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Research Paper

Optimisation of the harvesting time of rice in moist and non-moist dispersed fields

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Optimisation of the harvesting time of rice is significant for wheat growth and reducing the operational cost of harvesting rice in wheat-rice rotation regions. In China, rice grows in discontinuous and dispersed fields, and it is harvested with combine-harvesters provided by an agricultural machinery cooperative. The dispersed fields are divided into two types, moist and non-moist. The moist fields can be harvested only by a crawler-harvester, and the non-moist farmlands can be harvested by a crawler-harvester or a wheeled harvester. The objective of the agricultural machinery cooperative is to minimise the harvesting time of the rice. Minimising the differences in the operational time between different types of combine-harvesters is constrained. In this study, we proposed an operational model that considers using two different types of combine-harvester to harvest rice in dispersed fields with different soil moisture levels. Three versions of this operational model were derived for different types of farmland. Actual data from a village in Bengbu city were used to parameterise the model. The results indicate that optimisation significantly decreased the harvesting time of rice. The characteristics of the operational time of combine-harvesters are discussed separately to promote the efficient use of combine-harvesters.

1. Introduction

In rice-wheat rotation regions, reducing the harvesting time of rice significantly increases the period during which wheat can be sown. A wider sowing window for wheat can have a large effect on wheat growth (Timsina & Connor, 2001; You, Rosegrant, Wood, & Sun, 2009); for example, tillering and grain yield of wheat are affected by sowing date (Sun, Shao, Chen, Wang, & Zhang, 2013). A wider sowing window for wheat could be used to select the optimal growth and weather conditions for sowing (Tewari & Singh, 1995; Xia, Yin, & He, 2006). Optimisation of the harvest schedule can also significantly decrease the operational cost (Bochtis et al., 2010). In this study, we focused on a scientific management method to reduce the rice harvesting time in a rice-wheat rotation region.

In the study area (the middle and lower reaches of the Yangtze River, China), the altitude of the farmlands varies by region (usually because of the presence of a village) because of their different geographical positions (Xiang, Jin, Du, Sun, & Zhou, 2015). During the rice harvest season, a large variation in soil moisture occurs because of variations in the rainfall in October and the altitude of the various farmlands. Therefore, we can define two types of farmland for rice production associated with moist and non-moist fields at harvest. Moist

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Nomenclature

V	The node set of graph G
A	The arc set of graph G: $A = \{(i, j){:}0 \le i,\ j \le n, i \ne j\}$
N	The set of fragmental farmlands presented by $N = \{1, \ldots, n, \ldots\}$
K	The set of combine-harvesters presented by $K = \{1, \ldots, k, \ldots\}$
P	The set of trips presented by $P = \{1, 2, \ldots, p\}$
M	The set of types of combine-harvester, where $M = \{1,2\}$. A crawler-harvester is represented by 2, and a wheeled-harvester is represented by 1
S_m	The number of m type of combine-harvesters, presented by $K = \{S_1, S_2, \ldots, S_m\}$
I_1	The set of moist fields
I_2	The set of non-moist fields
T	The length of working day (h)
v_{k_m}	The harvesting speed of the combine-harvester k whose type is m (ha h^{-1})
t_{k_m}	The travelling speed of the combine-harvester k whose type is m (km h^{-1})
c_{ij}	The distance between different nodes, representing the distance of sending a combine-harvester from i to j (km)
a_i	The area of the fragmental farmland i (ha)
α	Threshold of the harvesting time difference between a combine-harvester k and the average harvesting time for all combine-harvesters
$x_{ijp}^{m_k}$	binary variable assigning the combine-harvester m_k to an arc (i, j) in trip p.
x_{ijp}^{k}	binary variable assigning the combine-harvester k to an arc (i, j) in trip p.

fields can only be harvested by a crawler-harvester, for example, a Kubota 4LZ-4(PRO988Q), because the soil has high water content. The non-moist fields can be harvested with a wheeled harvester, for example, a Foton Lovol GE20D, or a crawler-harvester. This phenomenon is widespread in the middle and lower reaches of the Yangtze River, China. The fields in Anhui province are small (the cultivated area per capita is 0.147 ha in Anhui province), fragmented and dispersed (Anhui Statistical Yearbook, 2015; He, Li, & Wang, 2018). The average family size is 3.08 people in Anhui province (China Statistical Yearbook, 2015). Each family contract 0.453 ha of dispersed fields. Meanwhile, the agricultural income of rural residents is about 6275 CNY in Anhui province (Anhui Statistical Yearbook, 2015). The price of combine-harvester is approximately 80,000 CNY, which is hardly affordable by the average family. Rice is therefore harvested by combine-harvesters organised by agricultural machinery cooperatives in the area. Rice harvest scheduling is complex because the fragmented fields are geographically dispersed and their moisture characteristics vary.

Because of the complexities of rice harvesting, rice harvest planning is done by the agricultural machinery cooperative, but such planning has not satisfactorily reduced the rice harvesting time. Decisions made on a scientific basis can be an effective means of increasing the efficiency of agricultural production (Amiama, Cascudo, Carpente, & Cerdeira-Pena, 2015; Behrendt, Cacho, Scott, & Jones, 2016; Le Gal, Lyne, Meyer, & Soler, 2008; Põldaru & Roots, 2014; Shrestha, Asch, Dingkuhn, & Becker, 2011). Scientific harvest planning rather than just using farmer experience is necessary for rice fields with different moisture levels. Optimal harvest planning is important to reduce the harvesting time. In large-scale farming regions, a rice harvest simulation has been used to optimise the routing of a combine-harvester (Busato, 2015; Lee, Kim, & Kim, 2016; Sahoo & Panda, 2014). Sugar cane and biomass have been cooperatively harvested with a combine-harvester with reasonable harvesting routing (Bochtis et al., 2013; Edwards, Sørensen, Bochtis, & Munkholm, 2015; Salassi, Breaux, & Naquin, 2002). In large-scale farmlands, the manpower cost has been optimised for rice harvest (Busato & Berruto, 2016). These previous studies have not considered fragmented farmlands, however. In addition, the difference between moist and non-moist fields has not been considered in previous studies. In this study, an operational model for rice harvesting was built considering different rice fields, and was used to reduce the harvesting time of rice planted in different types of farmland.

Experience indicates that the operational time for different combine-harvesters varies in harvest planning (He et al., 2018; Li, Rodriguez, Zhang, & Ma, 2015). Conflicts occur among different combine-harvester drivers because their revenue is affected by the combine-harvester's operational time. This problem cannot be solved by past experience. The operational time should be constrained to provide similar working time for the different combine-harvester drivers. In this study, we proposed an operational model for rice harvest scheduling. The problematic aspects of rice harvesting were:

1. The operational model focused on the rice harvest difficulties in fragmented farmlands.
2. Both moist and non-moist farmlands were considered. Moist farmlands can be harvested only with a crawler-harvester. Non-moist farmlands can be harvested with a crawler-harvester or a wheeled harvester.
3. A minimal harvest time of rice was considered.
4. The harvesting operational time for different combine-harvesters must be similar.

In this study, we proposed a 0–1 integer programming model for the rice harvest scheduling problem that took the actual conditions in rural China into account. The objective of this model was to minimise the harvest time of rice. Three versions of the operational model that focused on different circumstances were considered. The Huaguang village located in the middle and lower reaches of the Yangtze River is one of the major regions for rice planting in China. The farmlands in the Huaguang village are fragmented, of small area and a mixture of moist and non-moist, based on our investigation. So, to demonstrate the applicability of the proposed model in this study, we considered a case study based on Huaguang village. The village (located in Bengbu city, China) contained 13.11 ha of fragmental farmlands and two combine-harvesters. Shaonuo 9714 (a cultivar of rice in China) were planted on all fields of the village. The optimal harvesting