BIOSYSTEMS ENGINEERING 139 (2015) 149–164

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Coverage planning for capacitated field operations, part II: Optimisation

Martin F. Jensen [a,b,*], *Dionysis Bochtis* [a], *Claus G. Sørensen* [a]

[a] *Aarhus University, Faculty of Science and Technology, Department of Engineering, Inge Lehmanns Gade 10, DK-8000 Aarhus C, Denmark*

[b] *CLAAS E-Systems, Moellevej 11, DK-2990 Nivaa, Denmark*

ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form
19 May 2015
Accepted 1 July 2015
Published online 6 August 2015

Keywords:
Agricultural field operation
Operations management
Area coverage planning
State-space search
Travelling salesman problem

Capacitated field operations refer to the operations that involve material flow where there are capacity constraints to the load that the machine is able to carry. A capacitated operation cannot therefore be completed in one operation and the machine has to interrupt the operation, leave the field and travel to an out-of-field facility for refilling (or unloading) and to return back to the field to resume the operation. This paper develops an algorithmic approach for the optimisation of capacitated field operations using the case of liquid fertilising. The approach is based on the state-space search technique where a solution is a sequence of pre-defined driving actions which are applied to the initial state that transform it to a goal state under the criterion of the minimisation of the non-productive travelled distance. In order to minimise the branching factor of the state-space search, the sequence of the working tracks is optimised in a post-process stage where the non-productive travelled distance in headland turnings is further minimised by implementing the travelling salesman problem methodology. In order to assess the improvements in the operations efficiency derived from the presented method, three fertilising operations were recorded and the optimised plans were compared to the conventional plans followed during the operations. Savings in the non-productive travelled distance was 15.7 %–43.5 %, while savings in the total travelled distance was 5.8 %–11.8 %.

1. Introduction

Capacitated field operations refer to the operations that involve material flows (e.g. input material flow: fertilising, or output material flow: harvesting) and in which there are capacity constraints related to the load that the machine is able to carry. Consequently, a capacitated operation cannot be completed at once and the machine has to interrupt the operation, leave the field and travel to an out-of-field facility for refilling (or unloading) and return back to resume the operation, one or more times. Examples of capacitated operations include the liquid fertilising, spraying, and specific cases of harvesting, such as rise harvesting, where the harvester unloads outside the main field area. Although a number of coverage planning methods for agricultural vehicles have been recently developed (e.g. Bochtis, Sørensen, & Green, 2012; Spekken & de Bruin, 2013; Scheuren, Stiene, Hartanto, Hertzberg, & Reinecke, 2013) the case of capacitated operations has not been covered extensively. Oksanen and Visala (2009) presented a method for optimised paths in capacitated field operations by recursive

* *Corresponding author*. CLAAS E-Systems, Moellevej 11, DK-2990 Nivaa, Denmark. Tel.: +45 40 58 08 17.
E-mail address: martin.jensen@claas.com (M.F. Jensen).

http://dx.doi.org/10.1016/j.biosystemseng.2015.07.002

Nomenclature

Abbreviations

- A* — Well known computer algorithm that finds the optimal path in a state-space. Pronounced as "A star".
- VRP — Vehicle routing problem. Well-known optimisation problem in logistics and operations research.
- TSP — Travelling salesman problem. Well-known optimisation problem in logistics and operations research.
- U-turn — Turn that involves a 180° change in heading

Acronym of action

- MF — Work unworked track completely (make full)
- MP — Work unworked track partially (make partial)
- MS — Work two unworked track partially, making a U-turn in between (make split)
- WPP — Work partial worked track partially
- WPF-idle — Work partial worked track completely (fully) and drive **idle** on adjacent track
- WPF-idle-Uturn — Work partial worked track completely (fully), make a **U-turn**, and drive **idle** on adjacent track
- WPF-work — Work partial worked track completely (fully), and **work** part of adjacent track
- WPF-work-Uturn — Work partial worked track completely (fully), make a **U-turn**, and **work** part of adjacent track
- WS — Work two partially worked tracks completely or partially, making a U-turn in between (work split)
- R — Return to refilling location with the tank empty
- PR — Pre-emptive return to refilling location with the tank not empty

Symbol

- c — Non-productive driving distance, m.
- C — Machine tank capacity in working distance per load, m.
- $d(s)$ — Travel distance between the depot and the nearest unworked track end in the state s, m.
- $d_{Depot}(x;\beta_{Depot})$ — Function predicting the travel distance from a track end to the depot, m.
- $d_{Dubins}(\overline{x};\overline{\beta}_{Dubins})$ — Function predicting the travel distance when turning from a track end to another track end, m.
- L — The remaining material in the tank as a proportion of a whole tank load.
- $M(s)$ — Working distance represented by material remaining in the tank in state s, m.
- $m_{unworked}(s)$ — Working distance needed to work all the remaining unworked tracks in state s, m.
- o_{turn} — Machine turn offset. Constant in the turning distance model fitted to measured travel distances, m.
- R — Machine turning radius, m.
- $R_{min}(s)$ — Minimum number of refills at the depot necessary to work the field as a function of the state s.
- s — A state in the state-space representation of the optimisation problem. Encodes the portion of each track that has been worked, the current location of the machine, and the current load level of the tank.
- x_i — Specification of the track end that the machine is departing from in the path segment i.
- $\overline{x}_i$ — Specification of a starting pose of the machine at the departing track end and of the goal pose of the machine at the arriving track end in the path segment i.
- $x_i^s, y_i^s, x_i^g, y_i^g$ — Coordinates of the machine at the start and goal configuration in a path segment i, m.
- θ_i^s, θ_i^g — Heading of machine at the start and goal configuration in a path segment i, rad.
- y_i — Measured travel distance of path segment i, m.
- β_{Depot} — Depot distance offset. Constant in the travelling distance model fitted to measured travel distances, m.
- $\overline{\beta}_{Dubins}$ — $\overline{\beta}_{Dubins} = \{R, o_{turn}\}$.
- ε_i — Error between measured and predicted travel distance of path segment i, m.

selection of the best of a number of simulated routes within a limited horizon. The implemented version of the approach however, does not include the working of tracks partially as part of the searched solution space, and the search horizon usually only extends to the next refill. Bochtis and Sørensen (2009) cast capacitated operations as various instances of the well-known vehicle routing problem (VRP). However, this approach considers only whole tracks between refills, and not partially worked tracks. Thus, although in operations where many tracks can be worked by one tank load (e.g. spraying, mineral fertilising and seeding) the expected degree of optimality is high, in liquid fertilising, where a lot fewer tracks are typically worked by one tank load, it is expected that a high degree of optimality can only be achieved if partially worked tracks are considered in the solution space. Ali, Verlinden, and Van Oudheusden (2009) modelled the grain harvesting operation by posing the traversal of a field as being divided into cells as a VRP. The solution space of this model incorporates the working of tracks partially, however a challenge remains of determining the appropriate discretisation into cells and representing agronomical constraints e.g. that traversal of prior worked area is prohibited.

The objective of this paper is the development of an algorithmic approach for the optimisation of capacitated field operations using as case the liquid fertilisation. The approach is based on the state-space search technique where a solution is a sequence of pre-defined driving actions which are applied to the initial state that transform it to a goal state under the criterion of the minimisation of the non-productive travelled distance. In order to minimise the branching factor of the state-space search the sequence of the working tracks is optimised in a post-process where the non-productive