Optimal Dynamic Motion Sequence Generation for Multiple Harvesters

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ABSTRACT

Harvesting efficiency could be improved significantly by computing optimal harvesting patterns which minimize turning time. Hence, the execution of harvesting operations, especially in case of cooperating harvesters, needs to be carefully planned. In this paper, the operation planning for a fleet of harvesters is formulated as a discrete optimization, multi-Traveling Salesman Problem (m-TSP). Given number of "cities" and the cost traveling between every pair of them, the m-TSP searches for m round trips (one for every of m salesmen) in a way that every "city" is visited exactly once and the total cost is minimized. In our proposed formulation, the "cities" of the m-TSP correspond to the operating rows of the field. The cost is the nonproductive time, which is spent during the turnings at the headlands. This cost is computed based on the kinematics constraints of the vehicles and on the geometrical space constraints of the field.

An existing heuristic algorithm with low computational requirements (in the order of a few seconds) was adopted for the solution of the m-TSP. The advantage of low computational time makes it feasible to re-plan an optimal fieldwork pattern when it is necessary for the remaining non-harvested field, while the harvesting procedure is being executed. Simulations of scenarios of planning and re-planning optimal harvesting operations are presented.

Keywords: Autonomous machines, fieldwork pattern, harvesting, mission planning

1. INTRODUCTION

Recently, efficiency studies have been carried out based on collection of time-stamped position data while the machines were traveling in the field. Positioning data was gathered by accurate GPS-based systems (Auernhammer, 2002; Reid, 2002). The conclusion of all these studies is that machinery efficiency could be improved significantly by computing optimal fieldwork patterns for the agricultural machines which minimize turning time. According to Hansen et al. (2003), optimization of the combine harvesting pattern in corn fields can increase harvesting efficiency substantially. Pre-planning of combine movement in the field and the use of vehicle position indicators via GPS will contribute to a major improvement in overall efficiency. Furthermore, controlled traffic in the field will also reduce soil compaction. Taylor et al. (2002) have used DGPS data obtained during yield mapping operations to evaluate the potential for improving harvest efficiency. They concluded that harvest efficiency depends more upon turning time rather than unloading time. Hence, farm managers could improve harvest efficiency first by modifying harvest patterns to minimize turning and secondly by unloading grain on-the-go. Benson et al. (2002) supported these conclusions by simulation studies of the in-field harvest operations in the ARENA manufacturing language.

Field efficiency can be mathematically expressed as (Tsatsarelis, 2006; Hunt, 2001):

$$E_f = \frac{F(t_T)}{t_T + \sum t_i}$$

where $F(t_T)$ is a function of the theoretical field time (the time the machine is operating in the crop at an optimum travel speed and over its full width of action) and t_i , are the time losses due to "interruptions". A significant type of interruption is the time a harvester spends for maneuvering at the headlands. The resulting optimization problem is the minimization of the total maneuvering time. Furthermore, because of the problem's dynamic nature the implemented algorithm must generate solutions relatively fast.

In this paper, the problem of motion sequence generation for a fleet of *m* harvesters is formulated as a discrete optimization, multi-Traveling Salesman Problem (m-TSP). Given a weighted graph with vertices and edges, the m-TSP searches for *m* paths (sequences of edges), which - combined - contain all graph vertices. Each vertex must be visited only once by any path, and the total cost of all traversed edges must be minimized. In our proposed formulation, the vertices of the m-TSP correspond to the operating rows of the field. The cost is the nonproductive time, which is spent during the turnings at the headlands. This cost is computed based on the kinematics constraints of the vehicles and on the geometrical space constraints of the field.

An existing heuristic algorithm with low computational requirements (in the order of a few seconds) was adopted for the solution of the m-TSP. The advantage of low computational time makes it feasible to re-plan an optimal fieldwork pattern for the remaining non-harvested field, while the harvesting procedure is being executed. This may be required in case of unexpected changes in the fleet size (e.g., harvester blockage or restarting), or in cases of significant variation in some harvesters' working rates. Simulations of scenarios like the ones mentioned above were executed, and the corresponding optimal harvesting patterns were computed for various-size teams of harvesters.

2. PROBLEM STATEMENT

A fleet of identical harvesters $h_k \in H$, where $0 < k \leq \|H\|$ operate in a field using the alternation pattern, i.e., they travel from one end of the field to the other, in parallel rows, which are not necessarily straight. The number of rows is given by: $n = \lfloor w/l + 1 \rfloor$, where w is the effective operation width of the harvester and l is the length of the field face. For each harvester k two geographical field-points (not necessary different) are given: a starting point (s_k) end an ending point (e_k). These points may be the desirable initial and final row for the harvester operation, or may be some out-of-the-field points; however, they must always lie inside the area in which the harvester is moving on an open area. For example, if the next destination for a harvester is a silo which is connected with the field by a fixed road, then the ending point for the harvester operation is the beginning of the road. Let P be the set of these points $P = \{s_k, e_k / 0 < k \leq \|H\|\}$, let L be the set of the rows ($n = \|L\|$) and N be their union: $N = P \cup L$, $\|N\| = 2\|H\| + \|L\|$. All the elements of the set N will be referred to as *nodes*. These sets are in general time-dependent. For example, in case of a harvester blockage the fleet size is decreased and when the harvester restarts the fleet size is increased. Moreover, the ending point of a harvester may have to be changed, if for some reason another new destination is given. For such reasons, the field alternation pattern may have to be re-planned while harvesting the operation is being executed. After the beginning of a plan's execution the starting point for re-planning is the current harvester positions and the set L is the set of the remaining un-harvested rows.

The solution results in a permutation $\pi_\kappa \subset L$ for every harvester k that contains the sequence of the rows that the harvester must operate in, where $\pi_k(i)$ is the row that the harvester k operates at the step i. Formally the next summation has to be minimized:

$$\sum_{k=1}^{\|H\|}\left(c_{s_k,\pi_k(1)} + \sum_{i=1}^{\|\pi_k\|} c_{\pi_k(i),\pi_k(i+1)} + c_{\pi_k(\|\pi_k\|),e_k} \right)$$

where $c_{a,b}$ is the cost for the harvester transition from node a to node b.

2.1 Inter-row cost matrix

For our planning problem the optimization criterion is the minimization of the nonworking traveled distance (a harvester is traveling without harvesting), which is equivalent to the nonworking time. We categorize nonworking distance to *out-field* and to *in-field* nonworking traveled distance. The first category refers to the length of the paths that connect the harvesters' starting and ending points with their initial and final operating rows. This length includes only the off-road traveled distances. For the calculation of these distances there are two cases. In the first case the starting and ending points are significantly far away from the rows' vertices and we can consider the distances like a set of straight lines that connect these points to these vertices. In the cases where the starting and ending points are close enough to the field, or there are obstacles or other field restrictions, a path planning program is used (Vougioukas et al., 2005) to calculate the traveled distances, because the vehicles kinematics cannot be neglected.

The in-field nonworking distances refer to the total length of the maneuvers at the headlands. These distances depend on the harvesters' related characteristics (minimum turning radius, effective operating width) and the harvesters' maneuverability constraints due to field geometry (e.g., presence of obstacles, restricted areas). For the calculation of the distances that the harvester travels at the headlands we consider two types of harvester's maneuvers, the loop turn and the double corner turn (fig. 1). For these types we can assume that the harvester is a vehicle which moves forward on an empty plane. In this case, according to Dubins' Theorem (Dubins, 1957), the shortest path between any two harvester's configurations is a sequence of straight line segments (S) and circular arcs (C) of radius R_{min} of the form CSC, CCC or a subsequence of one of these, where R_{min} is the operative lower limit on the turn radius. More specifically, $R_{min} = max(R_{dmin}, R_{kmin})$, where R_{dmin} is the minimum dynamic turn radius, which generates the maximum permissible lateral acceleration $\alpha_{\max}$ for the vehicle for a given velocity v ($R_{dmin} = v / \alpha_{\max}^2$). Finally, R_{kmin} is the minimum kinematic turn radius which is imposed by the machine's steering mechanism. For typical working velocities of agricultural machines we can neglect the dynamic limitation.

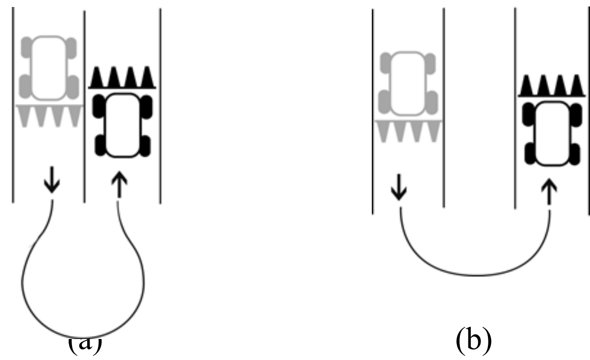

Figure 1. Headland maneuvers (a) loop turn, (b) double corner turn.

We consider that the harvester's configuration space (C-space) comprises of three degrees of freedom (x, y, θ) and its actuation space (A-space) is the space of the turning radius. The integral and differential equations, which map A-space to C-space in a flat 2D world, are given below:

$$\dot{x} = v\cos(\theta) \qquad x = x_0 + v\int_0^t \cos(\theta(t))dt$$

$$\dot{y} = v\sin(\theta) \qquad \mathrm{y} = y_0 + v\int_0^t \sin(\theta(t))dt$$

$$\dot{\theta} = v\frac{1}{R} \qquad \theta = \theta_0 + \frac{vt}{R}$$

where v is the machine's linear velocity, (x,y) are the coordinates of the rear-wheels axis center, θ is the machine's orientation, and R is the turning radius. We assume that the actuation space is the discrete space $A = \{R_{\min}, -R_{\min}, \infty\}$ (right turn: R=R_{min} , left turn: $R = -R_{\min}$, strait route: $R = \infty$). The usual maneuvers of an agricultural machine at the headlands are completed in three stages. For example, for the execution of a loop turn the three stages are: 1) right turn 2) left turn 3) right turn. We assume that during every stage the velocity and the steering angle are constants ($\dot{v} = \dot{\phi} = 0$). Let $\psi = [x, y, \theta]^T$ represents the state vector and Ψ the indefinite integral of the state vector. If we integrate the differential equations (2) for any stage the result is:

$$\psi_k = \psi_{k-1} + \Psi_k(t_k) \qquad k \in \{1,2,3\}$$

Adding the previous equations we get an algebraic system of three equations:

$$\psi_3 = \psi_0 + \sum_{k=1}^{3} \Psi_k(t_k)$$

where ψ_3, ψ_0 are the known final and initial state vectors. The duration of each of the three stages is computed by solving the above system.

Next, the total path length of the maneuver is computed by adding the corresponding line integrals:

$$\mu = \sum_k s(t_k) \quad \text{where} \quad s(t_k) = \int_c ds = \int_0^{t_k} |\dot{r}(t)| dr = \int_0^{t_k} \sqrt{[\dot{x}(t)]^2 + [\dot{y}(t)]^2}\, dt$$

By applying the previous method we get:

$$\forall i, j \in L \quad c_{ij} = \begin{cases} R_{\min}\left(3\pi - 4 asin\left(\dfrac{2\mathrm{R}_{\min} + |i-j| \cdot \mathrm{w}}{4\mathrm{R}_{\min}}\right)\right) & if \quad 2R_{\min} \leq |i-j| \cdot \mathrm{w} \\ |i \text{ - } j| \cdot w + (\pi - 2) R_{\min} & if \quad 2R_{\min} > |i-j| \cdot \mathrm{w} \end{cases}$$

3. SIMULATION RESULTS

The algorithm used in this paper is the Clarke-Wright savings algorithm, a well-known algorithm in vehicle routing (Clarke and Wright, 1964). The algorithm operates in two stages: i) the randomization phase, where an initial solution is computed ii) the improvement phase, where various improvement heuristics are performed based on the use of local search algorithms. These heuristics include: a) the Or-opt operation, which works by deleting a group of nodes from a tour and re-inserting it at another position in the tour (the group sizes may be of 1, 2, and 3 nodes), b) the 2-opt, which deletes two edges, thus breaking the tour into two paths, and then reconnects the paths in the other possible way, c) the swap operation in which two nodes on different routes may be removed from their routes and inserted into the opposite route (Snyder and Daskin, 2004).

Small-sized problems (concerning the number of the rows and the number of the harvesters) are presented for illustration purposes. For the same reason we assume that the harvesters are unloading on-the-go. The difference in the case when the harvesters have to unload at a predetermined place (e.g., a silo, or at the field side) is that in the second case for each harvester more than one routes are generated. All harvesters' minimum turning radius is $R_{min}=4m$ and the effective operating width is $w=3m$. We consider this relation between the harvesters characteristics ($w<R_{min}<2w$) to reduce their maneuverability. By doing so, the problem difficulty - and the necessity for an optimal plan - is increased. At the first scenario three identical harvesters are going to operate at the same field. The field is divided into 30 operating rows. The total work is distributed equally to the three of them. The destination for all the harvesters after their operation is completed is a point at the left side of the field. This point may be a silo for harvester unloading, a station for their parking or maintenance, the entry to a new field for harvesting, or the road that drives to other destinations. From the solution of the initial planning we get the three permutations: π_1=<1, 4, 7, 10, 13, 16, 12, 9, 5, 2>, π_2=<3, 8, 15, 19, 23, 20, 17, 14, 11, 6>, π_3=<22, 26, 29, 26, 28, 30, 27, 25, 22, 18>. Figure 2a, 2b, 2c illustrate this initial plan for the corresponding harvesters 1, 2 and 3. While at work, it is supposed, that a mechanical damage causes harvester 1 to reduce its working rate and eventually stop at the row $\pi_1(4)$=10. Re-planning must be performed for the remaining harvesters 2 and 3 ($\|H'\| = 2$) for the un-harvested rows ($\|L'\| = 16$) with new starting points $s_2' = \pi_2(5)$ and $s_3' = \pi_3(5)$. The new plan is illustrated in figures 2d, 2e and 2f. The next destination remains the same and this is the reason why the harvesters exit the field as close to the left side of the field as possible. The computational time for the initial planning was 1.9 s and for the re-planning 0.88 s.

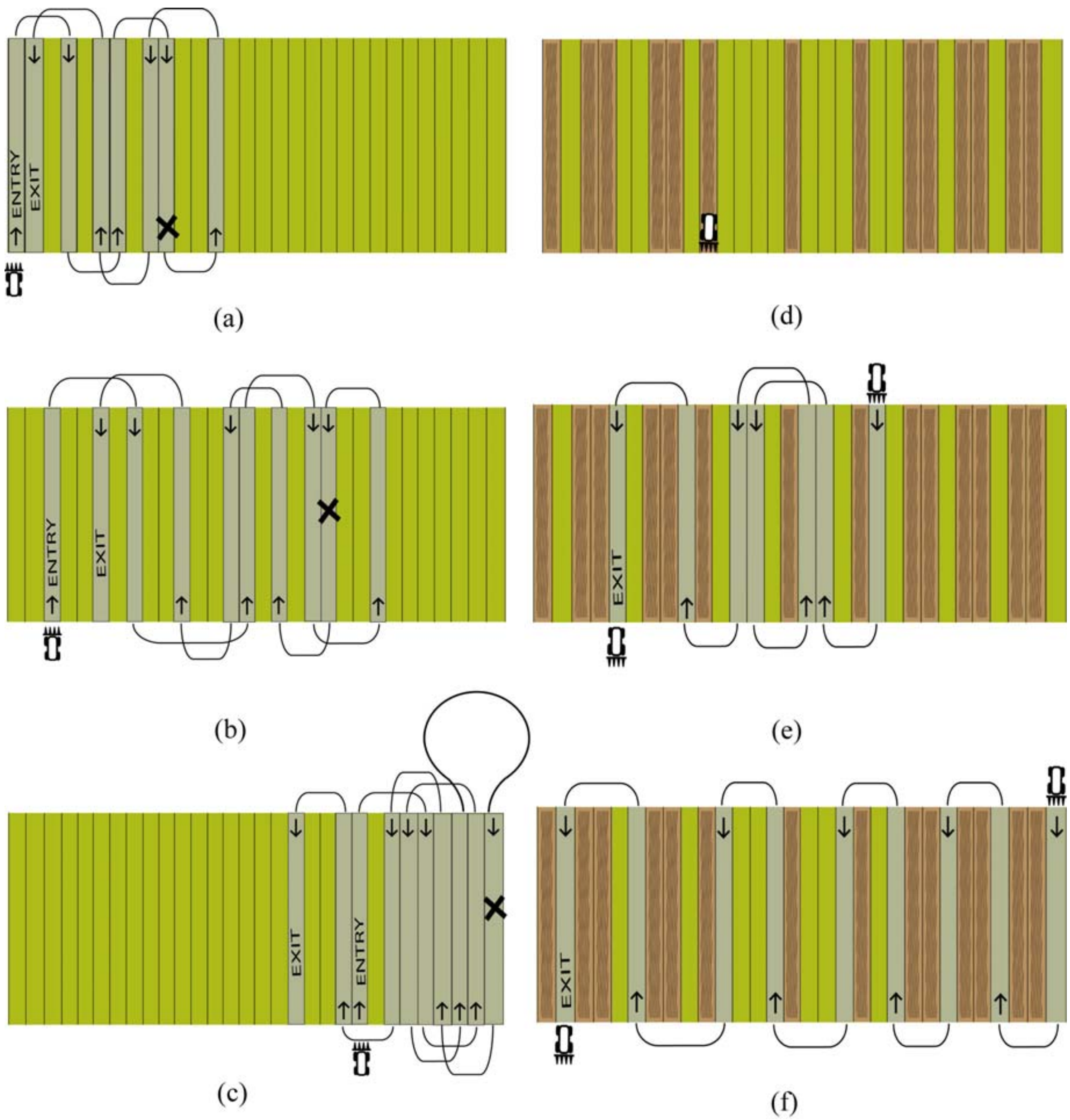

Figure 2. Motion sequence planning for three harvesters (a, b, c) and re-planning due to the blockage of one of them (e, f, g).

In the second scenario there are two harvesters with the same characteristics as the previous ones which are going to operate in a 20-row field. As the initial plan is executed (fig. 3a, 3b) the ending point for harvester 2 is changed, and the harvester - after its operation is completed - has to travel to a destination at the right side of the field (e.g., another silo must be used, or harvesting must continue to a field from this side, etc.) (fig. 3c, 3d). The solution time for the initial planning was 1.04 s and for the re-planning 0.65 s.

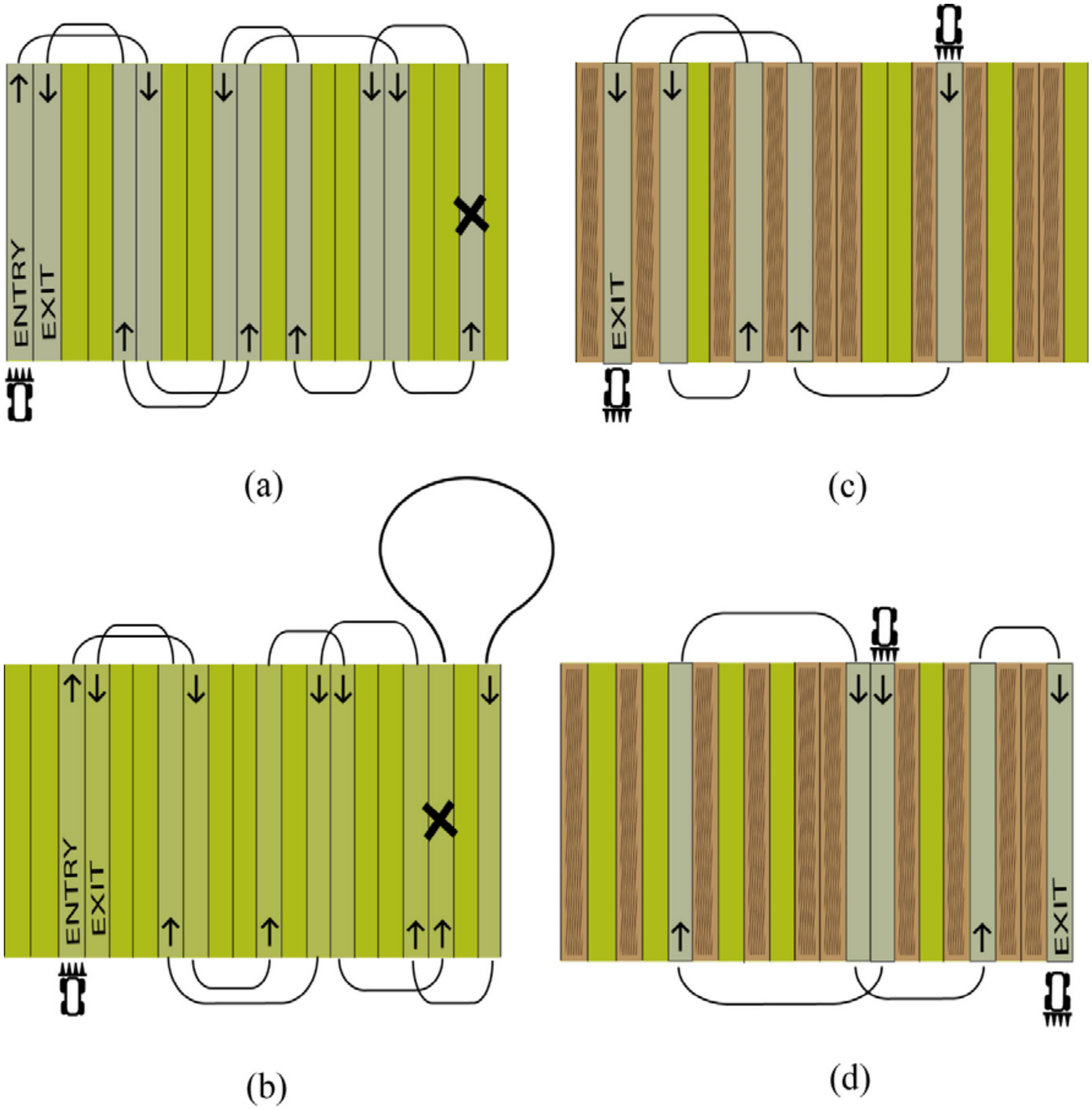

Figure 3. Motion sequence planning for two harvesters (a, b) and re-planning due to the change of the after operation destination of one of them (c, d).

The proposed algorithm can easily handle problem instances with hundred of rows and with a large number of operating harvesters. Figure 4 illustrates the solution progress for a problem instance of 100 rows and a fleet of four harvesters. It shows that near-optimal solutions are generated in a few seconds. Even the first solution, witch is generated in 0.06 s reduces the in-field nonworking traveled distance more than 500 m from the case of the typical straight alternation pattern (3715.2 m). If the planning includes the out-field paths, the improvement is even bigger. For these calculations a 2.8 GHz Pentium-4 processor (Windows XP) was used.

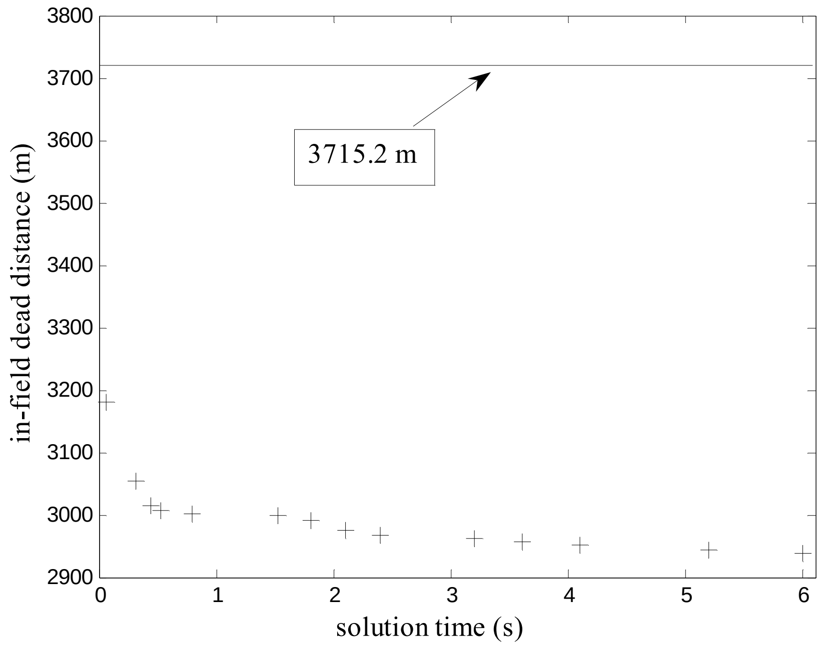

Figure 4. Solution progress for a problem instance of 100 rows and 4 harvesters.

The details (solution time and number of iterations) for two solutions (the best and the worst) are presented at table 1.

Table 1. Solution details.

Solution time (s)		Number of iterations				
Build	Improve	Swap	2-Opt	Or-Opt(1)	Or-Opt(2)	Or-Opt(3)
0.02	0.04	0	0	1	4	12
0.12	5.87	4	1	1	399	167

4. CONCLUSION

In this paper the problem of motion sequence generation for a fleet of harvesters operating according to the alternation pattern, was formulated as a routing problem. Two typical problem instances were solved using an existing heuristic algorithm. The advantage of this algorithm is its low computational requirements. Fast computation of solutions is extremely useful in dynamic problems, where some problem parameters may change during execution, or may be partially known before the execution.

Of course, for the complete adoption of routing algorithms for operations planning like this, modifications must be done which are related to the nature of agricultural operations. For example, the constraint that two harvesters must not move in adjacent rows in reverse directions must be added to the problem formulation. Even so, the planning improvement seems clear, especially when we have to deal with reduced maneuverability.

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