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Analysis of energy requirements for field cover

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The presented material provides consideration of reduction of the energy needs received as a result of introduction of the optimized planning of a covering of the areas. This paper presents an assessment of the reduction of energy needs that arises as a result of the introduction of optimization of coverage of field areas. The assessment concerns the analysis of energy needs and the comparison between non-optimized and optimized plans to cover the field area in the whole sequence of operations required in two different sowing systems: Miscanthus and Svitgrass production. An algorithmic approach for modeling field operations is developed, following both non-optimized and optimized samples of fieldwork. As a result, the corresponding time needs were assessed as a basis for further energy cost analysis. Based on the results, optimized routes reduce fuel energy consumption to 8 %, embodied energy consumption to 7 %, and total energy consumption from 3 % to 8 %. The methodology for assessing energy needs can be used in both food production systems and biomass production systems as a decision support system for the location of the machine system, as well as the choice of field coverage practices to achieve minimum energy consumption combined with minimum time. This study shows the minimum level of energy savings for specific crops, given that the forms of the physical field may be more complex than those presented here. The results of this study show a higher perspective of modern sustainable agricultural systems through the use of optimized field coverage. Algorithms such as those presented in this study can be applied to on-board systems of agricultural machinery, minimizing real-time energy costs and operational requirements.

Keywords*: energy needs sown areas, estimation, cost reduction, modelling, optimization.*

Formulation of the problem. Various types of sensors technologies, such as machine vision and global positioning system (GPS) have been implemented in navigation of agricultural vehicles. Automated navigation systems have proved the potential for the execution of optimized route plans for field area coverage. This paper presents an assessment of the reduction of the energy requirements derived from the implementation of optimized field area coverage planning. The assessment regards the analysis of the energy requirements and the comparison between the non-optimized and optimized plans for field area coverage in the whole sequence of operations required in two different cropping systems: Miscanthus and Switchgrass production. An algorithmic approach for the simulation of the executed field operations by following both non-optimized and optimized fieldwork patterns was developed. As result, the corresponding time requirements were estimated as the basis of the subsequent energy cost analysis. Based on the results, the optimized routes reduce the fuel energy consumption up to 8 %, the embodied energy consumption up to 7 %, and the total energy consumption from 3 % up to 8 %.

Analysis of recent research and publications. The satellite system GNSS (Global Navigation Sate lite System) is used to pinpoint the geographic location of abuser's receiver anywhere in the world. The main GNSS systems that are currently in operation are the Global Positioning System (GPS), the Global Orbiting Navigation Satellite System (GLONASS) and the Galileo. Each of these systems employs a group of orbiting satellites working in connection with a network of ground stations. In modern agriculture, automation systems are part of any kind of agricultural machinery and agricultural vehicles (tractorsandself-propelledmachines).

Various types of technologies, such as machine vision and satellite systems as GPS, have been implemented in navigation of agricultural vehicles [1–6]. The fully automated auto-steering systems are capable of driving the agricultural vehicle either in a straight or in a curved line over the field area with a lateral accuracy of a few centimeters when making use of highly accurate real-time kinematic (RTK) GPS receivers. Auto-steering systems based navigation can apply in any field operation, including planting, cultivating and harvest [7]. The position information from RTK GPS systems can be used not only for guidance but also for other applications such as seed mapping, controlled traffic, and controlled tillage [8].

The purpose of the article. The estimation of energy costs in planning different routes of field cover during sowing is considered. The most up-to-date topics in the field of energy resource conservation are raised. The article is original and useful for the future.

Basic research materials. Automated navigation systems have also provided the potential for the execution of optimized route plans for field area coverage. In the non-optimized practice of covering a field area, the route of an agricultural vehicle consists of a series of back-and-forth repetitions that follow a standard motif, such as, for example, to always enter the adjacent fieldwork track of the one that has been worked. On the other hand, optimized field area coverage provides routes that cannot be executed without the implementation of navigation-aiding systems. Recently, a number of route planning methods for field area coverage have been developed [9–17]. Biochips and Sorensen showed the potential of the vehicle routing problem (VRP) application and agricultural vehicles area coverage planning [12]. The implementation of the approach in field operations executed by conventional agricultural machines equipped with auto-steering systems has reduced the total non-working travelled distance up to 50 %, as it has been experimentally shown [18]. This optimized new type of fieldwork patterns, called B-patterns, is defined as: «algorithmically-computed sequences of field-work tracks completely covering an area and that do not follow any pre-determined standard motif, but in contrast, are a result of an optimization process under one or more selected criteria» [19]. An example of the optimization of route planning compared to the non-optimized for two operating widths (6 m and 12 m) is presented in Fig. 1.

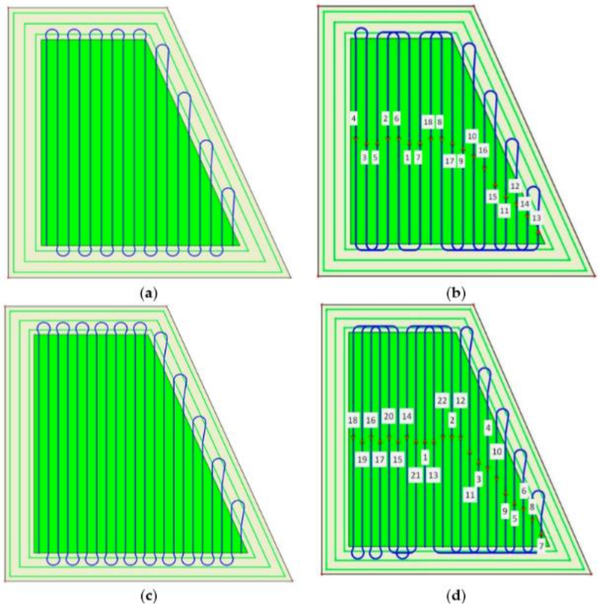

Figure 1. Non-optimized ((a) (non-optimized route) and (c) (non-optimized route)) and optimized ((b) (optimized route) and (d) (optimized route)) route planning for 14m (a, b) and 12m
(c, d) operating width

The benefits from B-patterns are significant reductions in non-working distance and increases in the area capacity compared to different types of non-optimized fieldwork patterns. The optimal route planning may focus on one or more optimization criterion such as, totalornon-workingdistance, total operational time, and so forth [20, 21], and it is directly connected with operating width and the minimum turning radios of the agricultural vehicle. The benefits from optimal route planning are directly correlated to fuel consumption and field machinery use. As a direct consequence, there is an energy cost reduction in the field operations when implementing optimized fieldwork patterns. The objective of this paper is to provide an assessment of the reduction of the energy requirements derived from the implementation of B-patterns. The assessment regards the analysis of the energy requirements and the comparison between the non-optimized and optimized plans for field area coverage in the whole sequence of operations required in a cropping system. Two cropping systems have been selected, namely, Miscanthus (Miscanthus×giganteus) production and Switchgrass (*Panicum virgatum*) production.

The structure of the present work is as follows: initially, a presentation of the methodology in terms of the main input parameters and the design of the assessment approach is introduced. This is followed by the results section, where two case scenarios are provided together with the energy cost analysis of the presented case studies. The paper wraps up with the discussion of the results.

The assessment is based on the savings in time requirements, including both working time and non-working time from the implementation of the optimized field-work-patterns, which result in savings in energy consumption compared with the non-optimized field-work patterns. This assessment does not include operations with coupled machines, where a primary unit has to be supported by a secondary unit as a service unit (for example, the harvesting tractor-wagon set). In the present study, for the harvesting operation, it is considered that the harvester has an on-board wagon to deliver the harvested material. The assessment of this study is based on combinations derived from the consideration of five field shapes, one type of non-optimized field-work pattern (AB-pattern: from A track line to B track line, and so on), two cropping systems case studies, and various combinations of implement operating widths and minimum turning radii.

For the abovementioned assessment the following assumptions have been considered:

- The covering of the headland area has been excluded from the comparison, and only the covering of the main field area has been considered.
- All the operations are executed continuously without any load capacity restriction.
- During the turnings the fuel consumption is considered to be the same as the one during the operation.

- The energy consumption for the material transportation is not considered in the comparison.
- The energy consumption for the machinery transportation from farm to field is not considered in the comparison.
- It has been considered that the field entrance can be anywhere in the field boundary.

For the investigate ion of the effect of the field shape on the energy savings, a set of template fields of the same area (10 ha) and different template shapes (Figure 2) that are representative for typical fields were selected [22].

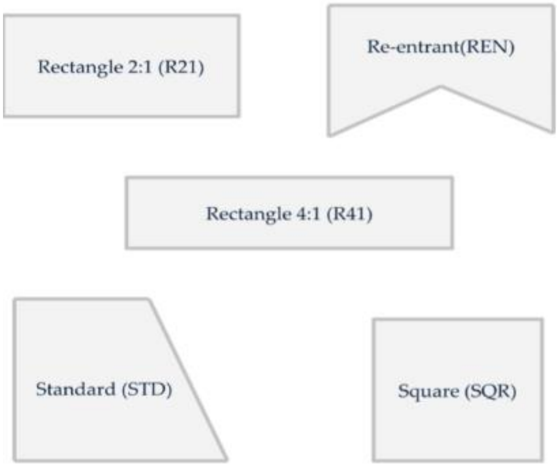

Figure 2. Representative template field shapes

This assessment was run in two energy crops as case studies, namely, CS1 for Miscanthus crop and CS2 for Switchgrass crop, in order to compare the results and evaluate the methodology under different crop production requirements. Both crops were evaluated for the basic in-field operations that are normally applied.

Miscanthus cultivation does not require any special soil management [23, 24]. Thus, a light ploughing up to 20 cm in depth and a disk harrowing were considered as the basic soil preparation operations. Afterwards and before the establishment of the crop, it is important to carry out weed control thoroughly to minimize weed competitiveness. After that, there is no need for weed control since the crop can protect itself from the weeds. Here, a single herbicide application has been considered as a pre-planting weed control. Given that Miscanthus is planted by rhizomes, a planter similar to the potato seed planter can be adopted for the planting operation. Irrigation should be applied in parallel with rainfall but it is beyond the scope of the current study. Miscanthus does not have high nutrient requirements since the crop itself can absorb most of the required nutrients from the soil. However, it has been reported that the addition of 50 kg N, 21 kg P_2O_5, and 45 kg K_2O per ha per year are sufficient to support adequate yields [25]. This fertilizers' allocation has been implemented in this study. Harvesting of the crop usually occurs every year, starting from the second year. It is usually carried out by using conventional forage harvesters for cutting and chopping the biomass.

Regarding Switchgrass, seedbeds are normally prepared by traditional ploughing and secondary cultivation processes. Here, ploughing and disk harrowing were considered for the soil preparation. During the first growth, it is crucial for the seedbed to be thoroughly weed controlled given that the crop is not competitive during the first establishment phase [26]. For this, a pre-seeding herbicide control was considered. Switchgrass is established by seed. As in the case of Miscanthus, apart from rainfall, irrigation is important but is not included in the presented study's scope. Switchgrass can provide high yields even under limited fertilization of 75 kg $N\cdot ha^{-1}$ [27]. In the establishment year, no nitrogen should be applied, as it can promote weed growth leading to competition against the new plants. Phosphorus and potassium should be applied only if soil availability is low. In the following years, the application of nutrients should be at a levelthatanticipatesrisingproductivity [23]. Switchgrass's growth is slow in the first year and there is a negative competition with weeds. For this reason, Switchgrass requires weed control both before the establishment and for the next two years. Regarding harvesting, there is no technical reason for the crop not to be cut and harvested by conventional grass harvesting machinery [26]. Before the forage harvester operates, a mower is considered in order to allow to the mowed plants to have adequate time to dry during winter [26].

Based on the operational requirements for the execution of each of the operations included in the abovementioned cropping systems, three different sizes of tractors varying in machine power, weight, productivity, and maneuverability (minimum turning radius) were used. More specifically, after extensive research on technical machinery features of different commercial models of tractors, a large-size tractor unit with a 6 m minimum turning radius, a medium-size tractor unit with a 4.5 m minimum turning radius, and a small-size tractor unit with a 3 m minimum turning radius, were selected as representative for the presented assessment. Variable operating widths were considered for the execution of the field operations in the two case studies. The combinations of operating width and turning radius for each executed field operation of the two case studies are presented. The considered combinations were symmetric excluding those that regard (I) small units connected to large operating widths, given that a small unit cannot provide the required power for a large operating width, and (II) large units combined with very small operating widths. It is worth noting that in the case of ploughing, a modified formulation of the optimization problem of the one presented in [18] has been considered, that takes into account the operational restrictions of ploughing operation. In particular, the operational restriction derived from the requirements for an even field surface generation regards the turning over of the mounted moldboards in the reversible plough each time the working direction changes.

The energy inputs that directly or indirectly connected with the agricultural machinery use are shown. The diesel energy coefficient that corresponds to the chemical energy of diesel is equal to 41,2 MJ·L^{-1} [28]. This coefficient is recommended for the United Kingdom and has been adopted for Europe because of the shorter distance that crude oil is transported from the Middle East. It includes crude oil energy content, production energy consumption, shipping energy consumption, and refining/distribution energy consumption. For the estimation of fuels energy cost, the diesel energy coefficient, the operational capacity extracted from the time requirements, the tractor power rand the Equation (1) from American Society of Agricultural and Biological Engineers (ASABE) standards for fuels consumption estimation (in L·(kW·h)$^{-1}$ were taken into account.

$$2.64 \times \mathrm{X} + 3.91 - 0.203 \times \sqrt{738 \times \mathrm{X} + 173} \qquad (1)$$

Where X is the ratio of equivalent power take-off (PTO) power required by an operation to the maximum available power from the PTO [29, 30]. Here, X is adopted to be equal to 0,55 for all types of tractors.

The assessment model is presented in Figure 3. The process is as follows: generation of the non-optimized field-work pattern; generation of the optimized field-work pattern; simulation of the operations following the non-optimized field-work pattern; simulation of the operations following the optimized field-work pattern, and; comparison of their results. Firstly, the estimation of the headland width and the corresponding number of headland passes was taken into account based on the implement's operating width, the turning radius and the unit's dimensions. The geometrical representation of the fields was created given the artificial coordinates of the field boundary and the number of headland passes. As a result, the coordinates of the field-work tracks were generated. In a second phase, for the estimation of the paths that connect each possible pair of tracks, the same path planning procedure was followed in order to produce the energy consumption table of the optimization problem. The problem was solved by applying the Clarke and Wright savings algorithm and, consequently, the optimized field-work pattern was generated [33]. The tracks sequence of the non-optimized AB field coverage was created given its geometrical field representation and mathematical description. Then the simulation of both non-optimized and optimized field-work patterns was implemented.

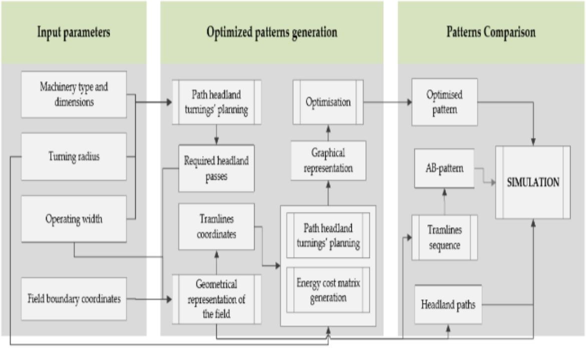

Figure 3. The assessment model structure

Results and Discussion. The current study regards the effect of the field shape on the execution time of each operation of the two case studies, including the effective and the non-working time. Both the non-optimized and the optimized field pattern scenarios where assessed and they are presented in the regarding the considered field operations of the two case studies. The time requirements in minutes are provided in order to demonstrate the timesaving's per operation. In Figure 4, the total time requirements for the different field shapes of the two case studies, including both non optimized and optimized field route planning, are shown.

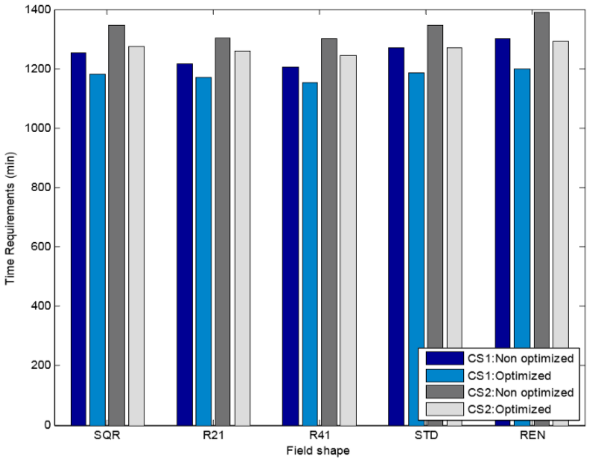

Figure 4. Total time requirements for each field shape (CS1: Miscanthus; CS2: Switchgrass)

Given the abovementioned time requirements results per operation, the field area capacity (Ha·H^{-1}) can be obtained for each operation of the two case studies. For the energy cost analysis,

Several studies have been conducted, pointing out the most important energy factors in single-crop production systems [23, 34, 35]. For the estimation of the energy cost of a crop, many energy inputs and other agronomical related inputs are taken into account, such as field machinery and implements inputs (such as fuels and lubricants energy, embodied energy, weights, estimated lives), operation-related inputs (operating width, turning radius, area capacity) and agrochemical material-related inputs(such as applied dosages of fertilizers and agrochemicals). In the current study, the energy cost parameters are connected to fuels energy and field machinery embodied energy. The material-related energy consumption is not included in this study, given that this study focuses on energy savings that are directly or indirectly associated with field machinery.

The fuel energy saving (%) the optimized field-work pattern is used instead of the non-optimized for the corresponding field operations of the two case studies for the five different field shapes are presented. The energy savings are related to the non-optimized fieldwork pattern. In Figure 5, the total energy savings (%) by fuels consumption is presented for the different field shapes.

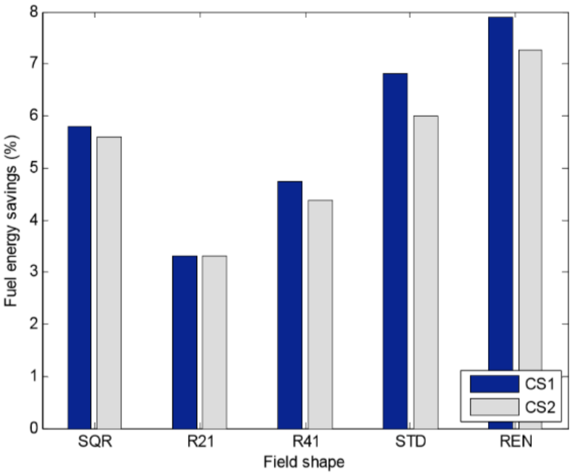

Figure 5. Savings (%) in fuel energy consumption in the optimized case studies

Regarding the second most important energy cost parameter estimation, that is, the field Machinery embodied energy, the factors that are included are the operational capacity, the total embodied energy of the tractor and its implement over their whole lifetime(in MJ), their estimated lifetimes, and their weights. Given these, the corresponding energy consumption of both tractor and implement for the total operational time were estimated for both non-optimized and optimized field-work patterns in the five different field shapes. The energy savings (%) from machinery embodied energy by following the optimized field-work pattern in the five different filed shapes for both case studies is demonstrated. The energy savings are related to the non-optimized fieldwork pattern. In addition, the energy savings (%) from machinery embodied energy including all the operations per field shape in both case studies are presented in Figure 6.

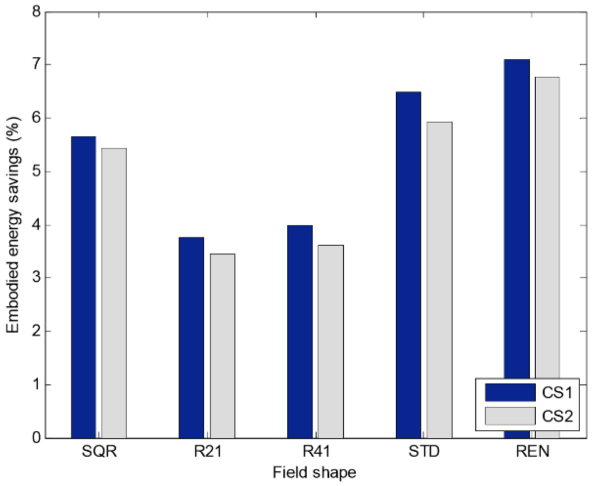

Figure 6. Embodied energy savings in the optimized case studies

It should be highlighted that this study focuses only on the most significant energy consumption factors as they have already mentioned above. Other less significant factors such as lubricant energy cost contribute much less to the total energy consumption. It should be mentioned, also, that each of these energy inputs contributes under different impact factor to the total energy cost savings results. In Figure 7 the total energy savings (%), including all the field operations by using the optimized field-work pattern in the five field shapes for both case studies, are shown.

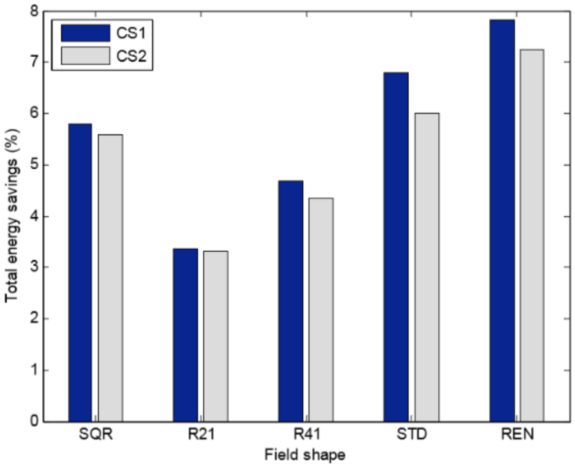

Figure 7. Total energy savings in the optimized case studies

The assessment of the energy cost savings for the two case studies has been based on specific machinery systems in terms of operating width and minimum turning radius. The selection of these machinery systems was based on the optimum combination tractor size and equipment for each specific field operation requirements. However, in real-life cases the implemented machinery systems in various operations are the ones that are available in the farm and in the majority of the cases is not the optimum selection in terms of machinery size. The effect of the different tractor sizes (S: Small-sized tractor (up to 50 kW); M: Medium-sized tractor (up to 120 kW), and; L: Large-sized tractor (up to 180 kW)) on the total energy savings (%) in the optimized scenarios is presented in Figures 8 and 9, for the CS1and CS2, respectively.

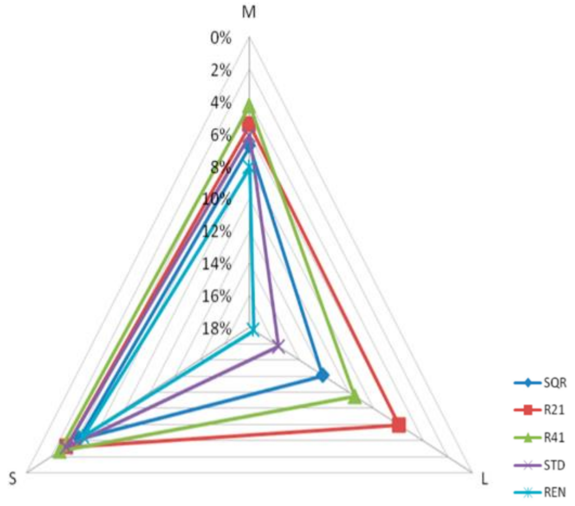

Figure 8. Energy savings (%) for different tractor sizes in CS1 (case study 1)

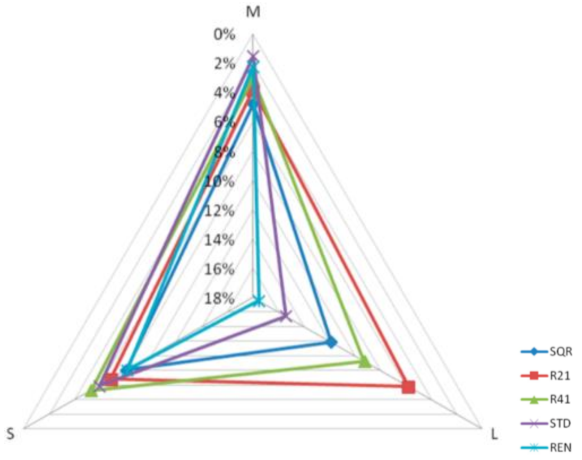

Figure 9. Energy savings (%) for different tractor sizes in CS2 (case study 2)

The selection of the size of the combination tractor-machinery is directly connected to the minimum turning radius and the operating width that are used in any specific field operation. In cases where the selection of machinery size is not optimum, the energy savings when optimized plan is applied can be up to 18 %.

Conclusion. An assessment on the energy savings by applying optimized fieldwork patterns in field machinery operations was presented in this paper. A comparison between the most widely implemented non-optimized fieldwork pattern (AB-pattern) and an optimized one (B-pattern) was presented under the criterion of time requirements, which is the basis for the subsequent energy cost analysis. The energy cost analysis for both fieldwork patterns demonstrated a reduction in the operational energy requirements in the range of 3–8 % when optimized route planning is implemented. In this paper, the field operations that are connected to the soil preparation before the establishment of the crop are executed continuously with no need for a time interval. By this way, the possibility of weed growth before the establishment of the crop or during its first growth is quite low. If disc harrowing is operated with a significant time interval after ploughing, the possibility of weed growth becomes higher because of the possible open furrows into the field due to the optimized fieldwork pattern with subsequent damage to the early growing plants. In order to avoid this, it is better either not to implement the optimized fieldwork pattern in case there is no direct soil cultivation operation, or avoid execution of ploughing at all. By excluding ploughing from the energy cost analysis and including only disc harrowing for soil preparation, the results on the energy consumption savings will be 3,2–7,2 % for CS1, and 3,2–6,5 % for CS2 for the different field shapes.

The energy requirements evaluation methodology can apply in both agri-food production systems and biomass production systems as a decision support system for machinery system dimensioning, and the field area coverage practice selection for achieving the minimum energy cost in combination with the minimum time cost. This research shows minimum level of energy savings for the specific crops given that physical field shapes may be more complex than those presented here. The results of this study show the higher perspective of modern sustainable agricultural systems by using optimized field coverage. Algorithms such the one presented in this study may have application on on-board GNNS systems of agricultural machinery minimizing in real time the energy cost and the operational capacity requirements [36].

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Анотація

Аналіз енергетичних потреб при покритті польових площ

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Викладений матеріал передбачає розгляд зменшення енергетичних потреб, отриманих в результаті впровадження оптимізованого планування покриття площ. У цій роботі представлена оцінка зменшення енергетичних потреб, що виникає в результаті впровадження оптимізації охоплення польових територій. Оцінка стосується аналізу енергетичних потреб та порівняння між неоптимізованими та оптимізованими планами покриття площі поля у всій послідовності операцій, необхідних у двох різних системах посіву: виробництві Miscanthus та Svitgrass. Розроблено алгоритмічний підхід для моделювання виконуваних польових операцій, дотримуючись як неоптимізованих, так і оптимізованих зразків польових робіт. Як результат, відповідні потреби у часі були оцінені як основа подальшого аналізу витрат енергії. На основі результатів, оптимізовані маршрути зменшують споживання енергії палива до 8 %, втілене споживання енергії до 7 %, а загальне споживання енергії з 3 % до 8 %. Методологія оцінки енергетичних потреб може застосовуватися як у системах виробництва харчових продуктів, так і в системах виробництва біомаси як система підтримки прийняття рішень для розміщення системи машин, а також вибір практики охоплення польових територій для досягнення мінімальних витрат енергії в поєднанні з мінімальними витратами часу. Це дослідження показує мінімальний рівень економії енергії для конкретних сільськогосподарських культур, враховуючи, що форми фізичного поля можуть бути складнішими, ніж представлені тут. Результати цього дослідження показують вищу перспективу сучасних стійких сільськогосподарських систем завдяки використанню оптимізованого охоплення полів. Алгоритми, такі як представлені в цьому дослідженні, можуть застосовуватись на бортових системах сільськогосподарської техніки, мінімізуючи в реальному часі енергетичні витрати та вимоги до експлуатаційної потужності.

Ключові слова: *енергетичні потреби, посівні площі, оцінка, зменшення витрат, моделювання, оптимізація.*

Аннотация

Анализ энергетических потребностей при покрытии полевых площадей

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Изложенный материал предполагает просмотр уменьшения энергетических потребностей, полученных в результате внедрения оптимизированного планирования покрытия площадей. В этой работе представлена оценка уменьшения энергетических потребностей, возникает в результате внедрения оптимизации охвата полевых территорий. Оценка касается анализа энергетических потребностей и сравнения между неоптимизированными и оптимизированными планами покрытия площади поля во всей последовательности операций, необходимых в двух разных системах посева: производстве Miscanthus и Svitgrass. Разработан алгоритмический подход для моделирования выполняемых полевых операций, соблюдая как неоптимизированных, так и оптимизированных образцов полевых работ. Как результат, соответствующие потребности во времени были оценены как основа дальнейшего анализа затрат энергии. На основе результатов, оптимизированные маршруты уменьшают потребление энергии топлива до 8 %, воплощенное потребления энергии до 7 %, а общее потребление энергии с 3 % до 8 %. Методология оценки энергетических потребностей может применяться как в системах производства пищевых продуктов, так и в системах производства биомассы как система поддержки принятия решений для размещения системы машин, а также выбор практики охвата полевых территорий для достижения минимальных затрат энергии в сочетании с минимальными затратами времени. Это исследование показывает минимальный уровень экономии энергии для конкретных сельскохозяйственных культур, учитывая, что формы физического поля могут быть более сложными, чем представленные здесь. Результаты этого исследования показывают высокую перспективу современных устойчивых сельскохозяйственных систем благодаря использованию оптимизированного охвата полей. Алгоритмы, такие как представленные в этом исследовании, могут применяться на бортовых системах сельскохозяйственной техники, минимизируя в реальном времени энергетические затраты и требования к эксплуатационной мощности.

Ключевые слова: *энергетические потребности, посевные площади, оценка, уменьшение расходов, моделирование, оптимизация.*

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