**Coverage planning for capacitated field operations, Part I: Task decomposition**

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Research Paper

# Coverage planning for capacitated field operations, Part I: Task decomposition


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In certain field operations, such as fertilising, capacity restrictions lead to significant non-productive in-field travelling and out-of-field transport, thereby reducing field efficiency and increasing operating costs. This indicates a potential benefit from improving the efficiency of capacitated operations by minimising the non-productive travelled elements. A prerequisite for the optimisation of a field operation is the identification of the activities which contribute to the reduction of the efficiency and the definition of the actions that take place during the operation. The objective of this paper was to identify the sources of non-productivity in capacitated field operations and decompose the operation to feasible driving actions. Based on the monitoring of operations and subsequent data analysis, the recorded driven paths were decomposed into four types of non-productive activities. The involved driving actions during the fertilising operation were then defined, and finally, the potential of minimising the contribution of each non-productive activity to the operation efficiency by the selection of appropriate driving actions, was quantified. This assessment revealed that the selection of a subsequent action, might on one hand decrease the contribution of a specific non-productive activity to the total non-working travelled distance, but on the other hand might increase this contribution of another activity. There is therefore a trade-off between the positive contribution to the overall efficiency between one activity and the negative contribution from another. This indicates that a targeted algorithmic optimisation method should be devised by searching for the optimal combination among the prescribed driving actions.



**Keywords:** Agricultural field operations; Fertilising; Time-motion studies; Machinery performance; Area coverage planning


**Nomenclature**

*a*

field area, $m^2$

*b*

weight proportion of effective fertiliser in the transported liquid

*c*

machine tank capacity in volume, $m^3$

*C*

machine tank capacity in working distance, m

$d$

dosage of effective fertiliser, kg $m^{-2}$

$D_{HT}$

length of headland turn, m

$D_{UT}$

length of U-turn, m

$L$

working distance corresponding to the amount of material remaining in the machine tank, m

$R_{min}$

minimum number of refills of tanker payloads required to work the field

$r_{min}$

fractional number of tanker payloads necessary to work the field

$RN$

length of the shortest out-of-field path in road network between the field exit and the depot location, m

$SP$

length of the shortest in-field path from current location to the field exit point, m

$T$

track length, m

$UW$

length of unworked part of track, m

$W$

length of worked part of track, m

$W_{min}$

proportion of a payload that can be returned to depot without increasing the number of refills

$\rho$

density of transported liquid, kg $m^{-3}$

***Abbreviations***

GPS

global positioning system

DGPS

differential global positioning system

***Acronym of actions***

R

refill

PR

pre-emptive refill

HT

headland turn

MF

work unworked track completely

MP

work unworked track partially

MS

work two unworked tracks partially

WSF

work split fully

WSP

work split partially

WPP-1, WPP-2

work partial worked track partially

WPF-idle, WPF-idle-Uturn

work partial worked track fully

WPF-work-1, WPF-work-2

work partial worked track fully

WPF-work-Uturn

work partial worked track fully using a U-turn

# 1 Introduction

In field operations, field efficiency is the ratio of the time the machine is operating effectively to the total time the machine is committed to the operation. In general, for agricultural operations it is reported to be in the range from 60% to 90% (ASAE D497.7, 2011). However, in certain operations, such as fertilising, where capacity restrictions are involved which lead to non-productive in-field travelling and out-of-field transport, field efficiency is considerably lower inducing considerable operating costs (Huijsmans, Verwij, Rodhe, & Smith, 2001; Sørensen, 2003). This indicates a high potential benefit from improving the efficiency of capacitated operations by minimising the non-working distance travelled elements.

The determined factor for improving the efficiency of a field operation (for a given machinery system and field features) is the area coverage plan. Many coverage planning methods have been presented in the scientific literature varying according to the type of the operation, the cost that has to be minimised, the set of feasible driving actions, and the degree of optimality (Ali, Verlinden, & Van Oudheusden, 2009; Bochtis, Sørensen, & Green, 2012; Bochtis & Sørensen, 2009; Oksanen & Visala, 2009; Spekken & de Bruin, 2013). However, the case of capacitated operations has not been examined in depth, a fact primarily caused by the complexity of the sequential decision making pertaining to the in-field driving actions inherent in such operations. In the case of fertilising, for example, when the tanker becomes empty and the action of returning to the refilling location, or depot, has to be initiated, the applicator can continue in the same direction on the same track or in an adjacent track, or it can perform a U-turn (180-degree turn) and take the opposite direction. The same situation stands in the case when the applicator resumes the application after refilling. Furthermore, the track sequencing within a tour where a tanker load is applied is a complex decision making process given that the applicator can drive back to the depot prior to the complete tanker load has been applied. The selection and sequence of these actions highly affects the operations efficiency and finding the optimal action is a complex algorithmic process.

A key prerequisite for the optimisation of an operation is the identification of the different activities which contribute to the reduction of the efficiency and the definition of the different actions that take place during the operation. This task decomposition can be derived from the operations monitoring and analysis of the generated data. The method of monitoring field operations with ~~global positioning system (~~GPS~~)~~ and auxiliary sensors to measure efficiency has successfully been applied in many studies. Grisso, Jasa, and Rolofson (2002) used GPS recordings to measure the distribution of operating speeds and the covered area and used it to compute field efficiency for a combine and a planter in various fields. Amiama, Bueno, Álvarez, and Pereira (2008) developed a system for acquisition of GPS recordings, sensor data, and manual entry data in a self-propelled forage harvester in order to study the effect of field size and crop yield on field capacity. Bochtis, Sørensen, Green, Moshou, and Olesen (2010) monitored fertiliser operations and decomposed the travelled distance into non-productive, in-field transport, and turnings. Duttmann, Brunotte, and Bach (2013) recorded the path of multiple vehicles in forage harvesting using GPS sensors in order to decompose the paths into separate tasks for the transport vehicles, such as transport to the harvester, loading, and transport with full load, and use these tasks to estimate field traffic intensities. Jensen and Bochtis (2013) used GPS monitoring and data post-processing to automatically classify activities in grain harvesting with multiple combines and grain-carts. The aim of all the previously mentioned studies was to analyse and decompose operations into productive and non-productive time or distance elements to gain more understanding of the sources of non-productivity and subsequently to propose methods to reduce them.

The objective of this paper is to identify the sources of non-productivity in capacitated field operations, decompose the area coverage process to feasible driving actions and analyse the potential of minimising the non-productivity. The field coverage operation of focus is liquid fertilising using a shallow injection applicator and a stationary storage location. Based on the monitoring of on-going operations and subsequent data analysis, the driven paths are decomposed into four types of non-productive activities. As a next step, the involved driving actions are defined, and finally, the potential of minimising the contribution of each non-productive activity to the operation efficiency by the selection of driving actions, is qualitatively described.

## 2 Methodology

The applied method, firstly, involves a combination of on-farm monitoring of field operations producing basic performance data (time stamps, GPS loggings, etc.). Next, the recorded data are diagnostically analysed to determine the "current state" of the field operations, and the tasks decomposed into productive and non-productive elements. Following this decomposition, prescribed actions affecting the non-productive activities are identified and the potential for the selection of these prescribed actions to minimise the non-productive activities were qualitatively assessed. Figure 1 shows the principal steps of the applied approach.

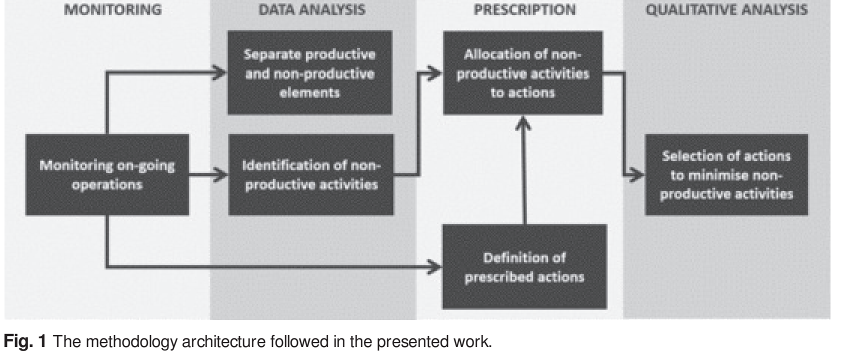



**Fig. 1** The methodology architecture followed in the presented work.

# 3 Monitoring of on-going operations

Four shallow injection fertiliser operations were carried out and recorded. The machinery features and operational characteristics are listed in Table 1. A tractor-pulled tanker was used to distribute the liquid fertiliser. In operations 1, 2, and 4, the depot was a buffer tank reloaded by a transport lorry. In operation 3, refilling of the tanker was done directly from a transport lorry at a rendezvous point. Depot locations were constrained to be near a road. Figure 2 shows the machinery used in the operations.

**Table 1** Characteristics of recorded soil injection fertilising operations.

| Operation ID | Tanker payload (m$^3$) | Working width (m) | Dosage (t ha$^{-1}$) | Field area (ha) | Distance from depot to nearest track (m) |
|---|---|---|---|---|---|
| 1 | 25 | 7.5 | 17 | 7 | 100 |
| 2 | 25 | 7.5 | 17 | 7 | 20 |
| 3 | 25 | 7.5 | 20 | 6 | 120 |
| 4 | 18 | 7.5 | 30 | 6 | 100 |

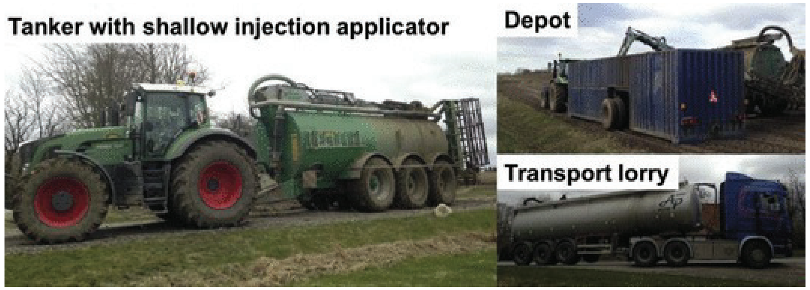



**Fig. 2** The machinery used in the operations.

The driving trajectories of the applicator were recorded using a Trimble AgGPS 132 differential GPS (~~differential global positioning system (~~DGPS) receiver with a frequency of 1 Hz. A terminal inside the tractor cabin displayed the current volume of fertiliser (m$^3$) in the tanker as well as the dispersing material flow (m$^3$ s$^{-1}$). A camera was mounted to monitor the terminal display with a frequency of 1 Hz. This enables an automatic recording of the operation status without any operator intervention. The monitoring system is illustrated in Fig. 3. The GPS data and the camera data were merged in such a way that for each individual time point along the recorded track it was indicated whether or not fertiliser was applied in order to identify productive and non-productive time and distances. Figure 4 shows the resulting tracks.

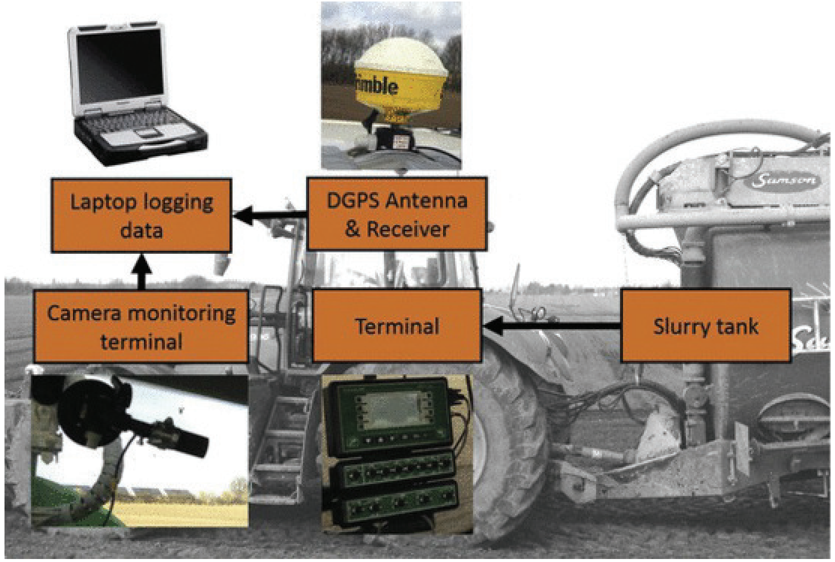



**Fig. 3** The monitoring system consisting of laptop, camera, DGPS and slurry tanker terminal.

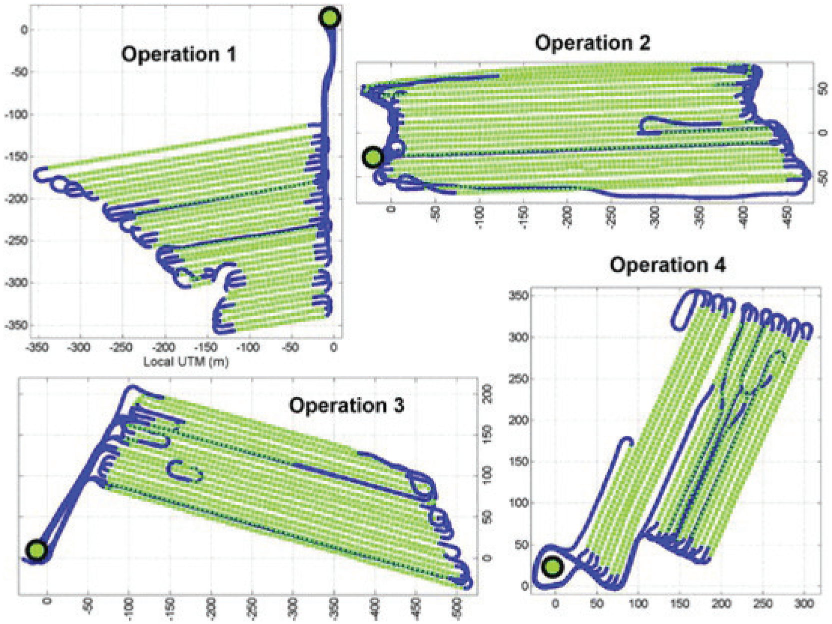



**Fig. 4** The recorded paths in the four field operations. The depot is located at the green dot. Blue continuous lines are non-productive activity and green dotted lines are productive activity (applying fertiliser).

# 4 Identification of non-productive activities

The recorded tracks were segmented into classes according to the activity occurring. At the first level, the productive (distribution of material) and non-productive (no material distributed) segments of the trajectories were identified based on the camera. At the second level, the non-productive segments were segmented into one part accounting for transportation in the field and one part accounting for loading at the depot. At the third final level, the in-field transportation sections were further divided in four non-productive activities:

1) Travelling on unworked tracks
2) Travelling on worked tracks
3) Turning on headlands
4) Transporting to/from the depot

Figure 5 shows the result of segmenting operation 3 into the four defined non-productive activity types.

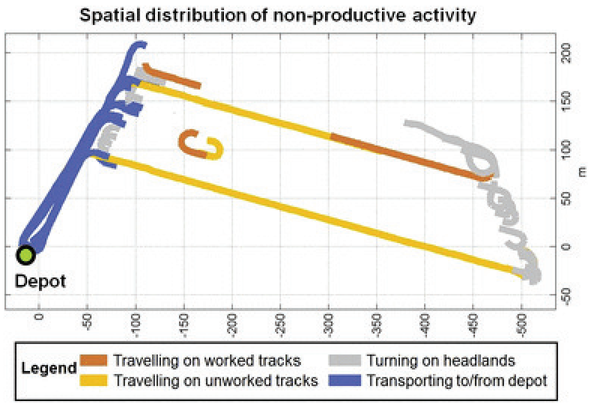



**Fig. 5** Segmentation of operation 3 into the four defined non-productive activities types.

Figure 6 shows the distribution of the non-productive distance travelled for each operation into the four defined non-productive activities. The most influential non-productive activity was “transporting to/from depot” which amounted to 25–56% with a mean of 46%. The influence of “transporting to/from deport” will increase as the distance to the depot increases. In the recorded operations the depot was located on the field boundary at a distance between 20 m and 120 m from the nearest track end. Headland turns was the second most influential activity amounting to 14–42% with a mean of 29%. The influence of “turning on headlands” activity correlates positively with the average number of tracks that can be worked with one payload as seen in Fig. 6. Thus, a tanker with higher payload would increase the influence of headland turns. The influence of the “travelling on unworked tracks” activity ranged between 8% and 34% and a mean of 22%. The least influential activity was “travelling on worked tracks” amounting to 0–4% with a mean of 2%.

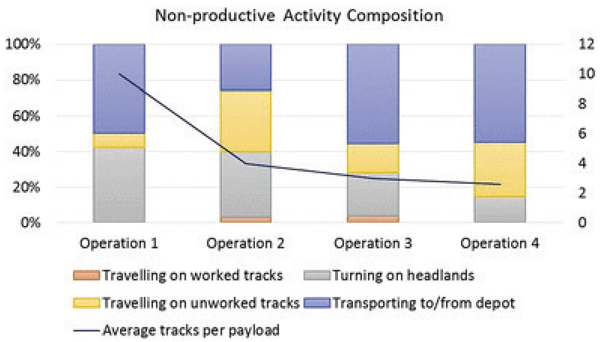
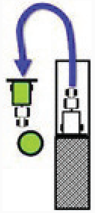
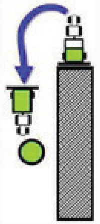
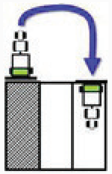
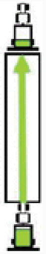
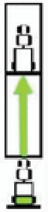


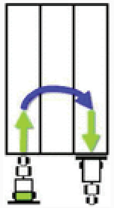
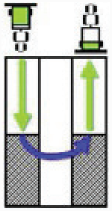
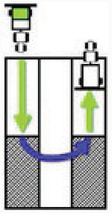
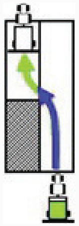
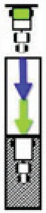
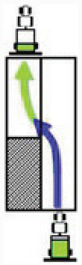

**Fig. 6** Left ordinate: composition of non-productive distance travelled in working the tracks. Right ordinate: average number of tracks worked per payload.

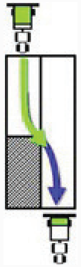
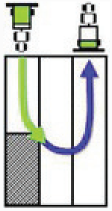
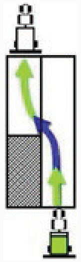
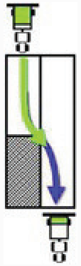
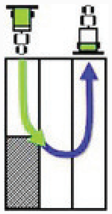
# 5 Definition of prescribed actions

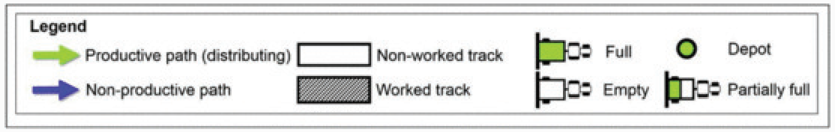
A field coverage operation is completed by the execution of a series of various types of *actions*. In the following, the actions involved in traversing the field-work tracks are defined based on the observation and the decomposition of the recorded data. All defined actions are summarised and listed in Table 2.

**Table 2** Summary of prescribed actions. *L*: Tanker load (in working distance), *C*: working distance corresponding to a full tanker load, *SP*: length of the shortest in-field path from current location to the field exit point, *RN*: length of the shortest out-of-field path in road network between the field exit and the depot location (only relevant if depot is outside field), *T*: length of track, $D_{HT}$: length of headland turn, $D_{UT}$: length of U-turn, *UW*: length of unworked part of track, *W*: length of worked part of track.

| Action | Schematics | Description | Acronym | Tanker load level pre-condition | Tanker load level end-condition | Productive distance | Non-productive distance | Non-productive activities involved in the action |
|---|---|---|---|---|---|---|---|---|
| Refill |  | Take shortest path to (from) depot from (to) track end | R | $L = 0$ ($L = C$) | $L = C$ ($L = C$) | 0 | $SP + RN$ | Transport to/from depot and travelling on unworked tracks |
| Pre-emptive refill |  | Similar to R, but with remaining tanker load | PR | $L > 0$ | $L = C$ | 0 | $SP + RN$ | Transport to/from depot and travelling on unworked tracks |
| Headland turn |  | Turn from a track end to another track end | HT | n/a | n/a | 0 | $D_{HT}$ | Turning on headlands |
| Work unworked track completely |  | Work a track from one end to the other | MF | $L \geq T$ | $L \geq 0$ | $T$ | 0 | None |
| Work unworked track partially |  | Work track from one end until tanker becomes empty | MP | $L < T$ | $L = 0$ | $L$ | 0 | None (however is followed by an R action) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Work two unworked tracks partially |  | Work a track partially; Make U-turn to an adjacent track; Work second track until the tanker becomes empty. | MS | $L < 2\ T$ | $L = 0$ | $L$ | $D_{UT}$ | Travelling on unworked tracks |
| Work split fully |  | Work track; U-turn into another partially worked track; Work track to the end | WSF | $L \geq 2U$ | $L \geq 0$ | $2^*U$ | $D_{UT}$ | Travelling on worked tracks |
| Work split partially |  | Work track; U-turn into another partially worked track; Work until tanker becomes empty; drive idle to the end of the track. | WSP | $U < L < 2UW$ | $L = 0$ | $L$ | $2UW - L + D_{UT}$ | Travelling on worked tracks (also it is followed by R action) |
| Work partial worked track partially |  | Drive idle on an adjacent track; make turn into the track; work track until tanker becomes empty. | WPP-1 | $L < U$ | $L = 0$ | $L$ | $W + L$ | Travelling on unworked tracks |
| Work partial worked track partially |  | Drive idle on track; work track until tanker become empty; meeting worked part. | WPP-2 | – | – | $L$ | $UW$ | Travelling on unworked tracks |
| Work partial worked track fully |  | Drive idle on adjacent track; makes turn into track; works unworked part of track completely | WPF-idle | $L \geq UW$ | $L \geq 0$ | $UW$ | $W$ | Travelling on unworked tracks |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Work partial worked track fully |  | Work track; turn into adjacent track; drive idle to the end of the track | WPF-idle | – | – | $UW$ | $W$ | Travelling on unworked tracks |
| Work partial worked track fully |  | Work track; make U-turn into an adjacent track; drive idle to the end | WPF-idle-U-turn | – | – | $U$ | $U + D_{UT}$ | Travelling on unworked tracks |
| Work partial worked track fully |  | Work adjacent track; make turn into track; work unworked part of the track. | WPF-work-1 | – | – | $T - \max(0, T - L)$ | $\max(0, T - L)$ | if $L \geq T$ None<br>if $L < T$ Travelling on unworked tracks |
| Work partial worked track fully |  | Work track; turn into the adjacent track; possibly some idle driving then work adjacent track to the end. | WPF-work-2 | – | – | $T - \max(0, T - L)$ | $\max(0, T - L)$ | if $L \geq T$ None<br>if $L < T$ Travelling on unworked tracks |
| Work partial worked track fully |  | Work track; U-turn into adjacent track; possibly some idle driving then work adjacent track to the end | WPF-work-Uturn | – | – | $T - \max(0, T - L)$ | $\max(0, 2UW - L) + D_{UT}$ | Travelling on unworked tracks |



The first action that is defined is the “work a track completely”, (MF), which refers to the simple case where the applicator covers completely and without any interruption a field work track. When an MF action is completed and the tanker is not empty, then two types of subsequent actions are feasible. The first one is the “pre-emptive refill” action, (PR), where the tanker drives back to the depot in order to refill even though the tanker is not yet completely empty. The second one is the “headland turn” action, (HT), where the machine turns from the end of one track to the beginning of another unworked track. In the latter case, if the remaining tanker load is not sufficient for working the unworked track completely, two actions are defined in which the track is worked partially. In the “work unworked track partially” action, (MP), the machine distributes material from the beginning of the track until the tanker is empty. After this action usually the machine in order to travel back to the refilling location has to drive a certain non-productive distance on the remaining unworked part of the track. To reduce this non-productive travelled distance, a remedying action, the “work two unworked tracks partially” action, (MS), can take place where the tanker distributes part of the remaining material on a first track, makes a U-turn into an adjacent track, and distributes the remaining part until the end of a second track. The two partially worked tracks are called a “*split*”. The productive distance is equal to that of the MP action and the non-productive distance is equal to the length of the U-turn.

If the tanker load level exceeds the quantity required for working the unworked parts of a split (generated during an MS action), an action “work split completely”, (WSF), is feasible where the tanker distributes material from the start of one track, works up to the worked part, makes a U-turn and works the unworked part of the other track of the split. If the tanker load is lower than the quantity required for the unworked parts of a split, but exceeds the quantity required for one of the two parts, the action “work split partially”, (WSP), can take place. The WSP action is identical to the WSF action except that a part of the second track remains unworked after the completion of the WSP action.

Two actions are defined in the case where a partially worked track, denoted a *partial track*, is worked. If the partial track cannot be worked fully, because the tanker load is lower than load needed to cover the unworked part, two types of the action “work partial track partially”, (WPP), are defined. In the first type, (WPP-1), the machine starts in the worked part, drives on an adjacent track to reach the unworked part, and distributes material until becomes empty before reaching the track end. In this case, the non-productive travelled distance equals to the length of the non-productive path on the adjacent track. In the second type, (WPP-2), the machine starts in the unworked part without distributing material, drives without distributing on the track until a specified point and after that point begins to distribute material until the worked part is reached and the tanker becomes empty. The non-productive distance of this action is the length of the initial non-distributing driving path along the track.

If the tanker load exceeds the amount needed for the unworked part of a partial track, two types of the action “work partial track fully”, (WPF), are feasible. In the first type, WPF-idle, the tanker starts in the worked part, drives without distributing along an adjacent track, turns into the partial track, and work the track fully to the end. In a modification of the WPF-idle type, the WPF-idle-Uturn action, a U-turn takes place when the machine has worked the unworked part up to some point on the track. In each of these actions the non-productive distance is the length of the idle driving paths on adjacent tracks. Another type, the WPF-work, the non-productive distance is reduced by working the adjacent track as well as the partial track. The WPF-work and WPF-work-Uturn actions are identical to their counterparts WPF-idle and WPF-idle-Uturn, except the entire or part of the idle driving on adjacent tracks in case the tanker level is low.

The final action that is defined is the “refilling” action, (R), where the machine drives from the location where the tanker becomes completely empty to the location of the depot, or the opposite case where the machine drives from the depot location to the location where the application resumes. The non-productive travelled distance in the R action equals to the total length of the path followed by the machine. If the depot is placed outside the field, the distance in the road network to the depot is included as well (note that this distance corresponds to the “transporting to/from depot” activity).

Since the purpose of the definition of the actions is the subsequent process of area coverage optimisation, no action that includes driving on worked tracks has been defined. In soil injection operations it is not desirable to drive on soil which has already been worked. One reason is that the tyres compact the soil considerably higher when the soil is wet. Another reason is that the tyres descend deeper into the soil giving worse conditions for the following operations, such as seeding.

# 6 Qualitative analysis of activities effecting efficiency

The efficiency of the operation depends on the sequence of actions required for a full coverage of the field area. Different sequences of actions result in different total non-working travelled distances and non-productive times. Each action contributes to a varying degree to the non-productive activities. Consequently, the selection of a subsequent action, on one hand might decrease the contribution of a specific non-productive activity to the total non-working travelled distance (or non-productive time), but on the other hand might increase this contribution of another activity. In this way there is a trade-off between the positive contribution to the overall efficiency between one activity and the negative contribution from another. In this section, indications for the negative or positive contribution to each of the four individual non-productive activities influencing the total efficiency are provided and summarised in Table 3.

**Table 3**(**I notice that Table 3 is placed in a *vertical* position in the Page Proof (PDF) version of the article.**
**I would prefer that you change the layout such that the table is positioned in a *horizontal* position. I think this would make it easier to read.**
**)** Summary of which driving actions should be made to reduce the influential non-productive activity as well as the potential amount of reduction.

| Non-productive activity | Action execution strategy to minimise activity | Effect of minimisation on the other activity types |
|---|---|---|
| Transporting to/from depot | Executing as many PR actions as possible while keeping the wasted payload below $W_{min}$ | Increases “travelling on unworked tracks” |

| | | |
|---|---|---|
| Travelling on unworked tracks | Executing as many PR and MS actions as possible, as long as consecutive WSF actions are feasible. (Activity can be reduced to zero) | Increases "transporting to/from depot" activity if many PR actions are executed |
| Travelling on worked tracks | Avoiding of partially worked track, between two fully worked tracks. (Activity can be reduced to zero). | Increase in "turning on headlands" and "transporting to/from depot" activities |
| Turning on headlands | Optimising the selection of the skip tracks in HT actions. | Increases "transporting to/from depot" activity if many PR actions are executed<br>Potential increases also "travelling on worked tracks" activity |

## 6.1 Activity: "transporting to/from depot"

The negative effect of "transporting to/from depot" activity to the operation efficiency can be reduced by minimising the number of refills that take place during the application. The minimum number of refills of tanker payloads required to work the field, $R_{min}$ , is determined by:

$$R_{min} = \lceil r_{min} \rceil = \left\lceil \frac{a \cdot d}{b \cdot \rho \cdot c} \right\rceil$$

where $r_{min}$ is the fractional number of tanker payloads necessary to work the field, *a* is the area of the field (m$^2$), *d* is the dosage of effective fertiliser e.g. N (kg m$^{-2}$), *b* is the weight proportion of effective fertiliser in the transported liquid, *ρ* is the density of transported liquid (kg m$^{-3}$), and *c* is the tank capacity in volume (m$^3$). The ceiling function, $f(x) = \lceil x \rceil$ returns the smallest integer larger than $x$ e.g. $\lceil 2.1 \rceil = 3$ . The proportion of a payload that can be returned to depot without increasing the number of refills, $W_{min}$ , is then given by:

$$W_{min} = R_{min} - r_{min}$$

Since the PR actions start at the end of a track (there is no in-field travelling) it is always preferable to perform as many as possible PR actions without the total number of refills exceeding $R_{min}$ . This can be achieved if the total remaining load in all PR actions is $< W_{min}$ If for example $R_{min} = 4$ and $W_{min} = 0.2$ then the minimum number of refills is achieved by performing 3 R actions and 1 PR action with a 20% payload remaining at the time that the machine interrupts the application. However, it is also possible to achieve the minimum number of refills with, for example, 2 R actions and 2 PR actions each with, for example, 10% payload remaining.

However, the replacement of an R action with a PR action reduces the non-productive travelled distance only in the case that the PR action is performed when the machine have completed the last track of the tour on the headland that is located near to the exit of the field. Otherwise, travelling on unworked tracks will take place.

### *6.1.1 Activity: "travelling on unworked tracks"*

The "travelling on unworked tracks" activity potentially takes place during an R action executed after an unworked track has been partially worked (MP), or a split that has not been worked fully (WSP), and in actions where partial tracks are worked partially or completely with non-productive travelling on adjacent tracks (WPP, WPF-idle).

Several approaches exist to reduce the "travelling on unworked tracks" activities. For example, to apply WPF-work actions instead of WPF-idle which, however, require the remaining load to be sufficient to cover an entire track, or to reduce the number of partial tracks made (reduction of MP actions) which also prevent the subsequent WPP or WPF-idle actions.

Reducing the number of MP actions will however increase the number of PR actions, which consequently will increase the non-productive travelled distance derived from the "transporting to/from depot" activity. An alternative to reduce the transport on unworked tracks that does not increase the number of PR actions, is the splitting the application in two tracks (MS actions). However, the remaining payload should be sufficient to work the unworked part fully (WSF action) instead of partially (WSP action) which requires a consecutive travelling back to the depot (R action) containing non-productive travelling on tracks.

To summarise, the increase in the number of times where the machine drives back to the depot without applying a full load (PR actions) decreases the travelling on tracks, but on the other hand increases the "transporting to/from depot" activity if the limit given by $W_{min}$ is exceeded. The optimal selection of actions is then a consideration of the trade-off between the two activities.

### *6.1.2 Activity: "turning on headlands"*

The "turning on headlands" activity takes place when the machine turns from a track end to another track end. Reducing the number of headland turnings (HT actions) can be achieved by implementing more pre-emptive refiling actions (PR) with the negative consequence of inducing larger non-productive transporting to/from the depot. The turning on headlands activity can be reduced by optimising the number of skips in each turn. Bochtis and Vougioukas (2008) describe the same problem and solution method for field coverage tasks with no refilling requirements. The resulting skip patterns are called B-patterns. The achievable savings depends among others on the manoeuvrability, size of the headland, and angle between headland and the working direction and it was shown that the non-productive travelled distance during headland turnings can be reduced by up to 50%. However, this method applies only to the optimisation of the track sequence of a single tour and this optimisation might end up requiring more PR actions.

### *6.1.3 Activity: "travelling on worked tracks"*

As seen in Figs. 5 and 6 the "travelling on worked tracks" activity contribute only in a small portion both in non-productive distance and non-productive time, respectively, and does not occur in all of the operations (operations 2 and 3). This activity tales place after the operator has worked a track partially while both of the adjacent tracks have prior been fully worked. It does not occur, for example, in operation 4 because the applicator operated in a skip pattern where at least one adjacent track to a partial track is unworked. However, the field work patterns which eliminate or reduce the "travelling on worked tracks" activity might increase the total distance travelled during headland turnings, and might also increase the pre-emptive refill actions increasing the "transporting to/from depot" activities.

## 7 Conclusions

Recorded data from on-farm monitoring of fertilising operations were analysed diagnostically and the tasks decomposed into productive and non-productive elements. Based on that, four non-productive activities have been identified. In four operations the most frequent non-productive activities were in order: "transporting to/from depot", "turning on headlands", "travelling on unworked tracks" and "travelling on worked tracks".

Following the decomposition into productive and non-productive elements, prescribed actions affecting the identified non-productive activities were defined and the potential for these prescribed action to minimise the non-productive activities, was qualitatively assessed. This assessment has revealed that the selection of a subsequent action, on one hand might decrease the contribution of a specific non-productive activity to the total non-working travelled distance, but on the other hand might increase this contribution of another activity. In this way there is a trade-off between the positive contribution to the overall efficiency between one activity and the negative contribution from another. This indicates that a targeted algorithmic optimisation method should be devised by searching for the optimal combination among the prescribed driving actions. This study sets the guidelines for the identification and specification of the constraints and criteria to be invoked when the subsequent algorithmic optimisation model is developed.

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**Highlights**

- Capacitated field operations (high dosage liquid fertilising) recorded with GPS.
- Non-productive activities identified and measured.
- Area coverage task decomposed into feasible driving actions.
- Field efficiency is highly affected by the selection of driving actions.

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