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SYNCHRONIZATION SCHEDULING OF MOBILE GRADING AND PRECOOLING RESOURCES BASED ON MULTI-OBJECTIVE OPTIMIZATION

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Abstract. *This study aims to reduce quality losses of fresh fruits and vegetables during the post-harvest stage by synchronically scheduling two kinds of preprocessing resources. A multi-objective model is formulated for the synchronization scheduling of mobile grading vehicles and mobile precooling vehicles to minimize the total operating costs and minimize the maximum precooling delay time. An improved Non-dominated Sorting Genetic Algorithm II (NSGA-II) that considers temporal-spatial distances is developed to solve the problem. The performance of the algorithm is tested by comparing its solution results with those of the standard NSGA-II. Results show that the algorithm in this paper outperforms standard NSGA-II in terms of solution quality and solution time. The case study of post-harvest blueberries further verifies the effectiveness of the proposed model.*
Keywords: Mobile grading and precooling, Synchronization scheduling, Multi-objective optimization, Non-dominated Sorting Genetic Algorithm II

1. **Introduction.** In recent years, more and more small-scale farmers are selling their fruit and vegetable products through Internet platforms such as live e-commerce and community group buying. However, fruits and vegetables often reach consumers with low freshness and high spoilage rates. Conducting effective precooling and grading operations on freshly harvested fruits or vegetables has been proven as an important strategy to reduce food losses. However, small-scale farmers often cannot afford corresponding equipment, so preprocessing service providers (PSPs) emerge to help them conduct related operations. For PSPs, how to synchronically optimize different preprocessing operations to satisfy many small-scale, and scattered requests becomes a challenging optimization problem.

Most of the existing studies regarding fruit and vegetable supply chain management have been conducted at a strategic level to propose network layout optimization for the post-harvest fruits and vegetables or to optimize the dispatch of commodity collection vehicles [1-3]. However, fruits and vegetables are perishable in nature. For PSPs, scheduling mobile grading and precooling resources synchronically can have a great impact on the quality of fruits and vegetables, which is similar to the integrated scheduling of

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production and distribution problem (ISPDP) for perishable products. Mousavi et al. [4] proposed a new optimization model for the delivery of perishable products with uncertain demands. Pratap et al. [5] studied the green routing and planning problem in perishable food production considering constraints of capacity, time windows, and carbon emissions. Giallombardo et al. [6] studied the harvesting, storage and distribution problem of perishable products and developed two mathematical models. Devapriya et al. [7] studied the truck routes constrained by the planning range under a certain fleet size. Li et al. [8] studied an integrated production inventory routing planning for intelligent food logistics systems. Aazami and Saidi-Mehrabad [9] studied a multi-cycle production and distribution problem for a perishable product with a fixed lifetime.

The above research on ISPDP has laid an important theoretical foundation for the development of this research in terms of model formulations and solution methods. However, the existing research on the ISPDP problem mainly focused on the integrated optimization in the strategic and long-term aspects, while this study mainly focuses on the integrated optimization in the operational and short-term aspects. Thus, the synchronization between the grading and precooling in this study is more complicated. First, the grading and precooling demands need to be served by different types of vehicles separately. Second, the maximum time interval constraint for grading and precooling should be considered to ensure service continuity.

Aiming at the synchronization optimization problem of grading and precooling, this paper comprehensively considers the service sequence constraint and the maximum time interval constraint between grading and precooling, and constructs a multi-objective optimization model to minimize the total cost and to minimize the maximum precooling delay time. Furthermore, combined with the key synchronization constraints of the problem, an improved Non-dominated Sorting Genetic Algorithm II is designed to solve the problem. Results show the effectiveness of the proposed model and algorithm.

2. Model Formulations.

2.1. Problem description. This paper assumes that the post-harvest processing center (regarded as a depot) provides both mobile grading trucks and mobile precooling trucks to meet the grading and precooling needs of farmers. Firstly, the grading trucks perform mobile grading operations for all farmers; Secondly, the precooling trucks serve those

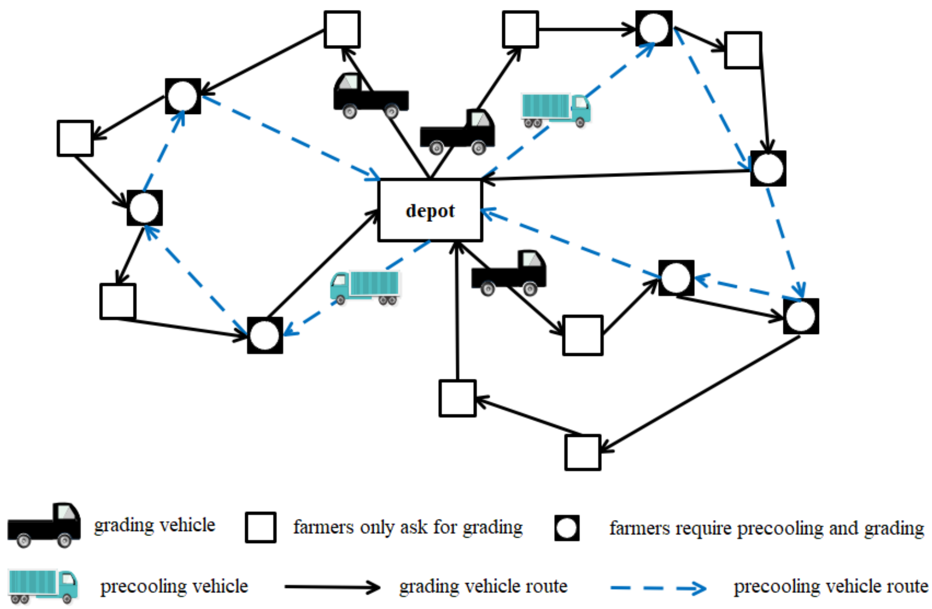

Figure 1. Synchronization scheduling of mobile grading and precooling resources

farmers which also have precooling demands, and such farmers are called dual-demand farmer nodes (as shown in Figure 1).

To ensure the precooling effect and improve the satisfaction of dual-demand farmers, the service routes of the grading truck and the precooling truck need to be planned in concert. In addition, to prevent a break in the chain of service for dual-demand farmers, the interval between the start of service of the precooling truck and the end of service of the grading truck should be limited to no more than the given maximum service interval, and the precooling truck should be allowed to arrive earlier.

2.2. **Symbol description.**

Set:

D: Post-harvest processing center (depot), $D = \{0\}$.

S: Types of services the depot can provide, $S = \{s|1, 2\}$, where 1 represents grading service, and 2 represents precooling service.

N^s: The set of farmers with s-type demand, N^1 is the set of grading demand farmers and N^2 is the set of precooling demand farmers, $N^2 \subseteq N^1$.

N: The set of the depot and (grading) farmers, $N = D \cup N^1$.

N^{DP}: The set of the depot and precooling demand farmers, $N^{DP} = D \cup N^2$.

V^s: The set of available vehicles that provide s-type services to farmers, $V^1 = \{k|1, 2, \ldots, K_1\}$ is the set of grading vehicles, and $V^2 = \{k|K_1 + 1, K_2 + 2, \ldots, K\}$ is the set of precooling vehicles.

Parameters:

FC^s: The fixed cost of the s-type vehicle.

VC^s: The travel cost per unit distance of the s-type vehicle.

EC^s: The energy consumption cost per unit time of equipment on the s-type vehicle.

PC_1^s, PC_2^s: The waiting/delay cost per unit time for the s-type vehicle arriving earlier/later than the required time.

v_s: The speed of the s-type vehicle.

w^s: Working speed of the s-type vehicle when providing corresponding services.

d_{ij}: The distance from node i to node j.

$T_{\max}^s$: The maximum duration of the s-type vehicle.

D_i^s: The demand for s-type service of farmer i.

ET_i^1, LT_i^1: The lower/upper bound of the grading time window of farmer i.

ST_i: The maximum interval time acceptable to farmer i, $i \in N^2$.

t_{ij}^s: The travel time of the s-type vehicle from node i to node j, $t_{ij}^s = d_{ij}/v_s$.

t_i^s: The time required for farmer i to perform s-type service, $t_i^s = D_i^s/w^s$.

M: Infinite positive number.

$C_{\max}^s$: The maximum handling capacity of the s-type vehicle.

Decision variables:

RT_{ik}^s: The time when the vehicle k corresponding to the demand of s-type arrives at farmer i.

ST_{ik}^s: The starting service time of the vehicle k corresponding to the demand of the s-type.

et_{ki}^s, lt_{ki}^s: The waiting/delay time for vehicle k to arrive at farmer i earlier/later than the time window.

$L_i(k)$: Precooling delay time, $L_i(k) = ST_{ik}^s - ET_i^1$, $\forall i \in N^2$.

$L_{\max}(k)$: Maximum precooling delay time, $L_{\max}(k) = \max_{i=1}^{N^2}\{L_i(k)\}$.

x_{ik}^s: If the s-type vehicle k is selected to serve the farmer i, $x_{ik}^s = 1$; otherwise, $x_{ik}^s = 0$.

y_{ijk}^s: If the s-type vehicle k serves from the farmer i to farmer j, $y_{ijk}^s = 1$; otherwise, $y_{ijk}^s = 0$.

g_k^s: If the s-type vehicle k is scheduled for service, $g_k^s = 1$; otherwise, $g_k^s = 0$.

2.3. **Function of precooling delay costs.** When the precooling time exceeds a certain critical value t_F, precooling will lose its significance. The curve will be inscribed with a function as shown in Equation (1), where α is the decay rate; t_{delay} is the optimum precooling delay time.

$$Q(t) = \begin{cases} 1, & 0 \le t < t_{delay} \\ e^{-\alpha t+1}, & t_{delay} \le t < t_F \\ 0, & t \ge t_F \end{cases} \tag{1}$$

Equation (2) is the relationship between precooling delay cost and time for fresh fruits and vegetables, which is mapped from $Q(t)$, where a_r is the cargo loss factor for fruits and vegetables in category r and D_i^2 is the customer's precooling demand.

$$z_q = \begin{cases} 0, & 0 \le ST_{ik}^2 < t_{delay} \\ \sum_{i\in N}\sum_{k\in V^2} a_r D_i^2 / e^{-\alpha ST_i^k+1}, & t_{delay} \le ST_{ik}^2 < t_F \\ M, & ST_{ik}^2 \ge t_F \end{cases} \tag{2}$$

2.4. **Mathematical model.** Based on the above analysis, a multi-objective optimization model is developed as follows.

$$\begin{aligned} f_1 = \min & \sum_{s\in S}\sum_{k\in V^s} FC^s \cdot g_k^s + \sum_{i\in N}\sum_{j\in N}\sum_{k\in V^1} VC^1 \cdot d_{ij} \cdot y_{kij}^1 \\ & + \sum_{i\in N^{DP}}\sum_{j\in N^{DP}}\sum_{k\in V^2} VC^2 \cdot d_{ij} \cdot y_{kij}^2 + \sum_{i\in N}\sum_{j\in N}\sum_{k\in V^1} EC^1 \cdot t_i^1 \cdot y_{kij}^1 \\ & + \sum_{i\in N^{DP}}\sum_{j\in N^{DP}}\sum_{k\in V^2} EC^2 \cdot t_i^2 \cdot y_{kij}^2 + \sum_{s\in S}\sum_{k\in V^s}\sum_{i\in N^s} \left(PC_1^s \cdot et_{ki}^s + PC_2^s \cdot lt_{ki}^s\right) + z_q \end{aligned} \tag{3}$$

$$f_2 = \min L_{\max} \tag{4}$$

s.t.

$$\sum_{s\in S}\sum_{k\in K}\sum_{i\in N^1} y_{i0k}^s = \sum_{s\in S}\sum_{k\in K}\sum_{i\in N^1} y_{0ik}^s = \sum_{s\in S}\sum_{k\in K} g_k^s \tag{5}$$

$$\sum_{i\in N^1} x_{ik}^s \cdot D_i^s \le C_{\max}^s, \quad \forall k \in V^s, \ s \in S \tag{6}$$

$$\sum_{k\in V^s} x_{ik}^s = 1, \quad \forall i \in N^s, \ s \in S \tag{7}$$

$$\sum_{k\in V^1} g_k^1 \le K_1 \tag{8}$$

$$\sum_{k\in V^2} g_k^2 \le K - K_1 \tag{9}$$

$$ST_{ik}^1 = \max\left\{RT_{ik}^1, ET_i^1\right\} \tag{10}$$

$$ST_{ik}^2 = \max\left\{RT_{ik}^2, ST_{ik}^1 + t_i^1\right\} \tag{11}$$

$$ST_{ik}^s + t_i^s + t_{ij}^s \le RT_{jk}^s + M\left(1 - y_{ijk}^s\right), \quad \forall i \in N, \ k \in V^s, \ s \in S \tag{12}$$

$$ET_i^1 \le RT_i^k + et_{ki}^1 - lt_{ki}^i \le LT_i^1, \quad \forall i \in N^1, \ k \in V^1 \tag{13}$$

$$ST_{ik}^1 - M\left(1 - x_{ik}^1\right) \le RT_{iu}^2 + M\left(1 - x_{iu}^2\right), \quad \forall i \in N^2, \ k \in V^1, \ u \in V^2 \tag{14}$$

$$ST_{ik}^1 + t_i^1 + SL_i \ge RT_{iu}^2 + et_{ui}^2 - lt_{ui}^2 \ge ST_{ik}^1 + t_i^1, \quad \forall i \in N^2, \ k \in V^1, \ u \in V^2 \tag{15}$$

$$ST_{ik}^1 + t_i^1 < ET_i^1 + T_{delay} + M\left(1 - y_{ijk}^1\right), \quad \forall i \in N^1, \ j \in N^1, \ k \in V^1 \tag{16}$$

$$et_{ki}^1 = \max\left\{ET_i^1 - RT_{ik}^1, 0\right\}, \quad \forall i \in N^1, \ k \in V^1 \tag{17}$$

$$lt_{ki}^1 = \max\left\{RT_{ik}^1 - LT_i^1, 0\right\}, \quad \forall i \in N^1, \ k \in V^1 \tag{18}$$

$$et_{ui}^2 = \max\left\{ST_{ik}^1 + t_i^1 - RT_{iu}^2, 0\right\}, \quad \forall i \in N^2,\ \ k \in V^1,\ \ u \in V^2 \tag{19}$$

$$lt_{ui}^2 = \max\left\{RT_{iu}^2 - ST_{ik}^1 - t_i^1 - SL_i, 0\right\}, \quad \forall i \in N^2,\ \ k \in V^1,\ \ u \in V^2 \tag{20}$$

$$\sum_{i=0}^{n} y_{ijk}^s = x_{ik}^s, \quad \forall j \in N^s,\ \ k \in V^s,\ \ s \in S \tag{21}$$

$$\sum_{i=0}^{n} y_{jik}^s = x_{jk}^s, \quad \forall j \in N^s,\ \ k \in V^s,\ \ s \in S \tag{22}$$

$$x_{ik}^s, y_{ijk}^s, g_k^s \in \{0,1\}, \quad \forall i,j \in N,\ \ k \in V^s,\ \ s \in S \tag{23}$$

Equation (3) is the total minimized cost. Equation (4) is the minimized maximum precooling delay time. Equation (5) means that both the precooling vehicles and the grading vehicles depart from the depot, and return to the depot after completing the service. Equation (6) constrains the maximum service capacity of grading and precooling vehicles. Equation (7) indicates that each demand of each farmer is only served by vehicles of the corresponding type and the demand cannot be split. Equations (8) and (9) are constraints on the number of different types of vehicles. Equations (10) and (11) represent the relationship between the arrival time and the starting service time of the grading and precooling vehicles, respectively. Equation (12) represents the time interval relationship between the arrival of any type of vehicle to adjacent farmers. Equation (13) is the grading time window constraint for farmers. Equation (14) constrains dual-demand farmers to be served in the order of grading first and precooling second. Equation (15) is a service level constraint. Equation (16) ensures that the end of the grading service is before the optimum precooling delay time. Equations (17) and (18) are the waiting time for grading vehicles arriving earlier than the time window and the delay time for arriving later than the time window, respectively. Equations (19) and (20) represent the waiting time resulting from the arrival of a precooling vehicle earlier than the end-of-service moment of the grading vehicle and the delay time arriving later than the maximum service moment, respectively. Equations (21) and (22) represent that the vehicle arriving and departing from a farmer is the same. Equation (23) represents the domain of decision variable.

3. Solution Method.

3.1. Generation of the initial population considering temporal-spatial distances.

The integer coding method is used to generate N chromosomes, and the length of the chromosomes is the number of all customers with grading needs. Firstly, all customers are randomly arranged and the temporal-spatial distance between all customers is calculated based on their grading time windows [10]. Secondly, the number of clusters is set to the number of grading vehicles enabled, i.e., n is equal to the sum of all farmers' grading demands/maximum grading vehicle service capacity. Finally, the clusters are assigned. The top m farmers of each chromosome are used as the centers of the clusters and the remaining customers are assigned proximity.

As mentioned above, the algorithm in this paper integrates temporal-spatial clustering into the procedure of initializing the population. When the customer scale is large, the temporal-spatial distance can be used to reasonably cluster a number of customer points, so as to generate a better initial path, reduce the waiting time of grading and precooling process, and achieve full utilization of vehicles.

3.2. Non-dominated sorting.

The parameters to be computed for the non-dominated sort are as follows: the number of dominated individuals n_p for each individual p and the set S_p of solutions dominated. First, each individual in the solution set is traversed to find the n_p and S_p corresponding to each individual. Subsequently, based on each Pareto optimal solution at the current F_{rank} level, visit its corresponding solution in S_p and let

$n_p = n_p - 1$, until all solutions have been traversed and the ordinal number of F_{rank} is increased by 1.

3.3. **Calculation of congestion.** The crowding degree n_d is calculated as follows: let $n_d = 0$, $n \in \{1, \ldots, N\}$. For each objective function f_m, the individuals of that rank are ranked according to that objective function. $f_m^{\max}$ is the maximum of all objective function values and $f_m^{\min}$ is the minimum of all objective function values. The value is found according to the congestion formula $n_d = n_d + (f_m(i+1) - f_m(i-1)) / \left(f_m^{\max} - f_m^{\min}\right)$.

3.4. **Other operators.** This paper uses a binary bidding tournament method to select offspring. After that, two-point crossover is conducted to, where two points are randomly generated on parental chromosomes A and B respectively, and the gene fragments between the two points are swapped. The steps of the mutation operation are as follows: randomly select genes i and j in an individual and swap the positions of i and j.

4. Numerical Experiments.

4.1. **Experiment 1.** The performance of the algorithm is tested using six examples from Solomon's standard library of instances with time windows. All instances have a customer size of 50, from which 25 points with precooling demand are randomly selected. Table 1 gives the results of 10 runs of the algorithm in this paper and NSGA-II, where f_1 is the total cost and f_2 is the maximum precooling delay time. It can be seen that the algorithm in this paper outperforms NSGA-II in terms of solution quality and solution time.

TABLE 1. Performance comparison of the two algorithms

Instance	Multi-objective genetic algorithm considering temporal-spatial distances						NSGA-II					
	f_1-best/ ¥	f_1-avg/ ¥	f_2-best/ min	f_2-avg/ min	Pare -tom	cpu/ s	f_1-best/ ¥	f_1-avg/ ¥	f_2-best/ min	f_2-avg/ min	Pare -tom	cpu/ s
C101	48915.34	50641.54	454.76	465.37	2	9.16	52418.65	54318.94	503.74	523.15	4	9.36
C201	58701.63	59873.21	562.31	587.43	2	9.17	63993.49	65732.49	593.76	612.05	5	9.48
R101	20265.99	20599.42	313.87	315.90	2	9.57	20682.45	20968.43	306.77	337.32	4	9.82
R201	29345.88	31850.34	384.89	388.58	3	9.02	35892.94	38697.32	449.65	463.64	5	9.40
RC101	19847.94	21400.17	325.33	332.68	3	9.72	22646.35	24497.28	330.41	338.32	7	10.67
RC201	32109.61	32685.14	413.25	415.23	2	9.53	40111.75	43521.27	495.97	498.89	6	10.36

4.2. **Experiment 2.**

4.2.1. *Case description.* A post-harvest mobile grading and precooling scenario for blueberries is simulated using blueberry field research data from 25 typical villages in Lishui County, Nanjing City, Jiangsu Province. In the case study, 12 customer points with precooling demand are randomly generated among the 25 farmer points, and the precooling demand is consistent with the grading demand at that point. According to the knowledge of related experts, blueberries are best precooling within 2 hours after harvesting and the fruit temperature is reduced to 5°C. Parameters settings are shown in Table 2, where values are set based on field study.

4.2.2. *Optimization results.* Considering that this paper is more concerned with the influence of the length of precooling delay on the precooling effect, the boundary solution with the smallest precooling delay in the Pareto optimal solution set is selected as the output, i.e., the total cost is 8631.56¥, the maximum precooling delay is 123.17min, and the corresponding scheduling scheme is shown in Table 3. During the service, the average unit cost of mobile grading service is 0.7¥/kg, which is 14.29% less than the manual sorting unit cost of 0.8¥/kg; the average unit cost of mobile precooling service is 1.09¥/kg, which is closer to the actual operational precooling cost. The delayed precooling cost of the precooling process is 20.38¥, accounting for only 0.66% of the total precooling cost,

Table 2. Parameter settings

Parameters	Value	Parameters	Value
FC^s	500CNY/vehicle($s=1$); 800CNY/vehicle($s=2$)	$T^s_{\max}$	600min($s=1$); 600min($s=2$)
VC^s	2CNY/km($s=1$); 1.5CNY/km($s=2$)	PC^s_1	0.5CNY/min($s=1$); 0.8CNY/min($s=2$)
EC^s	0.5CNY/min($s=1$); 0.8CNY/min($s=2$)	PC^s_2	1.5CNY/min($s=1$); 5CNY/min($s=2$)
v_s	30km/h($s=1$); 40km/h($s=2$)	ST_i	40min
w^s	20kg/min($s=1$); 15kg/min($s=2$)	t_{delay}	2h
$C^s_{\max}$	3000kg($s=1$); 2000kg($s=2$)	t_F	7h

Table 3. Vehicle scheduling plan

Vehicle type	Routes	Quantity served/kg	Service rate/%	Precooling delay cost/¥	Cost/¥	Unit cost/¥
Grading vehicles1	0-16-13-18-1-14-10-15-17-20-0	2860	95.33	–	1848.38	0.65
Grading vehicles2	0-22-19-4-9-3-23-25-12-0	2800	93.33	–	2086.25	0.75
Grading vehicles3	0-2-6-24-8-21-11-5-7-0	2360	78.67	–	1684.60	0.71
Average	–	–	89.11	–	–	0.70
Precooling vehicles1	0-16-13-18-1-10-15-0	1660	83.00	20.38	1165.01	0.70
Precooling vehicles2	0-22-19-4-3-24-0	1900	95.00	0	1303.53	0.69
Precooling vehicles3	0-8-0	290	14.50	0	543.79	1.88
Average	–	–	64.17	20.38(Total)	–	1.09
Total cost/¥	–	–	–	–	8631.56	–

Table 4. Precooling service information of dual-demand farmer points

Node	16	13	18	1	10	15	22	19	4	3	24	8	Average
Service interval/min	0	14.31	9.71	15.20	5.54	3.66	0	3.72	16.60	0	32.26	0	8.42
Precooling delay time/min	17.50	50.90	30.20	101.25	121.36	123.17	19.00	107.70	110.48	86.52	119.01	89.49	81.38

suggesting that the start of service for precooling vehicles is mostly within the optimal precooling delay time, and indirectly suggesting that the model is effective in ensuring timely precooling.

As can be seen from Table 4, only the grading-precooling service interval of customer 24 exceeded the maximum service interval time of 30min preset in this paper, and the average value of the service interval is 8.42min, which indicates that the model has high service coherence and can effectively reduce the wasteful waiting between grading and precooling. In addition, two points (customer points 10 and 15) have precooling delays that exceeded the optimal precooling delay time of 120min for blueberries, but since the two points are closer to the optimal precooling time, they would incur a smaller precooling delay cost. The mean precooling delay time is 81.38min, indicating that the model can produce high precooling timeliness, which in turn ensures precooling effectiveness and extended storage life of fruits and vegetables.

5. **Conclusions.** This study is particularly significant in developing countries to encourage preprocessing service providers to help small-scale farmers conduct preprocessing

operations and finally contribute to reducing large losses of fruits and vegetables in the post-harvest stage. However, the current study has some limitations. First, it only considers one post-harvest processing center, while in practice, there will be more than one post-harvest processing center in an area. At the same time, the current study only considers the order arrival before scheduling, and does not consider the dynamic arrival of the order. Therefore, in the future the potential research directions include 1) considering multiple depots when conducting on the synchronization optimization between grading and precooling; 2) considering the scenario where orders arrive randomly during the scheduling optimization process.

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