Chapter 6
Auto-Steering and Controlled Traffic Farming – Route Planning and Economics

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Abstract Agriculture nowadays includes automation systems that contribute significantly to many levels of the food production process. Such systems include GPS based systems like auto-steering and Controlled Traffic Farming (CTF). These systems have led to many innovations in agricultural field area coverage design. Integrating these advancements, two different route planning designs, a traditional and an optimised one, are outlined and explained in this chapter. Four different machinery scenarios were tested in four fields each, and the main aim was to compare the two different route planning systems under economic criteria and identify the best operational route coverage design criterion. The results show that there are significant reductions in operational costs varying from 9 to 20%, depending on the specific machinery and field configurations. Such results show the considerable potential of advanced route planning designs and further optimization measures. They indicate the need for research efforts that quantify the operational and economic benefits by optimising field coverage designs in the headlands, turnings or obstacles avoidance according to the actual configuration to minimize the non-working activities and, as a consequence, the overall operational cost.

Keywords Field coverage • Financial feasibility • Cost • Route planning • Optimisation

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6.1 Introduction

Automation systems in modern agriculture are included in any kind of agricultural machinery and tractors. Many different types of technologies such as radio frequency, laser, machine vision and GPS have been tried in the navigation of agricultural vehicles (Bochtis et al. 2014; Sørensen and Bochtis 2010; Sørensen et al. 2010; van Zuydam and Sonneveld 1994). The GPS-based navigation systems are the only navigation technologies that have become commercially available for navigation of agricultural vehicles. There are two types of GPS-based guidance systems; the GPS guidance-aided systems and the fully automated or 'hands-free' GPS guidance systems that actually steer the tractor with the driver only supervising it. The fully automated system is capable of driving the tractor in a straight line through the field with a lateral accuracy of less than 2 cm. This system uses a very accurate real-time kinematic (RTK) GPS receiver. The RTK-GPS achieve good geopositioning accuracy of a few centimetres. To achieve such accuracy in practice, a GPS base station located close to (10 km) the mobile unit and a radio data link (Gan-Mor and Clark 2001) are required. This system can work with any field and operation, including planting, cultivating and harvest (Batte and Ehsani 2006). The position information from RTK GPS can be used not only for guidance but also for other applications such as seed mapping, controlled traffic, controlled tillage (Chesworth 2008). The RTK-GPS technology systems have been established and used in many different countries throughout Europe (mostly in Northern and Central Europe) over the last 20 years or more (Engfeldt 2005). Auto-guidance field machinery systems in parallel with GPS are used little even in Northern Europe according to recent surveys; it varies from 2 to 24% of the respondents in Finland, Germany and Denmark (Lawson et al. 2011). One of the disadvantages of the use of these technologies is the cost of management and maintenance and, of course, the cost of investment making their use more affordable for large than for small farms (Lawson et al. 2011).

Modern agricultural machinery is equipped with many controls, therefore, operator fatigue is a serious concern. Automatic guidance can reduce operator fatigue and improve machinery performance by reducing overlap or 'skips' during field operations such as tillage and chemical applications (Tillett 1991). With automatic guidance, companies and farmers report that they are able to carry out most field operations in row crops on flat land with greater accuracy than manually steered systems. A typical increase in field capacity is around 15%. Another advantage of the system is particularly noticeable during low-visibility conditions (night time or fog). The present accuracy in row operations can enhance the placing of chemicals in narrow bands or cultivating close to the plant line. Furthermore, use of RTK-GPS guidance to work along contour lines in hilly and rough terrain can reduce erosion and provide additional benefits (Gan-Mor and Clark 2001). Finally, by using auto-steering systems, there are many economic and environmental benefits such as lower energy consumption and lower CO_2 emissions (Batte and Ehsani 2006).

Controlled Traffic Farming (CTF) systems are based on the principle that all the traffic inside the field is restricted to specific wheel tracks (tramlines) only. This can be achieved only by using accurate guidance systems i.e. auto-steering control and by aligning the machinery width with the tramline width. Apart from the investment cost of the CTF system, there are many significant benefits. The CTF systems were first introduced because of soil compaction caused by heavy agricultural machinery and tractors. Soil compaction causes reduction of soil infiltrability, conductivity, porosity and aeration and increases bulk density, which implies increased fuel consumption because of the increased pulling force required, which wastes energy (Gan-Mor and Clark 2001).

By using permanent wheel tracks in CTF, all the above problems are avoided because of the specific routes that are determined from the establishment of the crop in the field. In addition, time savings and material savings can reach 10–20% (Kroulík et al. 2011). Additional benefits include increased water retention in the soil, and also the total water runoff from the field is considerably less than in conventional systems. In conclusion, some of the advantages stemming from the implementation of CTF systems are: lower fuel consumption for field operations and cultivation, lower fuel consumption for driving over the soil, better seedbeds, improved soil structure, better fertilizer use efficiency, reduced quantities of agrochemicals, potential to retain more organic matter and living organisms and reduced CO_2 emissions.

6.2 Route Planning Design

Route planning regards the determination of a route that should be followed in the field with minimal costs. In agricultural field operations, the route planning problem is also encountered by operators that have to make a decision on how to traverse the field work tracks to minimize the non-working distance, time and cost. In conventional agriculture, the routes that are followed by agricultural machinery to cover a field area can be implemented several times without being designed properly. The most efficient route planning that should be followed on a given field area should be designed according to many factors such as the lowest fuel consumption, minimization of the non-working distance or non-working time, and as a consequence the minimization of the non-working cost. Route planning can be designed both in conventional and CTF systems given that basic automation systems such as auto-steering systems and GPS navigation exist.

Because of the requirement of creating practices for optimized field coverage, a new pattern has been suggested called B-pattern (Bochtis 2008). The B-patterns are defined as: algorithmically-computed sequences of field work tracks that completely cover an area and that do not follow any pre-determined standard motif, but in contrast are the result of an optimization process under one or more selected criteria (Bochtis et al. 2013). In B-patterns, the best result of the optimisation approach depends on the specific combination of the kinematics and dimensions of the mobile unit, the field shape, the operating width and the optimisation criterion or criteria that will extract the optimal sequences that should be followed. The B-patterns have been tested for an autonomous agricultural vehicle and have shown under the criterion of minimized non-working distance that this distance can be minimized up to 50% for a series of different field operations (Bochtis et al. 2015; Bochtis and Sørensen 2009, 2010 Bochtis and Vougioukas 2008; Bochtis et al. 2009b).

In agricultural operations, there are a number of constraints that must be taken into account such as soil compaction, the fact that a typical agricultural machine cannot usually operate while manoeuvering, and operating while following contour lines.

In addition, the fieldwork pattern followed in previous treatments or by other machinery types is another significant problem regarding route planning. Consequently, area coverage planning is mostly determined by agronomic parameters and constraints. For this reason, the whole problem of area coverage planning in field operations is considered as a sequence of sub-problems:

(a) Field area disintegration i.e. disintegration of the coverage region into sub-fields when needed and generation of headlands in the field or and in the sub-fields.
(b) Determination of the driving direction in each sub-field.
(c) Field track generation. It determines how the set of parallel field tracks is generated.
(d) Route planning over the geometrical representation extracted from the above sub-problems. The resulting route refers to the areal cover of sub-fields, meaning the generation of a track that covers each sub-region ensuring that the vehicle covers the main core of the in an optimum way, according to an optimization criterion (i.e. the minimum possible non-working travelled distance or the minimum non-productive time or the non-working cost), without overlaps or missed areas and avoiding all obstacles.
(e) Sub-fields sequence. It regards the determination of the sequence that the mobile unit visits the sub-fields given the access paths between them.

6.3 Results

An optimized route planning is presented under the criterion of optimization of operational costs. In operational costs, any cost is included that is directly or indirectly connected with the field operations application, e.g. fuel consumption, idle time costs, non-effective material cost etc.

In the following, the comparison between traditional and optimized route planning of field operations carried out by one unit is presented under the criterion of operational costs. In traditional route planning, the driver starts working in a block and moves to the next one only after the completion of the work in the first one. On the other hand, in optimized route planning, route planning can be mixed in the different blocks of the same field to minimize the operational costs. To examine the range of the size of agricultural machinery, four different machinery scenarios/cases are presented with the corresponding working width and turning radius (Table 6.1).

The corresponding four different field areas are:

- Field A: 6.01 ha
- Field B: 5.65 ha
- Field C: 5.70 ha
- Field D: 3.76 ha

The comparison of operational time in seconds for traditional and optimized route planning of field operations for the four fields examined is shown below in Fig. 6.1. Field efficiency is directly connected to the operational time; it can be defined as the ratio of the time a field machine is operating effectively to the total time that this machine is committed to the field operation (Bochtis et al. 2010b) given as a percentage.

Given that the average financial calculated cost per operational time (sec) is 0.0453 euros s^{-1}, the comparison of operational cost in euros for traditional and optimized route planning of field operations for the four fields examined can be extracted as shown below in Figs. 6.2, 6.3, 6.4 and 6.5. Among the four different field machinery scenarios, there is considerable divergence in operational cost from the smaller to the larger machinery and of course the cost is reduced by following the optimized route planning regardless.

Table 6.1 Characteristics of the machinery scenarios/cases

	Case A	Case B	Case C	Case D
Size	Small size	Small-medium size	Medium-large size	Large size
Working width (m)	1.5	3	3	6
Min turning radius (m)	3.5	3.5	5	5

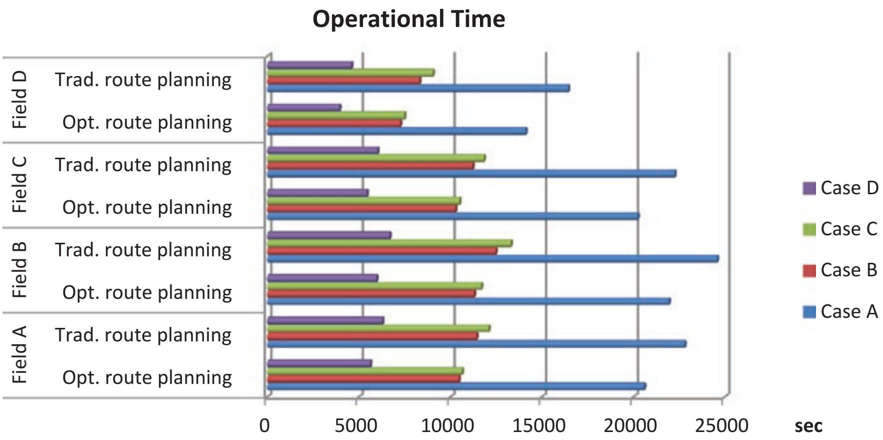

Fig. 6.1 The comparison between traditional and optimised route planning for operational time (s) in Fields A–D

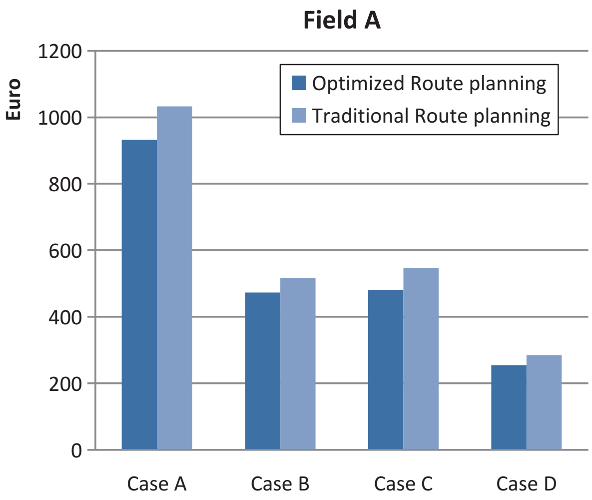

Fig. 6.2 The comparison between traditional and optimized route planning for operational cost (euros) in Field A

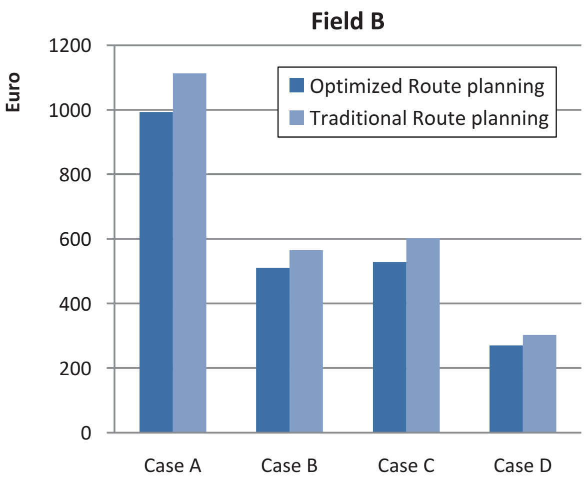

Fig. 6.3 The comparison between traditional and optimized route planning for operational cost (euros) in Field B

The comparison between the four fields presented above indicates the considerable savings achived by using optimized route planning. In Tables 6.2, 6.3, 6.4 and 6.5, these savings are presented for each field. Furthermore, these savings are shown graphically in Fig. 6.6.

Concerning the non-effective cost that comes from the non-effective time, the factors that have been taken into account are:

- Time of turning on headlands during operations at the main field
- Time of turning during operations at headlands
- Time of travelling from farm to field and back

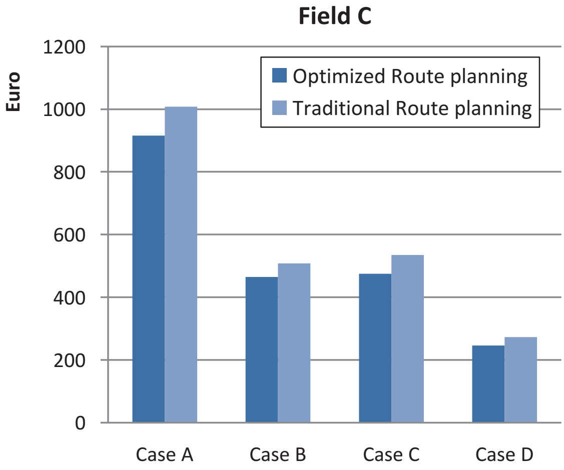

Fig. 6.4 The comparison between traditional and optimized route planning for operational cost (euros) in Field C

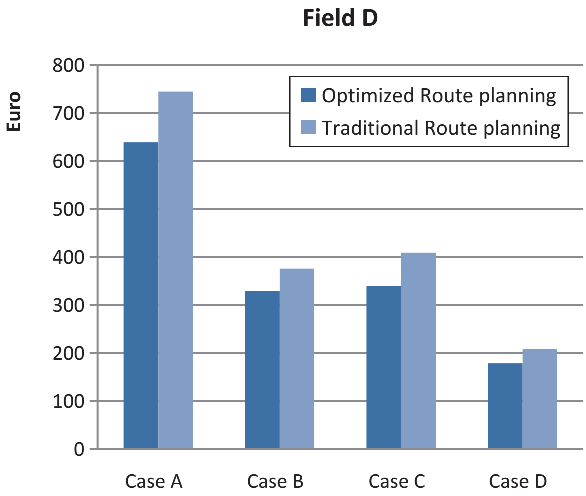

Fig. 6.5 The comparison between traditional and optimized route planning for operational cost (euros) in Field D

Table 6.2 Savings % in operational cost by using optimised route planning in Field A

	Working width (m)	Min turning radius(m)	Savings %
Case A	1.5	3.5	11
Case B	3		9
Case C		5	14
Case D	6		12

Table 6.3 Savings % in operational cost by using optimised route planning in Field B

	Working width (m)	Min turning radius(m)	Savings %
Case A	1.5	3.5	12
Case B	3		11
Case C		5	14
Case D	6		12

Table 6.4 Savings % in operational cost by using optimised route planning in Field C

	Working width (m)	Min turning radius(m)	Savings %
Case A	1.5	3.5	10
Case B	3		9
Case C		5	13
Case D	6		11

Table 6.5 Savings % in operational cost by using optimised route planning in Field A

	Working width (m)	Min turning radius(m)	Savings %
Case A	1.5	3.5	17
Case B	3		14
Case C		5	20
Case D	6		17

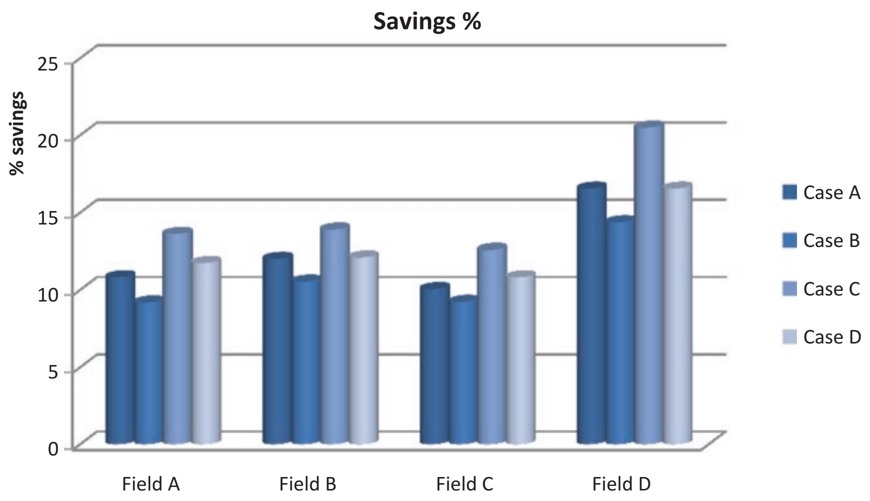

Fig. 6.6 Savings % in operational cost with optimised route planning for the four fields

Regarding the machine capacity the following factors should be taken into account:

- Machinery preparation time in the field before and after field operations without including daily services, lubrication and preparation for towing
- Machinery adjustment time
- Maintenance time (e.g. refueling)
- Operator's personal time

Concerning the implementation of the average of the above factors, a time delay of 1.65 min ha^{-1} (100 s ha^{-1}) was added to the operational time and an addition of 5% dedicated to personal breaks (Sørensen 2003; Sørensen and Nielsen 2005) (Tables 6.6, 6.7, 6.8, 6.9 and 6.10).

Table 6.6 Machine effective capacity for Field A

	Capacity (ha/h)		
	Traditional	Optimised	Increase %
Case A	0.95	1.05	11
Case B	1.90	2.07	9
Case C	1.79	2.03	14
Case D	3.44	3.84	12

Table 6.7 Machine effective capacity for Field B

	Capacity (ha/h)		
	Traditional	Optimised	Increase %
Case A	0.83	0.93	12
Case B	1.63	1.80	11
Case C	1.53	1.74	14
Case D	3.04	3.41	12

Table 6.8 Machine effective capacity for Field C

	Capacity (ha/h)		
	Traditional	Optimised	Increase %
Case A	0.92	1.01	10
Case B	1.83	2.00	9
Case C	1.74	1.96	13
Case D	3.40	3.77	11

Table 6.9 Machine effective capacity for Field D

	Capacity (ha/h)		
	Traditional	Optimised	Increase %
Case A	0.82	0.96	17
Case B	1.63	1.87	14
Case C	1.50	1.81	20
Case D	2.95	3.44	17

Table 6.10 The four machinery cases regarding the power engine

	Size	Power (kw)
Case A	Small	30
Case B	Small-medium	60
Case C	Medium-large	90
Case D	Large	120

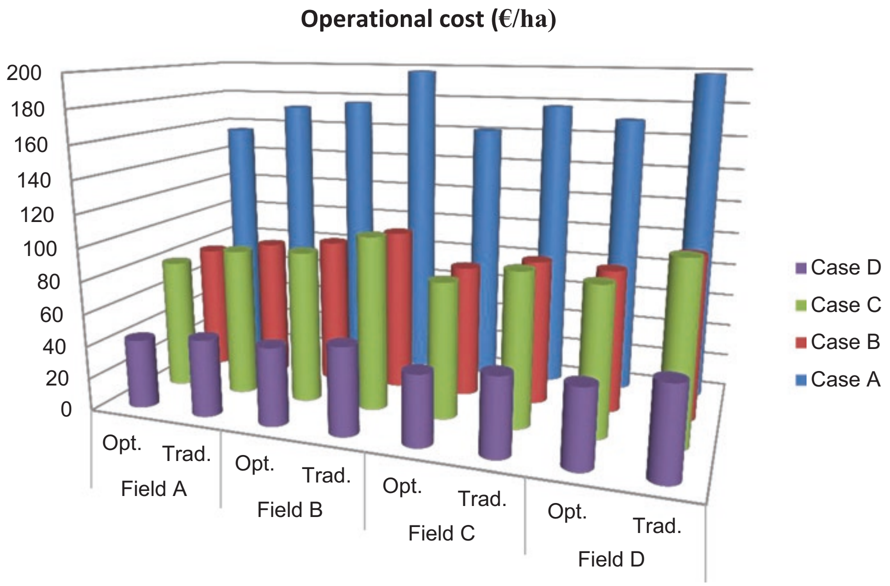

Fig. 6.7 Operational cost in euros/ha for both optimised (opt.) and traditional (trad.) route planning for the 4 fields

In Fig. 6.7 below, the operational cost in euros per ha is presented for both traditional and optimised route planning in the 4 fields examined.

To calculation fuel consumption, the equation given at Agricultural Machinery Management Data, D497.4 (ASAE 2003) was used:

$$2.64X + 3.91 - 0.203\sqrt{738X + 173} \text{ in } \frac{l}{kw \times h},$$

where X is the ratio of equivalent Power Take-Off (PTO) power required by an operation to the maximum available from the PTO. To evaluate an 'average' field operation, X was set to 75% while operating. During turnings X was set to 0% (the PTO was off).

The results that correspond to the above mentioned method of optimisation in fuel consumption is shown in Tables 6.11, 6.12, 6.13 and 6.14 for the examined field areas including the corresponding fuel savings in each case.

In Fig. 6.8, the fuel consumption in litres ha^{-1} is shown for machinery scenarios A-D for the four fields. The introduction of optimised route planning compared to the traditional ones results in reduced fuel consumption for different field sizes and variable field machinery equipment (Cases A–D). Furthermore, in Fig. 6.9, the cor-

Table 6.11 Fuel consumption in liters for traditional and optimised route planning for Field A

	Fuel consumption (l)		
	Traditional	Optimized	Fuel savings %
Case A	90.77	81.91	11
Case B	90.89	83.25	9
Case C	144.29	127.01	14
Case D	100.18	89.66	12

Table 6.12 Fuel consumption in liters for traditional and optimised route planning for Field B

	Fuel consumption (l)		
	Traditional	Optimized	Fuel savings %
Case A	97.79	87.30	12
Case B	99.32	89.85	11
Case C	158.79	139.42	14
Case D	106.49	94.99	12

Table 6.13 Fuel consumption in liters for traditional and optimised route planning for Field C

	Fuel consumption (l)		
	Traditional	Optimized	Fuel savings %
Case A	88.59	80.50	10
Case B	89.32	81.78	9
Case C	141.14	125.36	13
Case D	95.98	86.62	11

Table 6.14 Fuel consumption in liters for traditional and optimised route planning for Field D

	Fuel consumption (l)		
	Traditional	Optimized	Fuel savings %
Case A	65.44	56.14	17
Case B	66.08	57.78	14
Case C	107.88	89.53	20
Case D	73.11	62.73	17

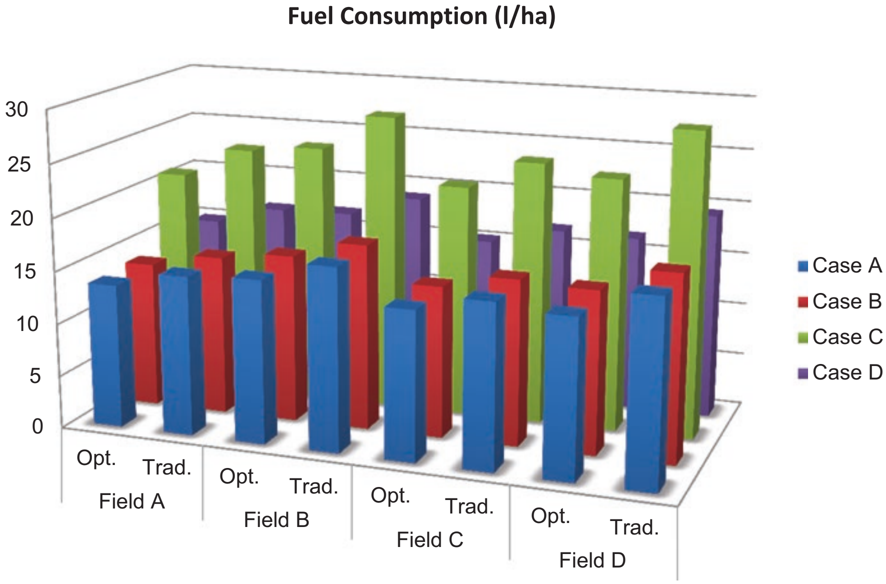

Fig. 6.8 Fuel consumption in litres/ha for both optimised (opt.) and traditional (trad.) route planning for the 4 fields

responding cost in euros from fuel consumption is presented given that the mean diesel fuel price throughout Europe at present is around 1.05 euro litre^{-1}.

6.4 Discussion

From the results above, we can indicate that the operational cost savings by using the optimised route planning are: for Field A the cost savings vary from 9 to14% with the best one in case C, in Field B the cost savings vary from 11 to 14% with the best one in case B, in Field C the cost savings vary from 9 to 13% with the best one in case C and finally in Field D the cost savings vary from 14 to 20% with the best one in case C. Furthermore, an optimised route planning for the Fields A, B, C and D will result in an increase in field machinery capacity of 9–14%, 11–14%, 9–13% and 14–20%, respectively. The results are similar for the reduction in fuel consumption and in fuel cost per ha for the four Fields. In conclusion, there is an immediate connection between the increase in field machinery capacity, the savings in operational cost and the savings in fuel cost.

The results show that in examples with very small or large machinery (case A and case D with corresponding working widths of 1.5 and 6 m, respectively, and corresponding minimum turning radii 3.5 and 5 m, respectively) route planning optimisation provides significant operational cost savings compared to non-optimised routings, thus case A and D provide the largest savings in terms of costs.

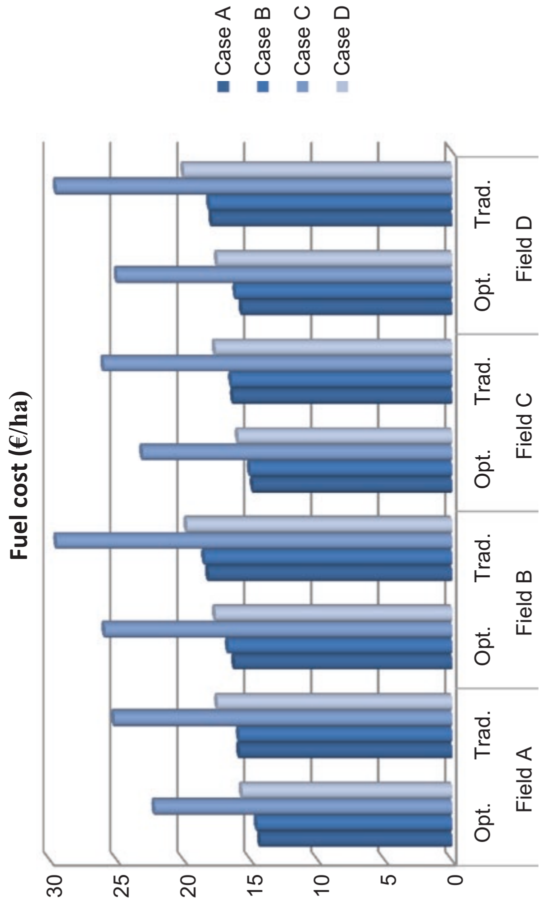

Fig. 6.9 Fuel cost in euros/ha for both optimised (opt.) and traditional (trad.) route planning for the 4 fields

This issue should be studied more extensively, given that even though large machinery is directly connected with large working widths and corresponding large field capacities, nevertheless, the largest increase in field capacity is not presented in case D. The same issue, in reverse, is seen with very small machinery that connects immediately with a small turning radius.

Beyond the benefits of CTF, as mentioned in the introduction section, also CTF has some drawbacks mainly derived from the constraints imposed in the paths that an agricultural machine can follow. This is more evident in the case of material handling operations such as organic fertilizing (i.e. manure application) where there is the need for in-field transport of the machine to refill. When there is no coordination between the length of the fieldwork track and the driving distance corresponding to the application of a full load, the traffic restrictions of the CTF system do not allow for in-field turning of the machine and the machine must drive empty along the remaining part of the field work track. This non-working travelled distance can increase further when the entry and exit locations of the field are not located in the travelling direction of the empty machine. Analogous situations occur when the machine comes back to the field after refilling (e.g. fertilizers) and must travel over a part of a field work track without applying fertilizers in order to reach the location where application may be resumed.

To that effect, in the case of material handling operations, the implementation of the CTF system can reduce the field efficiency of these operations because of the non-productive time spent during the in-field transport. Consequently, planning for field coverage in material handling operations under the CTF path restrictions becomes critical in order to reduce the trade-off in field efficiency. However, the interrelations between the properties of the motion sequences of the agricultural machinery and the configurations of the CTF layout are extremely complex.

Bochtis et al. (2009a) developed a discrete-event model for the prediction of travelled distances of agricultural machines operating in material handling operations in a CTF system. It was proved that the key factor that affects field efficiency in the case of material handling operations, and specifically in the case of organic fertilizing, is the in-field transport distance. Based on experimental results (Bochtis et al. 2010b) in two fields, it was shown that the implementation of CTF instead of the conventional traffic system considerably increases the in-field transport distances. Specifically for the operations examined in two fields, the estimated increase in the transport distance was 47.82% and 24.54% resulting in a reduction of field efficiency of 7.41% and 4.68%, respectively. In another study based on a simulation model, it was also shown that the implementation of the CTF system increases the operational time by up to 5%, resulting in a decrease in the field efficiency in the range of 11.52–8.25% (Hameed et al. 2012).

The route optimization described improves the field efficiency of material handling operations by minimizing the various non-productive travelled distances. However, the prerequisite for this minimization is the operational analysis for identifying the activities, the actions and their interconnections that contribute to the reduction of the efficiency (Jensen et al. 2015b). An approach on this minimization problem has been presented recently by Jensen et al. (2015a) based on the statespace search technique where the solution of the problem is a sequence of predefined driving actions that transform the initial state to a goal state under the criterion of minimizing the in-field non-working travelled distance. In the specific approach, the sequence of the working tracks is optimised in a post-process where the travelling salesman problem methodology (Hoffman et al. 2013) is applied to minimize the non-working distance travelled while turning at headlands. Results showed that by implementing the travelling salesman approach for the field coverage optimisation the savings achieved in the non-working travelled distance (including both in-field transports and headland turning) amounted to 15.7%, 43.5% and 23% for the three fertilizing operations examined. These numbers correspond to savings in the total travelled distance of 5.8%, 11.8% and 11.2%, respectively.

Another critical factor that can affect the field efficiency of the operations in the CTF system is the direction of the field work tracks in relation to the field shape, since a long-term configuration must be determined. When considering the field work tracks direction, however, the entire set of operations executed in the field has to be taken into consideration. Bochtis et al. (2010a) presented an approach to estimate the operational machinery costs in the CTF system based on a number of sub-models to evaluate the consequences, in terms of machinery performance, for different potential driving directions in a field when establishing the permanent fieldwork tracks. The approach takes into account the non-working distance travelled during the headland turnings, the in-field travelling distance for the case of the material handling operations, and moreover, the cost of lost material resulting from overlaps in the area covered. The most important result of this study was the conclusion that the rule prevailing in the conventional traffic system that the optimal driving direction is the one parallel to the longest edge of the field does not apply in the CTF system. For example, in the case of a specific field the annual cost of machinery operation decreased by 9% when the direction of the field work tracks was the one parallel to the shortest edge of the field. This is a result of various factors including the area overlapped in spraying and seeding, the unloading times in harvesting, the in-field transport in material handling operations and the non-working distance during headland turnings. Overall, the benefits from optimized route planning provide cost savings in the range of 9–20% and increased field machinery capacity also ranging from 9 to 20%. In the case of material handling, implementation of the CTF system increases operational time by up to 5% and reduces the field efficiency from 8 to 11%. The benefits mentioned can be obtained by implementing the route planning software, either as a manual decision support system or directly coupled to the auto guidance system.

6.5 Conclusion

Navigation systems and field machinery automation systems such as auto steering guidance and field management systems such as Controlled Traffic Farming that are used in modern agriculture have been assessed in this chapter for different machinery configurations. Traditional and optimised route planning systems have been compared in four different field areas. Considerable savings in operational and in fuel costs of up to 20% in optimised route coverage system were observed. Specifically, the cost savings ranged from 9 to 20% with an associated increase of the machinery capacity in the same range. Disadvantages from introducing CTF in the case of material handling include up to 5% increase in operational time and a reduced field efficiency of 8–11%. The benefits mentioned can be obtained by implementing the route planning software, either as a manual decision support system or directly coupled to the auto guidance system. These results could be examined further through extended research and experimentation in route planning design not only under the criterion of reduction of operational cost, but also under other environmental criteria, such as reduction of energy consumption and or a reduction of CO_2 emissions. The benefits that are quite significant, as described above, and thus this solution could play and important role in the criterion of minimizing the operational cost and time.

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