more fertilizer is needed, another trip to the farm is necessary.

Calculating at the farm allows for easier preparation. However, when everything else is calculated at the field, the algorithm may also already be started when the user enters the last input at the field. Table 6 summarizes the pros and cons of each option.

2.8 Sensor System

Lastly, there are different options for the sensor concept for measuring the data for the GW algorithm, such as the NDVI. The sensor can be handheld or mounted to the tractor or the implement. External sensors are also possible, such as a drone carrying a sensor or using satellite data.

Using a handheld sensor provides the highest accuracy of the measurement as the operator can position the sensor perfectly to the crop. On the other hand, it is the most laborious and, therefore, unrealistic if more data should be collected, especially of the entire field. Sharing the sensor among farmers is possible. Using a mounted sensor also provides high resolution with low effort. Additionally, the sensor data can be collected of the entire field and can even be used for live operations every time driving over the field. However, this option poses high costs as the sensor is fixed to the tractor or implement. When opting for a drone, it is possible to more easily share the sensor among farmers or offer scanning as a service. This reduces the initial investment. Individual long-term calculations are necessary, and the additional cost of the drone must be accounted for. Local regulations for drone usage and pilot licensing must be considered. Using a drone requires the data to be collected in advance. However, it allows data collection of the entire field with a high resolution. Satellite data is readily available for direct use, for example, with the FMIS. Here, data of the entire field is available. It requires no hardware to be purchased and, consequently, also no maintenance. However, the resolution of the data available for free is limited. Higher resolution data can be purchased. Table 7 summarizes the pros and cons of each option.

2.9 Overview of All Aspects and Considered Options

Table 8 provides an overview of all considered aspects.

Some options benefit each other and can mitigate the downsides of one another. Depending on the combination, the necessity and format of data transfer differ. This is considered when combining options to concepts in the next chapter.

 ISBN:978-3-911430-08-1

Table 7. Pros and cons of the different sensor systems for the GW parameter (e.g. NDVI)

	Pro	Con
hand held	- highest accuracy - sensor sharing	most laborous ->few measurements
mounted	- high resolution - low effort - entire field - data for live operation	highest cost
drone	- easy sharing - entire field - high resolution	- additional cost of drone - local drone regulations - pilot licensing - data collection in advance
satellite	- readily available - entire field - no hardware & maintenance	- limited resolution of free data - higher resolution data can be purchased

Table 8. Morphological chart with aspects and options for realizing GWs

		Option A	Option B	Option C	Option D
N-min to system		manual/wireless	mounted sensor	to FMIS	
algorithm calculation		TC	WSM	FMIS	
GW location	data format	polygons	grid	GW parameters	
	user definition	via VT	via app	to FMIS	
	memory	TC	WSM	FMIS	USB stick
user location		at the field	at the farm		
sensor concept		handheld	mounted	external	

Table 9. Applicable selection of the considered options for Concept 1

		Option A	Option B	Option C	Option D
N-min to system		manual/wireless	mounted sensor	to FMIS	
algorithm calculation		TC	WSM	FMIS	
GW location	data format	polygons	grid	GW parameters	
	user definition	via VT	via app	to FMIS	
	memory	TC	WSM	FMIS	USB stick
user location		at the field	at the farm		
sensor concept		handheld	mounted	external	

3. CONCEPTS

3.1 Combination of Options to Concepts

Using the considered options described, five distinct concepts for the way of implementation and operation are derived. This section will describe the emerging concepts by defining the required interfaces and tasks for each level of operation, such as the Farm Management Information System (FMIS), the Task Controller (TC), sensors, and the operator.

3.2 Concept 1 – Plan in FMIS

Concept 1 is a mixed solution with the planning of the GW handled by the FMIS, whereas the execution is done by the TC.

Looking at the morphological chart for Concept 1 (table 9), certain options are preferable for this concept. Whereas all the options for the input of the N-min into the system and the data format of the GW location are suitable. The user definition and memory of the GW are to be done in the FMIS. The algorithm calculation of the GW is to be executed in the TC. For the sensor concept, a mounted sensor seems best suited. However, a handheld sensor is also applicable but incurs extra effort. The specified way of implementation is to be done as depicted in fig. 2.

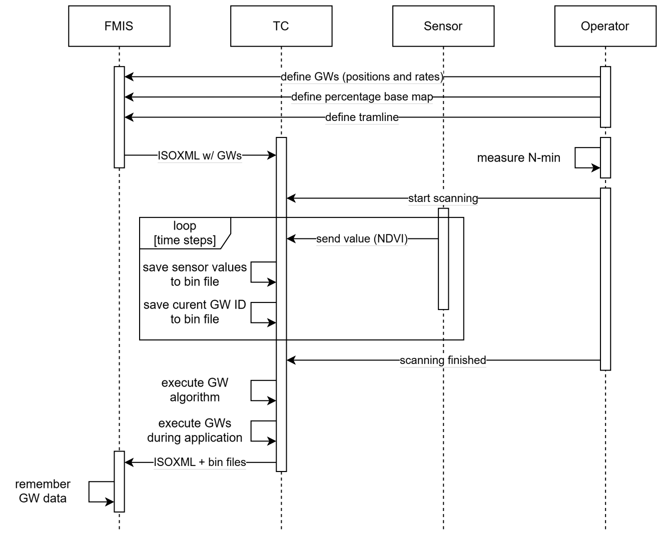

Fig. 2. Workflow and interfaces of the green window implementation for Concept 1

Table 10. Applicable selection of the considered options for Concept 2

		Option A	Option B	Option C	Option D
N-min to system		manual/wireless	mounted sensor	to FMIS	
algorithm calculation		TC	WSM	FMIS	
GW location	data format	polygons	grid	GW parameters	
	user definition	via VT	via app	to FMIS	
	memory	TC	WSM	FMIS	USB stick
user location		at the field	at the farm		
sensor concept		handheld	mounted	external	

To start off, the operator measures the n-min values on the field and decides where to place the GWs on the field. Subsequently, the operator defines the position and rates of each GW on a percentage-based map in the FMIS. The resulting application map, including the GWs, is exported via ISOXML and transferred to the TC. In the next step, fertilizer is applied as described in the map. Continuing briefly before the second fertilizer application, the NDVI values of each GW are first measured. Using the new NDVI values, the TC calculates the optimal application rates using the GW algorithm and uses these values for the next application. This process is to be repeated for each subsequent fertilizer application. For the last step a ISOXML, compromised of the application map, GW location/ID and corresponding NDVI values, is exported to the FMIS which should store this data.

3.3 Concept 2 – Plan in TC

This concept intends most of the tasks to be handled by the TC.

Focusing on the morphological chart for this concept (table 10), both the n-min to system and the data format of the GW location are declared as all options are suitable. Regarding the n-min values the input into the FMIS is slightly less suitable as most of the data is centralized on the TC. The user definition, memory and algorithm calculation of the GW are all to be done in the TC. Once more, a handheld sensor evaluation of the GW is possible however a mounted one is effortless.

Taking a look at fig. 3 the process starts anew with n-min measurements being taken and imported into the FMIS, a basic application map is created in the FMIS. The application

ISBN:978-3-911430-08-1

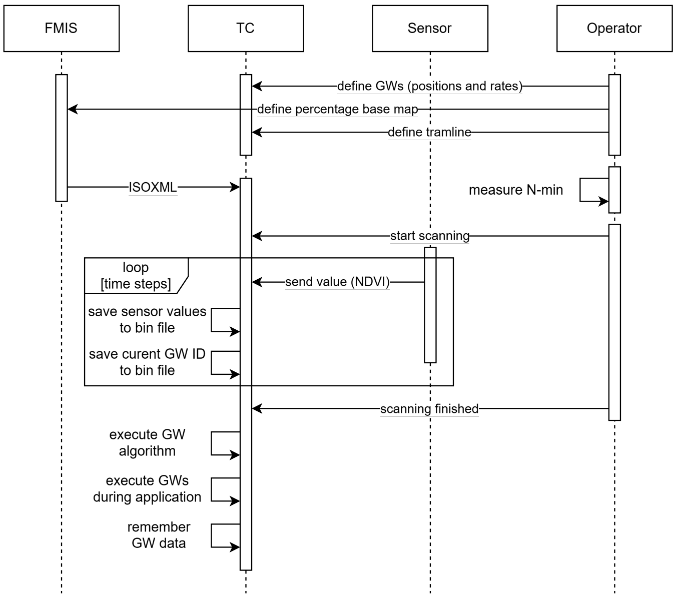

Fig. 3. Workflow and interfaces of the green window implementation for Concept 2

Table 11. Applicable selection of the considered options for Concept 3

		Option A	Option B	Option C	Option D
N-min to system		manual/wireless	mounted sensor	to FMIS	
algorithm calculation		TC	WSM	FMIS	
GW location	data format	polygons	grid	GW parameters	
	user definition	via VT	via app	to FMIS	
	memory	TC	WSM	FMIS	USB stick
user location		at the field	at the farm		
sensor concept		handheld	mounted	external	

map is again exported to the TC. The TC then generates a set number of GWs on a selected tramline and stores their location and the proposed application rates. The first fertilizer application can proceed. Before the second fertilizer application the NDVI values are measured, and the GW algorithm, executed by the TC, adjusts the application rate. This process is repeated for the succeeding applications. For this concept, the memory of the GWs stays inside the TC.

3.4 Concept 3 – Calculations in generic FMIS

As the majority of tasks are executed within the FMIS, an evaluation of the options considered for Concept 3 (table 11) shows that all input parameters must be available within the system. Additionally, for the NDVI measurement, this concept is best used combined with satellite or drone data.

Concept 3 intends most of the GW tasks to be done inside the FMIS. It once again requires the initial setup of the n-min and the application map. Furthermore, the GW parameters are added into the FMIS and the prescription map is exported to the TC. The first application is done as defined in the prescription map. The sensor values and the GW-Parameters are exported as ISOXML and bin-files into the FMIS. Using these values, the FMIS applies the GW algorithm and adjusts the prescription map, which will be used for the next fertilizer application. While proprietary DDIs can be used to implement this concept without any standardization, for better operability, the GW ID/location should be standardized.

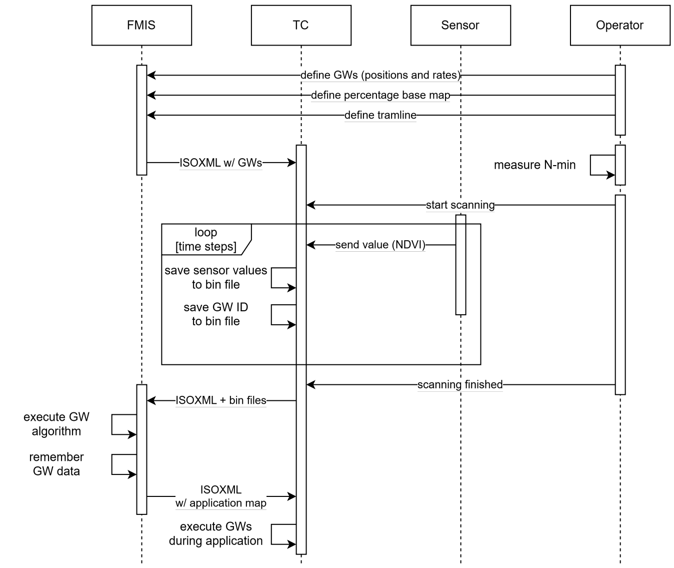

Fig. 4. Workflow and interfaces of the green window implementation for Concept 3

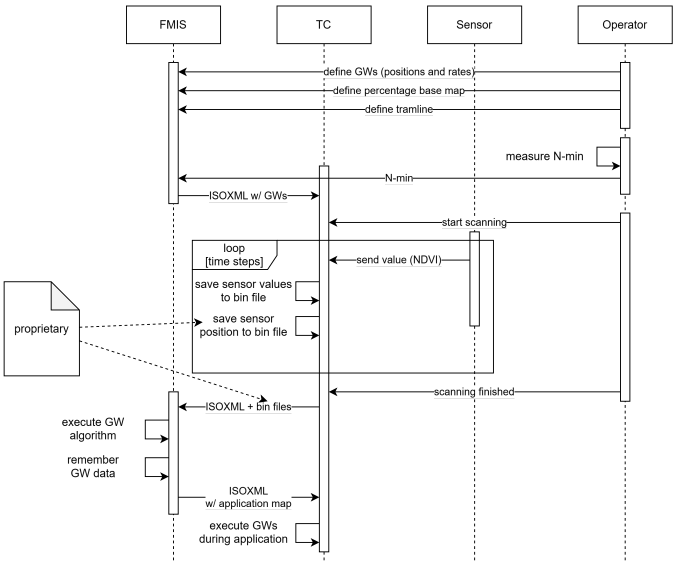

Fig. 5. Workflow and interfaces of the green window implementation for Concept 4

3.5 Concept 4 - Calculations in generic FMIS with proprietary data formats

Concept 4, a variation of concept 3, is derived, with the main difference being the usage of proprietary communication, which does not use existing standardized elements. Specifically, the data format in which the GW data is stored should be proprietary, with both the TC and FMIS being required to implement these. This should enable fast and seamless data transfer between the FMIS and TC. The difference can further be highlighted by looking at fig. 4 and fig. 5.

3.6 Concept 5 – Sensor Based

Concept 5 describes a sensor-based solution that requires very few changes to the TC.

Using this concept, it is required to input the n-min values in the VT as the sensor needs these values for the GW al-

 ISBN:978-3-911430-08-1

Table 12. Applicable selection of the considered options for Concept 5

		Option A	Option B	Option C	Option D
N-min to system		manual/wireless	mounted sensor	to FMIS	
algorithm calculation		TC	WSM	FMIS	
GW location	data format	polygons	grid	GW parameters	
	user definition	via VT	via app	to FMIS	
	memory	TC	WSM	FMIS	USB stick
user location		at the field	at the farm		
sensor concept		handheld	mounted	external	

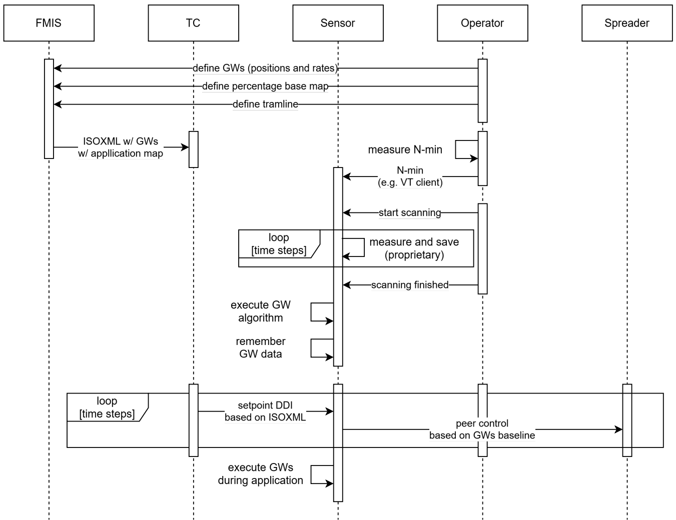

Fig. 6. Workflow and interfaces of the green window implementation for Concept 5

gorithm. This concept is specifically designed for continuous on-field measurement. Therefore, only a mounted sensor is suitable.

After the initial setup of measuring the n-min and creating the application map, the GWs are defined in the FMIS, and the prescription map is exported to the TC using ISOXML. In the next step, the n-min values are provided to the sensor, and further, the scanning and application of the GW can be started. In this case, the calculation of the GW algorithm is done by the sensor itself. As depicted in fig. 6, a setpoint DDI based on ISOXML is to be used and the fertilizer spreader will be manipulated using peer control and the GWs are applied. The GW parameters should also be stored in the sensor's memory.

3.7 Overview of the Concepts

With all the concepts described, certain differences and advantages are highlighted in table 13.

Concept 1 generally provides a high level of control in planning, as the location of the GW can be placed effortlessly and precisely. Furthermore, it only requires an initial setup and the memorization of the used GW parameters, and requires a low amount of standardization efforts. As the calculations for the GW are done by the TC, the exact amount of necessary fertilizer is only available on the field.

Concept 2 features centralized handling of the GW in the TC, which, for the most part, requires changes there. This concept uses an automated location-based generation of the GWs based on the tramline selection and GW parameters. This concept also requires little standardization and only the initial setup of the GWs without any data export. Just as Concept 1, the information on the amount of necessary fertilizer is only available on the field.

Concept 3 provides the highest level of control regarding the GW generation and algorithm. As this concept provides early information on the application adjustments done by the GW algorithm, further modifications can be applied. This concept also requires a low amount of standardization. However, it requires repeated import of the sensor values into the FMIS.

Concept 4, the subversion of concept 3 using proprietary communication, has similar attributes. It does require a high amount of cooperation in the TC and FMIS, yet it provides additional comfort for the data transfer between the TC and FMIS.

Concept 5 inherits the highest level of optimization due to on-field feedback of the NDVI values. This could enable real-time adjustments. It also provides the highest level of comfort for the user, as only an initial definition of the GWs is needed, as the GW data stays inside the sensor. Nevertheless, this concept entails a great amount of standardization as a new DDI will be required. Additionally, peer control for the spreader is to be implemented. Furthermore, this provides the least control over the fertilizer application.

4. EVALUATION AND DISCUSSION

The five proposed concepts illustrate different approaches to integrating highly automated Green Windows into an ISOBUS-based workflow. Their suitability depends on several interacting technical and operational factors rather than on any overall superiority of one approach.

A key consideration is where computation and data management occur. Concepts centered on the Task Controller (TC) enable close coupling with in-field operations but depend on the TC's computational capabilities and available standardization. FMIS-centric concepts offer greater processing power and planning comfort but require reliable data transfer between field and office. Sensor-based approaches reduce TC involvement but introduce demands on sensor hardware, integration, and cost.

The definition and storage of Green Window locations also influence usability and flexibility. FMIS-based placement allows detailed control, while TC-generated locations support faster in-field operation. Storage on the TC, FMIS, or portable media affects how easily machinery or operators can be switched during the season.

Differences in data formats and communication pathways — from standardized ISOXML to proprietary exchanges — impact interoperability, scalability, and implementation effort. Standardized paths offer compatibility with existing systems, while proprietary ones can streamline performance at the cost of openness.

Sensor choice further shapes system behavior. Handheld devices provide accuracy but require labor; mounted sensors enable automation with higher investment; drone or satellite sources offer wide coverage but depend on acquisition timing, regulations, and resolution constraints.

Operational preferences also matter. Some concepts provide fertilizer recommendations only once in the field, while others

ISBN:978-3-911430-08-1

Table 13. Consequential evaluation of GW concepts

Consequences for	Concept 1 *Plan in FMIS*	Concept 2 *Plan in TC*	Concept 3 *FMIS Calculation*	Concept 4 *Proprietary data FMIS calculation*	Concept 5 *Sensor Based*
ISO standardization	Extended ISO-XML needed to transfer GW information	No need to modify ISO-XML	Additional DDIs needed	Proprietary extensions for ISO-XML already possible	Additional DDIs needed (as in 3), unless full positioning logic is transferred to sensor
FMIS manufacturers	GW Planning tools must be added to FMIS, ease of use could be selling point	No changes necessary	Must implement planning and analysis tools	Requires TC and FMIS special partnership, implement planning and analysis tools	Planning tools and link to sensor needed (Sensor company could offer their own FMIS)
TC manufacturers	Must implement GW analyis	Must implement GW planning and analyis	No changes necessary	Requires TC and FMIS special partnership	No changes necessary
Sensor manufacturer	1-way data exchange	1-way data exchange	1-way data exchange	1-way data exchange	2-way data exchange, link to FMIS, link to machine, implement GW analysis
Data exchange link	Internet only needed in planning	Internet connectivity not needed	Internet needed between scanning and application	Internet needed between scanning and application	Internet only needed in planning
Farmers	Risk for interoperability failures	Must use the same TC (tractor) for all operations in the season	Risk for interoperability failures	Must use the given FMIS + TC	Failure on sensor cannot be substituted with another component
Contractors	Farmer and contractor are interoperable over ISOBUS interface	Same contractor is needed for all operations over season	Farmer and contractor are interoperable over ISOBUS interface	Contractor must use the same FMIS + TC combination	Contractor must use the same sensor system

enable earlier planning at the farm. Farms differ in their balance between real-time flexibility and upfront preparation.

Finally, the required level of new standardization varies. Some concepts rely heavily on existing ISOBUS functionality, while others would benefit from new DDIs, additional memory handling, or enhanced peer-control features.

In summary, each concept presents a different balance of interoperability, automation, user workload, data flow, sensing strategy, and standardization needs. The most suitable implementation depends on the specific technological environment, workflow preferences, and long-term integration goals of the farm or manufacturers.

ACKNOWLEDGEMENTS

The project "EcoSchemeN" is supported by funds of the Federal Ministry of Agriculture, Food and Regional Identity (BMLEH) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the strategy for digitalisation in agriculture.

REFERENCES

[1] X. L. YUE, Y. HU, H. Z. ZHANG, and U. SCHMIDHALTER, “Green window approach for improving nitrogen management by farmers in small-scale wheat fields,” *The Journal of Agricultural Science*, vol. 153, no. 3, pp. 446–454, 2015, pII: S0021859614000203.

[2] P. Heinemann and U. Schmidhalter, “Simplifying residual nitrogen (nmin) sampling strategies and crop response,” *European Journal of Agronomy*, vol. 130, p. 126369, 2021, pII: S1161030121001404.

[3] L. Pindl, A. Berchtold, M. Moll, M. Maier, U. Schmidhalter, and T. Oksanen, “A dataset for nitrate test-strip analysis via smartphone camera for agricultural soil testing,” Professorship of Agrimechatronics, Tech. Rep., 2025.

[4] H. Auernhammer, “Precision farming for the site-specific fertilization,” *Zeitschrift für Agrarinformatik*, vol. 7, no. 3, pp. 58–67, 1999.

[5] H. Auernhammer, M. Demmel, F. X. Maidl, U. Schmidhalter, T. Schneider, and P. Wagner, “An on-farm communication system for precision farming with nitrogen real-time application,” in *1999 ASAE/CSAE-SCGR Annual International Meeting*, ASAE/CSAE-SCGR. ASAE, 1999, jul.

[6] J. W. Rouse, R. H. Haas, J. A. Schell, and D. W. Deering, “Monitoring vegetation systems in the great plains with erts,” in *Proceedings, 3rd Earth Resources Technology Satellite (ERTS) Symposium*, vol. 1. NASA SP-351, 1974, pp. 48–62.

[7] E. M. Barnes, T. R. Clarke, S. E. Richards, P. D. Colaizzi, J. Haberland, M. Kostrzewski, R. J. Lascano *et al.*, “Coincident detection of crop water stress, nitrogen status and canopy density using ground-based multispectral data,” in *Proceedings of the 5th International Conference on Precision Agriculture*, 2000.

[8] CDSE. (2015) Sentinel-2 documentation. CDSE. [Online]. Available: https://documentation.dataspace.copernicus.eu/Data/SentinelMissions/Sentinel2.html

[9] K. Yu, A. Belwalkar, W. Wang, Y. Hu, A. Hunegnaw, A. Nurunnabi, T. Ruf, F. Li, L. Jia, L. Kooistra, Y. Miao, and F. N. Teferle, "Uav hyperspectral remote sensing for crop nitrogen monitoring: progress, challenges, and perspectives," *Smart Agricultural Technology*, vol. 12, p. 101507, 2025, pII: S2772375525007385.

[10] OpenDroneMap Authors, "Odm," 2020. [Online]. Available: https://github.com/OpenDroneMap/ODM

[11] S. Reusch, "Entwicklung eines reflexionsoptischen sensors zur erfassung der stickstoffversorgung landwirtschaftlicher kulturpflanzen /," Ph.D. dissertation, Universität Kiel, 01 1997.

[12] J. Mezera, V. Lukas, I. Horniaček, V. Smutný, and J. Elbl, "Comparison of proximal and remote sensing for the diagnosis of crop status in site-specific crop management," *Sensors (Basel, Switzerland)*, vol. 22, no. 1, 2021.

[13] R. Ostermeier, H.-I. Rogge, and H. Auernhammer, "Multisensor data fusion implementation for a sensor based fertilizer application system," in *Automation Technology for Off-Road Equipment*, M. Rothmund, M. Ehrl, and H. Auernhammer, Eds., Automation Technology for Off-Road Equipment (ATOE). Eigenverlag, 2006, pp. 215–225, sep.

[14] V. Stöcklin and M. Zimmer, *Development of future machine concepts for the needsbased fertilisation of individual plants – The RAUCH MultiRate dosing system for pneumatic spreaders AERO GT and AERO X*. VDI Wissensforum GmbH, 01 2019, pp. 447–454.

ISBN:978-3-911430-08-1