A Scheduling Research in Plant Factory with Considering Multi-Period Harvest

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Abstract. A plant factory is an environmentally controlled facility that can sustain stable crop cultivation while ensuring fast production and better quality by setting temperature, humidity, lighting, nutrient supply, and other cultivating factors. In this study, we focus on the crop-scheduling problem of a plant factory and consider the special properties of crops that can be harvested multiple times. This scheduling problem is formulated as a mixed integer programming problem. The objective is to determine the maximum revenue for the plant factory under different practical conditions including types of crops, number of cultivation rooms, and multiple harvesting periods. This study develops a heuristic algorithm method to solve the problem effectively for a large-scale production.

Key words: plant factory, crop scheduling problem, mixed integer programming, heuristic algorithm method

1. Introduction

Population expansion and climate change require the development of agricultural technologies to fill the gap between the rising global demand for food and insufficient agricultural production (Zhang et al., 2016). Establishing plant factories is an efficient means of meeting the demands of food production for the increasing population. These facilities can plant crops locally with high quality and stable yield.

A plant factory is a controlled environment for plant production systems with artificial light, temperature, humidity, carbon dioxide, water supply, and cultivation solution. Plants are grown consistently in the greenhouse using integrated high technology systems, with irrigation systems and others resources that are available all the time.

However, because of the high start-up and operating cost of this industry, the plant factory system is most often used to cultivate crops with high-profit returns. High-profit vegetables cultivated by plant factory systems include high value-added, small volume crops that cannot be cultivated locally such as seedlings, herbs, and off-season fruits for consumers willing to pay more for these goods.

The main purpose of this research is to develop a robust and highly efficient method for solving the crop scheduling problem by considering certain growing properties of plants (such as growing volume over time) and determining how some plants could be harvested several times within a life cycle. To achieve this purpose, we focus on the crop-scheduling problem for a plant factory and consider the special properties of its crops. By considering these properties, we formulated a practical problem of in a plant factory and also added or modified the constraints to reflect the special properties of the plants and allocate finite resources (e.g., limited space for cultivated crops) over time to accomplish a given set of tasks so as to maximize total revenues.

The first plant property is volume change. Unlike the products from a manufacturing factory, the volume of plants produced grows over time (Fig.1). If we consider this property within the cultivated duration, we can improve the usage rate of the greenhouse. Before harvest, the growing process of plants is a non-interruptible cultivate-continuous process.

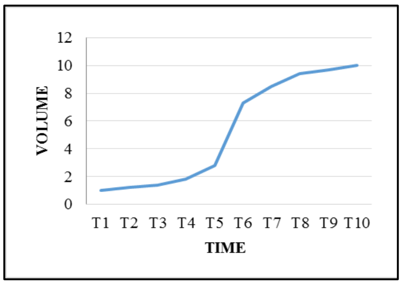

Figure 1: The volume change over time

The second property is multi-period harvest. Some plants can be harvested more than once, such as lettuce (Figs. 2 and 3), cabbage and strawberry. Single-period harvest means that the crop would be harvested at the time it matures and can no longer be cultivated. However, some crops can be cultivated to next harvest time, which defines this property.

Figure 2: The lettuce before be harvested (Light Farm)

Figure 3: The lettuce after be harvested (Light Farm)

Related studies in crop scheduling include solutions with linear programming and different considerations of constraint. Kantorovich (1960) proposed a mathematical model to opitimize the surface area needed to cover crop demands. Biswas and Pal (2005) demonstrated how fuzzy goal programming can be used efficiently for modelling and solving land-use planning problems in agricultural systems for optimal production of several seasonal crops in a planning year. Ioslovich and Gutman (2000) proposed a crop growth model to opitimize the age-dependent spacing between individual plants in a plant factory. Alfandari et al. (2009) proposed a Mixed-Integer Linear Programming model for a class of multi-period crop rotation optimization problems with demand and incompatibility constraints between cultivation and fallow state on a land plot.

Haneveld and Stegeman (2005) presented a linear programming model based on the limited order of planting. Their results showed pattern in the solution; the length of the entire planting cycle time is dependent upon the rotation planting plan with the longest period. Pochet and Warichet (2008) proposed a continuous time mixed integer linear programming model for the cyclic scheduling of a plant composed of batch and continuous tasks to maximize productivity.

Dos Santos et al. (2008) proposed a 0–1 optimization model to determine the crop rotation schedule for each plot in a cropping area. The rotations had the same duration in all plots and the crops were selected to maximize plot occupation (Lana Mara Rodrigues dos Santos et al., 2008). They proposed another linear formulation for the crop rotation scheduling problem, in which each variable is associated with a crop rotation schedule to solve the rotation decision problem whereby each rotation plan must respect ecologically based constraints, such as the interdiction of certain crop successions, and the regular insertion of fallows and green manures (Lana Mara R. dos Santos et al., 2010).

Numerous studies on agricultural supply chain management and strategy have been conducted. Hu et al. (2014) focused on the entry and competition of a plant factory supply chain in vegetable markets, using a Nash-Cournot model to simulate this competition. Yulius (2011) developed an approach system that considered several factors affecting the revenue of an operating plant factory to choose appropriate crops for cultivation at proper time to maximize the revenue. Govindakrishnan et al. (2011) developed a decision support system to provide information on the optimum time of planting and the possible sequences of early or late planting of different potato varieties. Salassi et al. (2013) presented a transshipment network formulation to model the crop rotation decision problem associated not only with the expected net returns from alternative rotation sequence choices, but also with the relative effects of net income risk on the decision process.

Solving complicated mixed-integer optimization problems usually require considerable time and effort to obtain a feasible optimal solution as the problem size increases. Therefore, the goal is usually to obtain a good, near-optimal efficient solution. Lagrangian relaxation is a mathematical programming technique that efficiently handles optimization problems with complicated constraints.

However, the Lagrangian relaxation algorithm usually stops after a fixed number of iterations and generates some nonfeasible solutions (Bragin et al., 2014). To fix the feasibility problem, we heuristically adjusted the solution to become feasible. In Lagrangian relaxation algorithm, Lagrange multipliers are updated based on stepsizes and subgradient directions. The surrogate subgradient method is widely used in Lagrangian relaxation because it is easy to program and has worked well on many practical problems (Fisher, 2004). Thus, we applied the Lagrangian relaxation with surrogate subgradient method to reduce computational requirements and to obtain the near-optimal solution.

2. Definition of crop scheduling problem in plant factory

Normally, a plant factory has several greenhouses and a range of crops in the greenhouses is grown every period. The succession of crops in a given field affects production through environment setting such as yield, nitrogen requirements, disease pressure, etc. Therefore, the decision maker should attempt to determine the optimal succession of crops at the proper time because the value of crops change through time (Fig.4) and the space of the greenhouse is limited.

2.1 Notation

We consider the following notations for the Maximize-Revenue crop scheduling problem:

Index sets

- $i = 1, \dots, I$: the number of types of crops
- $j = 1, \dots, J$: the period of the planning horizon
- $t = 1, \dots, T$: the period when the crop is cultivated
- $r = 1, \dots, R$: the number of greenhouse/s
- $k = 1{,}2$: the growing status of crops, where k=1 means seedling status, k=2 means matured status.

Parameters:

- S: the space of greenhouse.
- V_{ij}: the price of crop i at period j.
- HC_i^k: the planting time needed by crop i with k status.
- ITV_i: the interval time of crop i between harvesting time. ITV_i equals 0 if crop i is a single-harvest crop
- HN_i: the additional harvest times of crop i. HN_i equals 0 if the crop i is a single-harvest crop
- Vol_i: the production volume of united traps of crop i.
- VR_i^k: the various rate of volume of crop i with k status. VR_i^k must be 1 when k equals 1.

Decision variables:

- X_{ijrt}^k: the number of planting crop i at period j in greenhouse r with growing status k which is cultivated at period t.
- $HDijrt$: the number of crop i at period j in greenhouse r which is cultivated at period t to be harvested.
- Qij: the total production volume of crop i at period j.

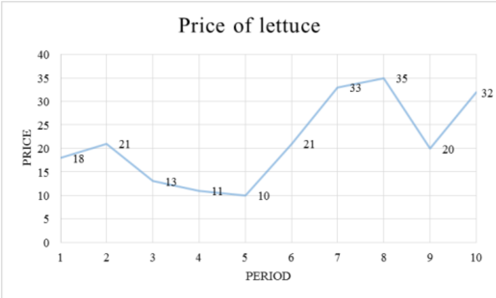

Figure 4: Price of lettuce

(Council of Agriculture, Taiwan)

2.2 Problem formulation

Using the symbols above, an optimization model for the crop scheduling problem in a plant factory is presented:

Objective. We set the goal of maximizing total revenues to consider the different prices at different periods.

$$Z = \text{Max} \sum_i \sum_j V_{ij} * Q_{ij}, \qquad (1)$$

where V_{ij} and Q_{ij} are the prices of different periods and production volumes at different period, respectively.

Cultivated period constraint (seedling status). The cultivated time should follow the planting time of crop i with seedling status.

$$\sum_{j=t}^{t+HC_i^1} X_{ijrt}^1 = HC_i^1 \times X_{itrt}^1 \qquad (2)$$

$$\forall i = 1, \dots, I \text{ , } \forall r = 1, \dots, R \text{ , } \forall t = 1, \dots, J - HV_i$$

Each cultivation decision (X_{ijrt}^k) represents the number of crop i at period j which began to be cultivated in greenhouse *r* at period *t*. HC_i^1 is the planting time of crop *i* with seedling status.

Cultivated period constraint (matured status). The cultivated time should follow the planting time of crop *i* with matured status (HC_i^2).

$$\sum_{j=t+HC_i^1}^{t+HV_i} X_{ijrt}^2 = HC_i^2 \times X_{itrt}^2 \quad (3)$$

$$\forall i = 1, \dots, I,\ \forall r = 1, \dots, \mathrm{R}_i,\ \forall t = 1, \dots, J$$

where HC_i^2 is the planting time of crop i with matured status.

Planting amount consistency constraint. Equations (4) and (5) indicate that planting amount should be consistent with seeding time and matured status, respectively. Equation (6) shows that planting amount at last seedling period and first matured period should be consistent. The equation also means that the amount of cultivated crops would no longer change before the first harvest once we plant.

$$X_{ijrt}^1 = X_{i(j+1)rt}^1 \quad (4)$$

$$\forall i = 1, \dots, I,\ \forall j = t, \dots, t + HC_i^1 - 1,$$

$$\forall r = 1, \dots, R,\ \forall t = 1, \dots, J - HV_i$$

$$X_{ijrt}^2 = X_{i(j+1)rt}^2 \quad (5)$$

$$\forall i = 1, \dots, I,\ \forall j = t + HC_i^1, \dots, t + HV_i - 1,$$

$$\forall r = 1, \dots, R,\ \forall t = 1, \dots, J - HV_i$$

$$X_{it+HC_i^1rt}^1 = X_{i(t+HC_i^1+1)rt}^2 \quad (6)$$

$$\forall i = 1, \dots, I,\ \forall r = 1, \dots, R,\ \forall t = 1, \dots, J - HV_i$$

where $X_{it+HC_i^1rt}^1$ is the planting amount of crop *i* at last period with seedling status and $X_{i(t+HC_i^1+1)rt}^2$ is the first period with matured status.

Planting amount decreasing constraint. In terms of the planting amount consistency constraint, the planting amount should be equal to or less than the amount of the following period after the first harvest.

$$X_{ijrt}^2 \ge X_{i(j+1)rt}^2 \quad (7)$$

$$\forall i = 1, \dots, I,$$

$$\forall j = t + HV_i, \dots, Min\{J - 1, t + HV_i + HN_i * ITV_i - 1\},\ \forall r = 1, \dots, R,\ \forall t = 1, \dots, J - HV_i$$

Production volume constraint. Equations (8) and (9) show the production volume of first time harvest and multi-period harvest, respectively.

$$HD_{i(t+HV_i)rt} = X_{i(t+HV_i)rt}^2 \times G_i \quad (8)$$

$$\forall i = 1, \dots, I,\ \forall r = 1, \dots, R,\ \forall t = 1, \dots, J - HV_i$$

$$HD_{ijrt} = X_{ijrt}^2 \times G_i \quad (9)$$

$$\forall i = 1, \dots, I,$$

$$\forall j = t + HV_i + 1, \dots, Min\{J, t + HV_i + HN_i * ITV_i\},$$

$$\forall r = 1, \dots, R,\ \forall t = 1, \dots, J - HV_i$$

where G_i is the base production volume of crop *i* cultivated.

Space constraint. The crops are cultivated in the limited space of the greenhouse; the volume of crops increase over time.

$$\sum_i \sum_t^j \sum_k X_{ijrt}^k \times VR_i^k \le S \quad (10)$$

$$\forall j = 1, \dots, J,\ \forall r = 1, \dots, R$$

where VR_i^k is the various rate of volume of crop *i* with *k* status and S is the space of a greenhouse. The space occupied by the cultivated crops cannot exceed the space of the greenhouse S.

Total production volume constraint. Equation (11) presents the total production volume of each crop at each period.

$$Q_{ij} = \sum_r \sum_{t=1}^j HD_{ijrt} \quad (11)$$

$$\forall i = 1, \dots, I,\ \forall j = 1, \dots, J$$

Natural number constraint. The number of each planting decision should be a natural number.

$$X_{ijrt}^k \in \mathrm{N} \quad (12)$$

$$\forall i = 1, \dots, I,\ \forall j = 1, \dots, J,\ \forall r = 1, \dots, R,$$

$$\forall t = 1, \dots, J,\ \forall k = 1,2$$

3. Solution framework

The core concept of Lagrangian relaxation is to increase the penalty when the constraints are violated and update the Lagrange multipliers to identify good feasible solutions.

In our study, we focus on the revenue-maximize problem. Good feasible solutions can be obtained frequently by adjusting the infeasible solution obtained from Lagrangian relaxation. Therefore, we proposed a Lagrangian relaxation-based plant factory algorithm (LRBPFA) to solve the crop scheduling problem in plant factory by relaxing the Space constraints (10) and to simplify the linear programming model. Several steps are necessary to obtain a near-optimal solution: solving subproblems, constructing a feasible solution, and updating the needed parameters.

3.1 Approximate model

By introducing Lagrange multipliers $\{\mu_{jr}\}$ to relax the space constraints (10), the relaxed problem is obtained as

$$Z_D(\mu) = \text{Max}\sum_i \sum_j V_{ij} * Q_{ij}$$

$$-\sum_j \sum_r \mu_{jr}(\sum_i \sum_t^j \sum_k X_{ijrt}^k * VR_i^k * Vol_i - S) \qquad (13)$$

Subject to (2)-(9) and (11)-(12).

where μ_{jr} is a vector of Lagrange multipliers.

We know that $Z_D(\mu)$ is finite for all μ. In this case, we know that $Z_D(\mu) \geq Z$. The relaxation is defined for $\mu \geq 0$, which is a necessary condition for $Z_D(\mu) \geq Z$ to hold.

3.2 Construct feasible solution

This section is concerned with the use of the infeasible solution of Lagrangian relaxation to obtain a feasible solution. If the relaxed constraints contain some inequalities, a Lagrangian problem solution would be infeasible for the primary problem. We consider the relaxed constraints and propose a heuristic method to transform the Lagrangian problem solution to near-optimal feasible solution.

According to the relaxed space constraints, we can determine whether the constraint is violated if the subgradient is greater than zero, as shown below:

$$\sum_i \sum_t^j \sum_k X_{ijrt}^k * VR_i^k * Vol_i - \text{S} \geq 0 \qquad (14)$$

When a violation in the space constraint exists, we calculate the value-ratio to compare left value ratio (LVR) of each planting decision. For example, we find a violation in greenhouse *r* at period *j*, then we calculate all left value ratio of the crops using the following equation:

$$LVR_{ijrt} = \frac{\sum_t (HD_{ijrt} \times Value_{ij})}{\sum_{j=t}^{J}(\sum_i \sum_{t=1}^{j} \sum_k X_{ijrt}^k \times VR_i^k \times Vol_i)} \qquad (15)$$

The LVR is similar with the price-performance ratio. The larger LVR is, the more possible it is to obtain more revenues in the following period. After calculating all LVR, we eliminate the planting decision with the smallest LVR until the constraint is satisfied (all subgradients are less than 0). By this process, we can obtain a feasible solution.

3.3 Update parameters

A main parameter μ exists in Langrangian relaxation. We adopt surogate subgradient(Chen & Luh, 2003) method to update the Lagrange multipliers to solve the equation efficiently. The field of nondifferentiable optimization using subgradients has recently become an important topic of study in the application of Lagrangian relaxation (Fisher, 2004).

The concept of subgradient method is to replace gradients by subgradients. Given an initial value μ^0 a sequence is generated by the following rule:

$$\mu^{h+1} = \mu^h + \theta^h(\sum_i \sum_t^j \sum_k X_{ijrt}^k * VR_i^k * Vol_i - S) \qquad (16)$$

where μ^h is the Lagrange multipliers of *h* iteration and θ^h is a scalar step size. Usually $\mu^0 = 0$ is the most natural setting.

We update the step size by the most common rule:

$$\theta^h = \frac{\beta[Z_D^* - z^h]}{\left\|\sum_i \sum_t^j \sum_k X_{ijrt}^k * VR_i^k * Vol_i - S\right\|^2}, \qquad (17)$$

where β is a parameter satisfying $0 < \beta < 1$ and Z_D^* is estimated by $Z^U = (1 + \omega/\theta^\rho) \times z^{[h]}$,where ω, θ, and ρ are three parameters, $z^{[h]}$ is the best feasible solution that is estimated by applying the heuristic to adjust infeasible solution of $Z_D(\mu)$ before iteration h. Parameters ω and ρ are chosen within [0.1, 1.0] and [1.1,1.5], respectively, and parameter θ is adaptively adjusted with θ = max(1, θ-1) if $z^h > z^{[h]}$, and $\theta = \theta + 1$ otherwise.

3.4 Stop criteria

We set the limited number of non-improved iterations and the gap between $Z_D(\mu)$ and adjusted the feasible solution.

4. Numerical testing

The parameters are shown in Table 1. We present a comparison of our LRBPFA with an integer program solver in Table 2. All computations reported in this paper have been carried out on a personal computer with an Intel Core i5 processor at 1.70 gigahertz and 4 gigabytes of RAM. The integer program solver is IBM ILOG CPLEX 12.6 version. LRBPFA was coded in Java using CPLEX package.

Table 1: Parameters setting

Level of term-plan	short	middle	long
Number of total planning periods	20	30	40

In Table 2, for each approach, we report the value of the best integer solution obtained within a time limited equal to 3600 seconds.

Table 2: Performance of IP Solver and LEBPFA

5 greenhouses and 10 crops		
Method	IP Solver	LRBPFA
30 periods	9142850	7709150
Gap	-	15.68%
Time(s)	6.672	63.134
40 periods	1.26E+07	1.07E+07
Gap	-	14.84%
Time(s)	3642.84	61.261
50 periods	1.48E+07	1.23E+07
Gap	-	16.91%
Time(s)	3635.292	62.619

Table 2 shows that the IP solver is more time-consuming when the problem size is large. In these instances, LRBPFA provides an efficient way to obtain the near-optimal solution in the crop scheduling problem. However, LRBPFA has more difficulties searching widely to obtain the optimal solution, which results in some gap between the results of the IP solver and LRBPFA.

5. Conclusion

This paper presents a practical linear programming model to describe a production system in a plant factory. This model considers many special properties of plants, such as volume change and multi-period harvest. The traditional IP solver is time-consuming; hence, we propose a heuristic algorithm (LRBPFA) to obtain the near-optimal solution in an efficient manner. In this case, IP solver takes much time and did not get the optimal solution. However, LRBPFA could get the near-optimal solution in a relative efficient way. The core of LRBPFA is to transform the solution from infeasible to feasible by calculating the LVR of the crops. Results show that through this method, this feature helps obtain the near-optimal solutions to the large-scale problem. In future research, we will consider to compare the current method with other metaheuristics algorithms (e.g. GA, PSO or ACO) to verify the efficiency of LRBPFA.

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