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Multi-Objective Job Rotation in Rice Seed Harvesting With Equitable Injury Risk and Cost Allocation

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ABSTRACT

This article presents a non-linear multi-objective optimization model with four different objectives for manual rice seed harvesting, aiming to ensure members' fairness and mutual benefits for a group of rice field owners responsible for seed planting and a group of workers tasked with harvesting rice seeds. The harvesting plan primarily focuses on minimizing the average injury risk to workers and secondarily balances this risk among workers. Simultaneously, the model seeks to minimize and equitably allocate wage costs for rice field owners. Worker characteristics, including age, gender, and body mass index are considered to influence injury risk differentially. The optimal solution involves rotating workers to different rice stalk types in several fields, all within appropriate work and rest periods. This approach serves to prevent musculoskeletal disorders and fatigue among the workers while helping rice field owners reduce their costs. This collaborative planning has the potential to enhance sustainability within the farming community.

KEYWORDS

Augmented Epsilon Constraint, Collaborative Planning, Equitable Injury Risk Allocation, Job Rotation, Multi-Objective Optimization, Rice Seeds Harvesting

1. INTRODUCTION

Rice has long been a crucial plant in the global economy. Currently, over half of the world's population consumes rice as their main dish. Thailand has consistently been recognized as a kitchen of the world or global food production hub, particularly for rice, and is among the top three rice-exporting countries (World Data Atlas, 2020). Therefore, it is of paramount importance the rice produced in Thailand be of high quality; and the cultivation of rice in this country, especially for export, should be given

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special concern. One essential factor in ensuring high-quality rice is the careful management of rice seeds. Rice seeds can be categorized into three generations or stages. The first-, second-, and third-generation rice seeds are called foundation rice seed, registered rice seed, and certified rice seed, respectively (National Bureau of Agricultural Commodity and Food Standards, 2015). The progeny of the rice breeder seed is called foundation rice seed. Later, the rice produced from the foundation rice seed is called registered rice seed. These registered rice seeds are distributed to a dedicated group of field owners to cultivate the seeds into certified rice seeds. The certified rice seeds are distributed to rice field owners nationwide, eventually leading to the production of commercial rice for domestic consumption and export.

The focus of this study is photoperiod-sensitive rice, known for its sensitivity to the timing of harvesting, which significantly impacts its quality. For photoperiod-sensitive rice, which is classified as a short-day plant, the highest seed quality occurs four to five weeks after the panicle becomes fully visible during the heading stage. Harvesting must be completed during the final two weeks, or 14 days, of this peak period; otherwise, seed quality deteriorates (Itani et al., 2004). Preserving the purity of rice seeds is crucial for maintaining the authentic characteristics of each rice variety. Traditionally, rice seeds are harvested by hand, but nowadays combine harvester machines are widely used. Traditional, or manual, harvest requires workers to use a hand-held agricultural tool to cut the rice stalks. Even though the combine harvester machine saves a great deal of time over the traditional harvest method, it poses a higher risk of cracking or damaging rice seeds and of unintentional cross-breeding if not cleaned properly (Medrano et al., 2016), resulting in a loss of purity in rice seeds. However, manual labor in agricultural work poses health risks to workers. According to a report by the US Bureau of Labor Statistics (2019), workers in agricultural careers are consistently in the top-ten rank for injury and illness probabilities. Thai rice field workers, as reported by Sombatsawat et al. (2019), often experience symptoms of injury during and after fieldwork, including back and neck pain. As mentioned earlier, the harvest of photoperiod-sensitive rice must be completed within 14 days, additionally, uneven land and varying rice stalk conditions (upright, lodged, and inundated), lead to different levels of work difficulty and injury risk for workers, depending on their working postures, as displayed in Figure 1. Workers in inundated fields, where they must bend their bodies frequently, face the highest risk of physical injury (Taechasubamorn et al., 2011) and fatigue (Pirmoradi et al., 2017). Fatigue from working can affect work efficiency (Ahmed et al., 2017), leads to work-related musculoskeletal disorders (WMSDs), and later can result in an incapacity for work.

WMSDs encompass illnesses and discomforts affecting the musculoskeletal system, in which the causes are multifactorial (World Health Organization, 1985; Yassi, 2000). A high prevalence of

Figure 1. Working postures with three risk stalk types

musculoskeletal problems is widespread among rice farmers, and this prevalence is influenced by various associated factors, such as age, gender, and body mass index (BMI) throughout the entire rice-growing process. (Luangwilai et al., 2014). Workers reported experiencing pain in different parts of their bodies depending on the tasks they performed (Poochada et al, 2022). The symptoms are often alleviated through the use of medications. Pain relievers were the most used form of self-medication among farmers (Nguyen et al, 2023). However, this treatment is not a cure for the underlying causes and may lead to adverse reactions. Therefore, it is essential to enhance the agricultural management system in the rice growing process to improve efficiency and implement strategies to reduce work-related pain. To address these concerns, ergonomics, an applied science concerned with designing and arranging workplaces so that people and workplaces interact most efficiently and safely (Bridger, 1995) is often employed. Ergonomic risk assessments have been applied in both the industrial and agricultural sectors, with numerous tools and methods developed to assist workers in assessing incorrect postures and related activities, aiming to improve these postures to reduce the risk of work-related injuries, which are a key cause of WMSDs. Once the risk assessment is completed and the necessary correction is determined, the next step is to ergonomically redesign or adjust the workplace, including workstations, tools, and other elements of the working environment. However, in some circumstances, there are some limitations to implementing the ergonomic approach.

Job rotation, defined as the process of switching a person from one job to another (Edwards, 2015), offers an effective management approach that can be used in place of ergonomic solutions. It involves the scheduled interchange of employees within the workplace and has proven advantages across various sectors. Job rotation can increase productivity, enhance job satisfaction, ensure fairness in workload distribution, increase working capacity, improve work efficiency, and reduce costs (Jonsson, 1988; Techawiboonwong & Yenradee, 2003; Jaturanonda & Nanthavanij, 2011; Nasiri & Rahvar, 2017; Sadjadi et al., 2014; Rerkjirattikal et al., 2020). Job rotation, which is used to balance tasks among workers, has been proven to reduce the risk of WMSDs (Pual et al., 1999; Mehdizadeh et al., 2020), protecting against occurrences of WMSDs (Jonsson, 1988). Although it has many applications in the agricultural sector, job rotation models have not been made available enough in this sector. As important as job rotation are adequate rests or breaks, which can also enhance work efficiency, reduce fatigue, and prevent accidents (Li et al., 2020). Apart from ergonomic concerns, cost is an important consideration for all rice field owners. When all rice fields are ready for harvest at a similar time, field owners prefer hiring workers with cheaper wages. Field owners must compete among themselves for available local workers. Therefore, it is necessary to establish collaboration among field owners to allocate costs fairly. A collaborative approach is essential for achieving sustainability within the organization or supply chain (Takhom et al., 2020). These efforts lead to a favorable social impact and an increase of happiness in people's lives. Collaboration can reduce total costs, improve work flexibility, and enhance organizational efficiency through the sharing of resources and workers' skills. (Cai et al., 2017; Matsushita et al., 2021).

This study proposes a harvesting plan for all field owners tasked with producing rice seeds that involves rotating manual workers to harvest different types of rice stalks in multiple fields over continuous periods and days. Each type of rice stalk has a differing degree of impact on the physical risk taken by the worker. Factors such as the age, gender, and BMI of the workers are considered significant factors for the increase of injury risk. The primary contribution of this study is the development of a multi-objective job rotation model that reflects the interests of two stakeholders in rice harvesting by reducing the physical injury risk for harvesting workers and reducing costs for field owners. Moreover, it aims to ensure equitable risk distribution among workers and equitable cost sharing among field owners. This collaborative harvesting rotation model benefits both field owners and workers, enabling sustainable relationships, with workers experiencing reduced injury risks, while field owners share costs and save on labor expenses.

2. LITERATURE REVIEW

Presently, each of the popular ergonomic assessment methods used in agriculture has its own unique characteristics. They include the Ovako Working Posture Analysis System (OWAS), developed by Karhu et al., (1977), which has been popular because of its simplicity, as it considers the worker's body as a whole. Rapid Upper Limb Assessment (RULA), developed by McAtamney and Corlett (1993) is suitable for assessing jobs in sitting posture, as it focuses on assessing the upper body. For the agricultural sector, the Agricultural Lower Limb Assessment (ALLA), developed by Kong et al. (2010), is a tool to assess the lower body of workers. Later, Kong developed the Agricultural Upper Limb Assessment (AULA), to assess the upper body of workers, and the Agricultural Whole-Body Assessment (AWBA), which is a combination of ALLA and AULA. Although AWBA can assess the main body parts, such as the body, back, shoulders, and arms, it is not in very detailed. The assessment tool that can completely assess the entire body is the Rapid Entire Body Assessment (REBA), developed by Hignett and McAtamney (2000). REBA has been used to assess working posture in agricultural work in various studies, including those by Kamendra et al. (2019) and Jain et al. (2018). In rice seed harvesting, workers use all parts of the body, making AWBA a seemingly good fit. However, AWBA primarily evaluates only major body parts, which may not provide sufficient detail for evaluating the posture involved in rice seed harvesting. Consequently, this study selected REBA as the preferred method for posture evaluation.

On the basis of the literature reviews, several characteristics of workers, namely age, gender, and BMI, can increase the risk of WMSDs. Age can influence the increased risk of musculoskeletal pain in certain parts of the body. Rice farmers of higher age were found to be associated with a degree of pain in elbows, lower arms, and lower back (Sombatsawat et al., 2019). In terms of gender, rice farmers, both men and women, often suffer from discomfort or pain in different parts of their bodies. However, it was found that during various rice farming activities, women experienced much more discomfort than men (Das, 2015). Similar findings were also observed among Thai rice farmers (Luangwilai et al., 2014; Sombatsawat et al., 2019). It was speculated that this could be due to the fact that, in addition to working regularly in the rice fields, women farmers also engage in many household activities, which could exacerbate discomfort or pain in various body parts. Concerning the BMI factor, a previous study in the working population reported an association between BMI and musculoskeletal symptoms (Viester et al., 2013). The results revealed that obese employees were at a higher risk of developing symptoms and less recovery from symptoms than normal-weight employees. A study of Thai rice farmers also identified BMI as one of the factors associated with musculoskeletal disorders. It was indicated that farmers with abnormal BMI had a greater probability of having a higher total body pain score than those with normal BMI (Luangwilai et al., 2014). This suggested that weight reduction in farmers with overweight and obesity may be an effective way to reduce the incidence of musculoskeletal problems.

The model addressed in this study is a multi-objective optimization model. It has been applied widely across various research domains (Deb, 2014). Three primary approaches have been established to solve the multi-objective optimization problem (MOP): a priori, interactive, and a posteriori (Hwang & Masud, 1979). The a priori approach involves gaining information about decision maker preference before the optimization process. This information, often referred to as weights, tells which objective is more preferred by the decision maker over another. A well-known method within this approach is the weighted sum method, as described by Deb (2014). Examples of illustrative research that utilize the weighted sum method to solve MOPs are the studies of Sandar (2019), Tram and Raweewan (2021), and Thippo et. al. (2022). The interactive approach, on the other hand, involves expressing preference information during the optimization process. This method involves continuous interacting with the decision maker. In each iteration, the decision maker has to determine preferences to obtain Pareto optimal solutions aligned with their interests. An example of the interactive approach is the lexicographic weighted Tchebycheff method, as introduced by Steuer (1986), and the research of Varas et al., (2020). The a posteriori approach aims to generate all possible Pareto solutions simultaneously, allowing the decision maker to select their preferred Pareto solution from the set as their final solution. This approach requires the longest computational time. One example of the a posteriori approach is the Ɛ-constraint method (Hwang & Masud, 1979) and the research of Sarker & Ray (2009). Another example of this approach is the augmented Ɛ-constraint (AUGMECON) developed by Mavrotas (2009), which is selected to solve MOP in this study.

This study focuses exclusively on multi-objective optimization related to crop harvesting problems. There are other examples of multi-objective optimization studies in crop harvesting. For instance, Fathollahi-Fard et al., (2023) proposed a model to facilitate sustainable harvest planning to minimize both economic and environmental objectives. Thippo et al., (2022) addressed collaborative rice seed harvesting, optimizing objectives such as average total cost, the number of harvesting days, workload distribution, and worker satisfaction. Aliano Filho et al. (2021) presented a method for planning sugarcane harvesting and transportation to minimize costs and time. He & Li (2018) solved the routing problem for wheat harvesting and transportation, also aiming to minimize cost and time. Florentino et al., (2018) examined sugarcane harvesting with a multi-objective approach, aiming to maximize the sweetness of harvested sugarcane while minimizing transportation costs for mechanical harvesters between sugarcane farmers. Sethanan and Neungmatcha (2016) developed a sugarcane harvester route plan to minimize distance and maximize yield. Table 1 provides a summary of MOPs related to crop harvesting, outlining five key characteristics of the literature review. The "crop" category specifies the crop studied in each reviewed work, while the "harvest method" category indicates the choices of manual or machine methods utilized in harvesting. The "solving approach" indicates whether

Table 1. Summary of the MOP literature review on crop harvesting problems

Paper	Crop	Harvest method		Solving approach			Number of objective functions	Objective function element								
		Manual	Machine	A priori	Interactive	A posteriori		Profit/Cost/Loss	Time	Yield/Efficiency	Waste/Quality	Carbon emission	Resource used	Satisfaction	Fairness/Equity	Injury risk
Fathollahi-Fard et al., 2023	Blueberry		✓			✓	3	✓			✓	✓				
Aliano Filho et al., 2023	Sugarcane		✓			✓	3	✓	✓	✓						
Thippo et al., 2022	Rice seed	✓		✓			4	✓	✓					✓	✓	
Aliano Filho et al., 2021	Sugarcane		✓			✓	2	✓	✓							
Jarumaneeroj et al., 2021	Sugarcane		✓			✓	4	✓		✓		✓				
Jarumaneeroj et al., 2021	Sugarcane		✓			✓	3		✓	✓					✓	
Varas et al., 2020	Grape	✓	✓		✓		2	✓			✓					
He and Li, 2018	Wheat		✓			✓	3	✓	✓				✓			
Florentino et al., 2018	Sugarcane		✓			✓	3	✓	✓						✓	
Sethanan and Neungmatcha, 2016	Sugarcane		✓			✓	2	✓		✓						
This study	Rice seed	✓				✓	4	✓							✓	✓

the methods employed are a priori, interactive, or a posteriori. The "number of objective functions" indicates the count of objective functions considered in each paper. Finally, the "objective function elements" comprise diverse objectives, including profit/cost/loss, time, yield/efficiency, waste/quality, carbon emission, resources used, satisfaction, fairness/equity, and injury risk. As depicted in Table 1, there is a limited number of studies focusing on manual harvesting. Additionally, only a few studies have researched seed production, specifically rice seed, which typically demands gentler harvesting techniques than other crops.

In summary, the significant contributions of this study are as follows:

1. This is the first work to apply a job rotation strategy to schedule workers in the agricultural sector, specifically for the manual harvesting of rice seeds. The primary objective is to reduce and balance the physical injury risk among workers.
2. This study is the first to consider the individual characteristics of workers, including age, gender, and BMI, as significant factors that influence injury risk, as assessed by an ergonomic tool.

3. METHODOLOGY

3.1 REBA Method

The REBA ergonomic assessment tool was designed specifically for a rapid evaluation of the risk of WMSDs associated with specific job tasks. It employs a systematic approach to evaluate both upper and lower parts (i.e., the entirety) of the musculoskeletal system. The REBA considers various factors, including postural load requirements, forceful exertions, types of movement or action, repetition, and coupling. The REBA method utilizes a single-page worksheet for ergonomic risk assessment, divided into two sections: section A addresses the neck, trunk, and legs, while section B focuses on the arms and wrists. Once data on posture, force, and repetition for each body region are collected and scored, a composite score representing the overall level of WMSD risk is calculated. The REBA score ranges from a minimum of 1 to a maximum of 15. In this study, REBA is used to evaluate WMSD risk by assessing the working postures of a typical worker, who is male, has a normal BMI, and is of average working age (20–40 years). The REBA scores of workers who are different from the typical worker are adjusted to determine their injury risk termed as risk loads.

3.2 Augmented Epsilon (Ɛ) Constraint (AUGMECON)

In a multi-objective optimization model, objectives often conflict with each other. A Pareto optimal solution is employed to address this issue. Augmented Ɛ-constraint (AUGMECON), an innovative adaptation of the ε-constraint method (Haimes et al., 1971), is a method used to solve multi-objective models, as developed by Mavrotas (2009). The AUGMECON method optimizes one of the most important objective functions while using the constraints of the remaining objective functions. The strength of this method is that it does not require random weighting of objectives; thus it can enhance computational efficiency and find efficient optimal solutions faster. AUGMECON is employed to identify Pareto or efficient solutions within a multi-objective mathematical model. It generates a set of solutions, enabling the decision maker to choose the most preferred or suitable one. Thus, it can guarantee an appropriate solution. In practice, the Ɛ-constraint method can effectively handle small to medium-sized MOPs, providing a representative subset of the Pareto set. However, it might struggle with larger MOPs, resulting in weak solutions. Therefore, AUGMECON was developed to address large-sized MOPs that can obtain efficient solutions. The formulation of AUGMECON can be expressed as follows:

$$\max\left(f_1\left(x\right) + eps \times \left(s_2 + s_3 + \ldots + s_i\right)\right)$$

s.t.

$$f_2(x) - s_2 = e_2$$
$$f_3(x) - s_3 = e_3$$
$$\vdots$$
$$f_i(x) - s_i = e_i$$
$$x \in S \text{ and } s_i \in R^+ \quad (1)$$

where eps is a small number, typically ranging between $10^{-3} - 10^{-6}$, e_i is the right-hand side of each constrained objective function, s_i is a slack variable designed to prevent weakly efficient solutions, and r_i is the range of the i th objective function. To avoid scaling issues, it is necessary to divide each s_i by r_i. Consequently, the objective function in Equation 1 can be expressed as follows:

$$\max\left(f_1(x) + eps \times \left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \ldots + \frac{s_n}{r_n}\right)\right) \quad (2)$$

The AUGMECON method consists of the following steps:

1. Lexicographic optimization of the objective functions to create a payoff table. This optimization procedure consists of two phases: first, optimizing the value of the first objective function, and second, optimizing the value of the second objective function by imposing a constraint on the value of the first objective function. In cases with more than two objectives, the process continues by sequentially adding constraints from the previously optimized objectives until all constraints are covered.
2. Once the payoff table is complete, grid points are computed on the basis of the ranges of the secondary objective functions. The number of grid points can be set according to the preferences of the decision maker. One common approach is to divide the ranges of each objective function into 10 equal intervals and utilize the resulting 11 grid points derived from the e_i values in Equation 1.
3. The AUGMECON method proceeds to solve the model and obtain the optimal solutions on the basis of the grid points and constraints.

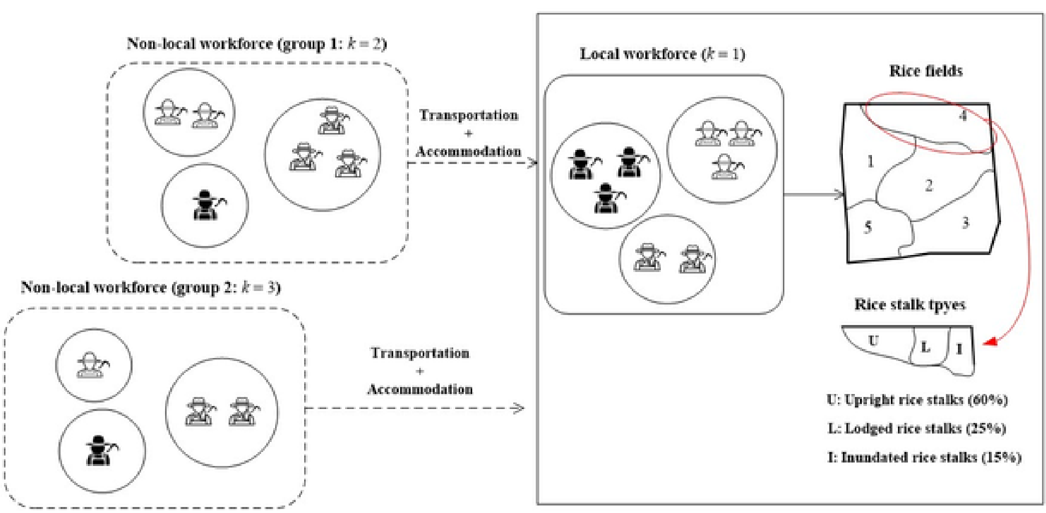
4. RICE SEED HARVESTING PROBLEM

4.1 Problem Description

This paper focuses on registered rice seeds cultivated in Ubonratchathani province, Thailand. A Thai governmental unit, called the Rice Department (RD), is a unit that oversees rice seed production. The RD comprises two centers: the Rice Research Center (RRC) and the Rice Seed Center (RSC). Generally, the RRC is responsible for rice breeding, producing breeder seeds, and planting foundation rice seed, while registered rice seeds are propagated under the monitoring of the RSC and distributed to a group of rice field owners, who often live and have their rice fields and in the same vicinity (or, in the same village), and who then cultivate the seeds into certified rice seeds. These rice seed field owners have to become members of the RSC and make an agreement to produce the certified rice seeds in a quantity mutually agreed on by the field owners and the RSC. The breeder seed in this study is Thai jasmine rice, or *kao hom mali* in the Thai language. Thai jasmine rice is well known globally as the best rice in the world because of its unique flavor, fragrance, and texture, consistently ranking as a top-exported rice variety for years. The RSC requires the use of manual harvesting, performed by workers with their individual sickle, for Thai jasmine-registered rice seed production to meet quality standards.

Each rice field owner possesses only one rice field. In each field, there are three different rice stalk types, ranked from the easiest to the most difficult to harvest; these are upright, lodged, and inundated rice stalks. The harvesting workforce hired by the rice field owners consists of two primary groups: local and nonlocal workers. The local workforce consists of workers who live in the same area, often within the same village, as the rice fields, while nonlocal workers are from different areas than the rice fields. The nonlocal workforce can be subdivided into two groups, called nonlocal group 1 and nonlocal group 2, differentiated by distance. The workers in the first subgroup live farther away than the other subgroup. The information on workforce groups and rice stalk types is expressed in Figure 2. The workforce's harvesting capabilities vary with factors such as age, gender, and BMI. The RSC assigns each rice field owner a specific production quantity based on their rice field size. Each rice field owner must estimate the minimum daily production quantity to provide enough meals and drinks for the workers. However, if the production gained from harvesting is lower than this estimation, the rice field owner must incur the cost of the deducted production. Harvesting is contained for 14 days to maintain the high quality of rice. Each working day is divided into two periods in the morning and another two periods in the afternoon, for a total four periods within a day; there is a one-hour lunch break between morning and afternoon. Each working period spans one and a half hours. The REBA is used to evaluate WMSD risks by assessing working postures across three rice stalk types. The score of each worker, obtained from the REBA, will be leveled up in different degrees depending on individual age, gender, and BMI; this score is termed "risk load." A worker's risk load in a working interval is the sum of the risk loads taken over continuous periods. To protect a worker from physical injury risk and fatigue, the RSC specifies a maximum allowable risk load. A worker's risk load must remain below this threshold; otherwise, a break will be enforced to reset the risk load. The lunch break between morning and afternoon periods automatically resets the risk load.

Figure 2. Workforce groups and rice stalk types



The solution to this problem involves determining which worker is assigned to work on which job. A job in this problem represents a specific rice stalk type in a specific rice field, period, and day. Thus, workers can rotate to work on various jobs, including jobs in different rice stalk types, rice fields, periods, and days, within the 14-day horizon. A worker assigned to work on a job is referred to as a laborer. The optimal solution is to achieve four objectives: minimizing the average injury risk load per job, minimizing the variance (i.e., the mean square error) of injury risk load among workers, minimizing average wage cost per job for rice field owners, and minimizing the variance of wage cost per job among rice field owners.

4.2 Notations

Indices:

i : Index of rice field owners in set $I = \{1,2,\ldots,I\}$, where rice field is owned by a single rice field owner, i.e., rice field owner i owns rice field i). Note that the term "rice field owner" and "rice field" are used interchangeably depending on the context.

j : Index of rice stalk types in set $J = \{1,2,\ldots,J\}$.

k : Index of workforce locations in set $K = \{1,2,\ldots,K\}$.

l_k : Index of workers in set $L_k = \{1,2,\ldots,L_k\}$. All L_k where $k \in K$ are mutually exclusive, and $\bigcup_{k=1}^{K} L_k = L$ where L is the set of all workers from all locations.

t : Index of time periods in the time horizon in set $T = \{1,2,\ldots,T\}$.

p_m : Index of time periods in the morning in each day in set $P_m = \{1,2,\ldots,P_m\}$.

p_a : Index of time periods in the afternoon in each day in set $P_a = \{1,2,\ldots,P_a\}$.

Parameters:

$Cap_{ijkl_k}^{tp_m}$: Quantity of rice seeds that worker l_k from workforce location k can harvest from rice field i rice stalk type j in period p_m on day t (tons/period).

$Cap_{ijkl_k}^{tp_a}$: Quantity of rice seeds that worker l_k from workforce location k can harvest from rice field i rice stalk type j in period p_a on day t (tons/period).

CH_k : Wage of a worker from workforce location k (Thai baht (THB)/ton).

CP : Loss cost if the quantity of rice seeds harvested from any rice field is less than the expected minimum daily quantity of that rice field (THB/ton).

D_i : Quantity of rice seeds demanded by the RSC from rice field i (tons).

Q_i : Maximum quantity of rice seeds that can be harvested from rice field i throughout the planning horizon (tons).

V_i : Expected minimum daily quantity of rice seeds to be harvested from rice field i (tons/day).

M : A very large positive number.

MRL : Maximum allowable risk load (risk points).

$RL_{ijkl_k}^{tp_m}$: Risk load of worker l_k from workforce location k when harvesting in rice field i rice stalk type j in period p_m on day t (risk points).

$RL_{ijkl_k}^{tp_a}$: Risk load of worker l_k from workforce location k when harvesting in rice field i rice stalk type j in period p_a on day t (risk points).

Decision Variables:

$$X_{ijkl_k}^{tp_m} = \begin{cases} 1, \; If\,worker\;\; l_k\; from\,workforce\,location\,k\,is\,assigned\,to\,work\,in\,rice\,field\,i \\ rice\,stalk\,type\,j\,in\,period\,p_m\,on\,day\,t \\ 0, Otherwise \end{cases}$$

$$X_{ijkl_k}^{tp_a} = \begin{cases} 1, \; If\,worker\;\; l_k\; from\,workforce\,location\,k\,is\,assigned\,to\,work\,in\,rice\,field\,i \\ rice\,stalk\,type\,j\,in\,period\,p_a\,on\,day\,t \\ 0, Otherwise \end{cases}$$

$W_{kl_k}^t$: If worker l_k from workforce location k is assigned to work in at least one rice field during at least one period on day t (at least one job on each day), this worker will be counted as a worker who works on day t where:

$$W_{kl_k}^t = \begin{cases} 1, \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{p_m=1}^{P_m} \sum_{p_a=1}^{P_a} \left(X_{ijkl_k}^{tp_m} + X_{ijkl_k}^{tp_a} \right) \geq 1, \;\; \forall k, l_k, t \\ 0, \;\; Otherwise \end{cases}$$

$Y_{ikl_k}^t$: If rice field i is worked by worker l_k from workforce location k on day t where:

$$Y_{ikl_k}^t = \begin{cases} 1, \sum_{j=1}^{J} \sum_{p_m=1}^{P_m} \sum_{p_a=1}^{P_a} \left(X_{ijkl_k}^{tp_m} + X_{ijkl_k}^{tp_a} \right) \geq 1, \;\; \forall i, k, l_k, t \\ 0, \;\; Otherwise \end{cases}$$

Z_{kl_k} : If worker l_k from workforce location k is assigned to work at least one job over the entire planning horizon, this worker will be counted as a worker in this harvest planning where:

$$Z_{kl_k} = \begin{cases} 1, \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{p_m=1}^{P_m} \sum_{p_a=1}^{P_a} \left(X_{ijkl_k}^{tp_m} + X_{ijkl_k}^{tp_a} \right) \geq 1, \;\; \forall k, l_k \\ 0, \;\; Otherwise \end{cases}$$

4.3 Multi-Objective Optimization Model

In this section, a multi-objective optimization model, which is a nonlinear model, for the rice seed harvesting problem is presented under the following assumption:

1. Harvesting rice seeds in each rice field is independent.

2. A laborer can work on only one job within any period, ensuring an equal number of jobs and laborers throughout the planning horizon.
3. Weather conditions do not affect worker performance or rice seed production.
4. Workers cannot switch to harvest in the other rice fields within a single day.

This model is expressed as follows:

$$Min \frac{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\left(\frac{\sum_{p_m=1}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}\right)Y_{ikl_k}^{t}\right)+\sum_{p_a=1}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right)}{\sum_{p_m}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_m}\right)+\sum_{p_a}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_a}\right)}\right)}{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}Z_{kl_k}} \tag{3}$$

$$Min \frac{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\left(\left(\frac{\sum_{p_m=1}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}\right)Y_{ikl_k}^{t}\right)+\sum_{p_a=1}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right)}{\sum_{p_m}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_m}\right)+\sum_{p_a}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_a}\right)}\right)-\overline{RL}\right)^2}{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}Z_{kl_k}} \tag{4}$$

$$Min \frac{\sum_{i=1}^{I}\left(\frac{\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}CH_k\left(Cap_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}+CP\sum_{t=1}^{T}\max\left(V_i-\left(\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(Cap_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right),0\right)}{\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}w_{ikl_k}^{t}}\right)}{I} \tag{5}$$

$$Min\frac{\sum_{i=1}^{I}\left(\left(\frac{\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}CH_k\left(Cap_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}+CP\sum_{t=1}^{T}\max\left(V_i-\left(\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(Cap_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right),0\right)}{\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}w_{ikl_k}^{t}}\right)-\overline{C}\right)^2}{I} \quad (6)$$

s.t.

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}(Cap_{ijkl_k}^{tp_m}X_{ijkl_k}^{tp_m})Y_{ikl_k}^{t}+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_a=1}^{P_a}(Cap_{ijkl_k}^{tp_a}X_{ijkl_k}^{tp_a})Y_{ikl_k}^{t}\geq D_i,\forall i \quad (7)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\left(Cap_{ijkl_k}^{tp_m}X_{ijkl_k}^{tp_m}\right)Y_{ikl_k}^{t}+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_a=1}^{P_a}\left(Cap_{ijkl_k}^{tp_a}X_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\leq Q_i,\forall i \quad (8)$$

$$\sum_{i=1}^{I}\sum_{J=1}^{J}X_{ijkl_k}^{tp_m}\leq 1,\forall k,l_k,t,p_m \quad (9)$$

$$\sum_{i=1}^{I}\sum_{J=1}^{J}X_{ijkl_k}^{tp_a}\leq 1,\forall k,l_k,t,p_a \quad (10)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(X_{ijkl_k}^{tp_m}+X_{ijkl_k}^{tp_a}\right)\leq MW_{kl_k}^{t},\forall i,k,l_k,t \quad (11)$$

$$\sum_{j=1}^{J}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(X_{ijkl_k}^{tp_m}+X_{ijkl_k}^{tp_a}\right)\leq MY_{ikl_k}^{t},\forall i,k,l_k,t \quad (12)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(X_{ijkl_k}^{tp_m}+X_{ijkl_k}^{tp_a}\right)\leq MZ_{kl_k},\forall k,l_k \quad (13)$$

$$\sum_{i=1}^{I} Y_{ikl_k}^{t} \leq 1, \forall k, l_k, t \tag{14}$$

$$\sum_{i=1}^{I}\sum_{J=1}^{J} RL_{ijkl_k}^{tp_m} X_{ijkl_k}^{tp_m} + \sum_{i=1}^{I}\sum_{J=1}^{J} RL_{ijkl_k}^{tp_{m+1}} X_{ijkl_k}^{tp_m} \leq MRL, \forall k, l_k, t, p_m \tag{15}$$

$$\sum_{i=1}^{I}\sum_{J=1}^{J} RL_{ijkl_k}^{tp_a} X_{ijkl_k}^{tp_a} + \sum_{i=1}^{I}\sum_{J=1}^{J} RL_{ijkl_k}^{tp_{a+1}} X_{ijkl_k}^{tp_a} \leq MRL, \forall k, l_k, t, p_a \tag{16}$$

$$X_{ijkl_k}^{tp_m} \in \{0,1\}, \forall i, j, k, l_k, t, p_m \tag{17}$$

$$X_{ijkl_k}^{tp_a} \in \{0,1\}, \forall i, j, k, l_k, t, p_a \tag{18}$$

$$W_{ikl_k}^{t} \in \{0,1\}, \forall i, k, l_k, t \tag{19}$$

$$Y_{ikl_k}^{t} \in \{0,1\}, \forall i, j, k, l_k, t \tag{20}$$

$$Z_{kl_k} \in \{0,1\}, \forall k, l_k \tag{21}$$

The first objective function, as expressed in Equation 3, aims to minimize the average risk load per job for workers. To calculate the average risk load per job, it has to sum the average risk loads per job for each worker and then divide by the total number of workers. The average risk load per job for each worker is determined by summing the risk loads from all jobs they perform and dividing by the number of jobs. The second objective in the model, as expressed in Equation 4, is to minimize the variance of risk loads among the workers. The third objective function, expressed in Equation 5, is to minimize the average wage cost per job for rice field owners. This is calculated by summing the average wage costs per job for each rice field owner and then dividing by the total number of rice field owners. The average wage cost per job for each rice field owner is determined by dividing the total wage cost paid to all laborers (or for all jobs) by the number of jobs or laborers. The fourth objective function, expressed in Equation 6, is to minimize the variance of wage costs per job among rice field owners. To ensure that the total quantity of harvested rice seeds from each rice field meets the total demand agreed on with the RSC and does not exceed the maximum quantity that can be harvested from each rice field, these constraints can be expressed in Equations 7 and 8, respectively. Equations

9 and 10 restrict workers, ensuring that they work at most only one rice field and one specific rice stalk type during each morning and afternoon period of each day. Equations 11 to 13 define the if-conditions for the decision variables. Equation 14 restricts workers from switching between rice fields on the same day. Equations 15 and 16 set limits on the total risk load for each worker during morning and afternoon periods, ensuring that it does not exceed the maximum risk load determined by the RSC. Lastly, Equations 17 to 21 indicate that all decision variables must be binary numbers.

4.4 AUGMECON Model

The multi-objective nonlinear model in section 4.3, as reformulated to fit the AUGMECON model, can be written as follows:

$$Min \frac{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\left(\frac{\sum_{p_m=1}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_m} x_{ijkl_k}^{tp_m}\right)Y_{ikl_k}^{t}\right)+\sum_{p_a=1}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_a} x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right)}{\sum_{p_m}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_m}\right)+\sum_{p_a}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_a}\right)}\right)}{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}Z_{kl_k}} + eps \times \left(\frac{s_2}{r_2}+\frac{s_3}{r_3}+\frac{s_4}{r_4}\right) \tag{22}$$

s.t.

$$\frac{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\left(\left(\frac{\sum_{p_m=1}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_m} x_{ijkl_k}^{tp_m}\right)Y_{ikl_k}^{t}\right)+\sum_{p_a=1}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(RL_{ijkl_k}^{tp_a} x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right)}{\sum_{p_m}^{P_m}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_m}\right)+\sum_{p_a}^{P_a}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}x_{ijkl_k}^{tp_a}\right)}\right)-\overline{RL}\right)^2}{\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}Z_{kl_k}} + s_2 = e_2 \tag{23}$$

$$\frac{\sum_{i=1}^{I}\left(\frac{\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}CH_k\left(Cap_{ijkl_k}^{tp_m} x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a} x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t} + CP\sum_{t=1}^{T}\max\left(V_i-\left(\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(Cap_{ijkl_k}^{tp_m} x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a} x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right),0\right)}{\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}w_{ikl_k}^{t}}\right)}{I} + s_3 = e_3 \tag{24}$$

$$\frac{\sum_{i=1}^{I}\left(\left(\frac{\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}CH_k\left(Cap_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}+CP\sum_{t=1}^{T}\max\left(V_i-\left(\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}\sum_{p_m=1}^{P_m}\sum_{p_a=1}^{P_a}\left(Cap_{ijkl_k}^{tp_m}x_{ijkl_k}^{tp_m}+Cap_{ijkl_k}^{tp_a}x_{ijkl_k}^{tp_a}\right)Y_{ikl_k}^{t}\right),0\right)}{\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{l_k=1}^{L_k}\sum_{t=1}^{T}w_{ikl_k}^{t}}\right)-\overline{C}\right)^2}{I}+s_4=e_4 \tag{25}$$

and Equations 7 to 21.

It should be noted that since the secondary objective functions involve minimization, the operation within Equations 23, 24, and 25 between the objective function (the first term) and the slack (the second term) must be changed from subtraction to addition.

4.5 Data

The sample problem consists of five rice fields. The rice stalk types are categorized as upright, lodged, and inundated rice stalks, with assumed proportions of 60%, 25%, and 15%, respectively. The available time for harvesting is 14 days, with each working day divided into two morning and two afternoon periods, separated by a one-hour lunch break. The demands and maximum production capacities for each rice field, shown in Table 2, vary based on the size of the rice field. There are three workforce groups or locations, with 15, 10, and 5 workers, respectively, in location 1 (local), location 2 (nonlocal group 1), and location 3 (nonlocal group 2). These 30 workers have variations of age (53.33% between 20 and 40 years, 46.67% between 41 and 60 years), BMI (classified into four categories according to Asian populations; WHO Expert Consultation, 2004; 13.33% underweight, 46.67% normal, 26.67% overweight, and 13.33% obese), and gender (56.67% male and 43.33% female). The quantity of rice that a worker can harvest per period (Chinsuwan et al., 2000) is shown in Table 3. These quantities

Table 2. Demand and maximum production of rice seed

Rice fields no.	Demand (tons)	Maximum production (tons)
1	15.00	18.00
2	10.00	12.00
3	13.00	15.60
4	12.00	14.40
5	14.00	16.80

Table 3. Quantity of rice seed a worker is capable of harvesting

Rice stalk type	Quantity of rice seed (tons/day)
Upright	*U* (0.16-0.22)
Lodged	*U* (0.13-0.19)
Inundated	*U* (0.09-0.15)

vary on the basis of individual capabilities and the type of rice stalk being harvested. Therefore, the probability distribution for the quantity of rice harvested by each worker assumes a discrete uniform distribution for each type of rice stalk. These quantities follow a descending order of means and are generated randomly within a uniform range relative to the worker's age, gender, and BMI.

The wages for local, nonlocal group 1, and nonlocal group 2 are 1,200; 1,300, and 1,500 THB per ton, respectively. Additionally, there is a loss cost of 500 THB for each ton below the expected quantity. The minimum quantity of rice expected from a worker is 0.125 tons per day. By assessing the working posture of a typical worker when working in upright, lodged, and inundated rice stalk fields, the REBA scores are 3, 7, and 10, respectively. The risk loads of workers are uniformly distributed, as presented in Table 4. Workers face a high risk when the REBA score falls within the range of 8–10. Consequently, the RSC has set a maximum risk load of 16, permitting workers to remain in a high-risk state for a maximum of two consecutive working periods. For the computational experiment, optimization software named What's*Best!* (Version 16.0.2.5) was utilized on a PC with an Intel Core i7-6700 CPU @ 3.40 GHz and 8.00 GB RAM.

5. RESULTS AND DISCUSSIONS

Lexicographic optimization is initially used to construct a payoff table, as displayed in Table 5. Later, once the payoff table is complete, grid points are computed based on the ranges of the secondary objective functions. In this study, the objective function ranges are divided into four equal intervals, with five grid points (Table 6). In the final step, the objective function constraints are transformed into equalities by explicitly incorporating the appropriate slack variable.

The efficient solutions obtained by solving the AUGMECON formulation are presented in Table 7. There are five grid points and three secondary objective functions; a total of 5^3 or 125 iterations are performed to solve the AUGMECON model. In the first three iterations, the solution is found to

Table 4. Risk load of workers

Weight status of BMI	Upright	Lodged	Inundated
Underweight	*U* (3.5-4.5)	*U* (7.5-8.5)	*U* (10.5-11.5)
Normal	*U* (3-4)	*U* (7-8)	*U* (10-11)
Overweight	*U* (3.5-4.5)	*U* (7.5-8.5)	*U* (10.5-11.5)
Obese	*U* (4-5)	*U* (8-9)	*U* (11-12)

Table 5. Payoff table obtained by the lexicographic optimization

	f_1	f_2	f_3	f_4
$Min\ f_1$	6.035	0.499	210.933	33.129
$Min\ f_2$	6.218	0.199	201.142	32.284
$Min\ f_3$	6.270	0.645	201.084	20.006
$Min\ f_4$	6.228	0.567	207.347	0.673

Table 6. The value of the secondary objective functions in five grid points

Grid points	$f_2(x)$	$f_3(x)$	$f_4(x)$
g0	0.199	201.084	0.673
g1	0.311	203.547	8.787
g2	0.422	206.009	16.901
g3	0.534	208.471	25.015
g4	0.645	210.933	33.129

be infeasible. The resulting solution from the 93rd iteration contains the optimal primary objective function value and middle point all three secondary objective function values. To provide a clearer presentation, a three-dimensional graph (Figure 3) displays all the values from the 125 iterations shown in Table 7. The values of the primary objective and two secondary objectives are plotted on the Z-axis, X-axis, and Y-axis, respectively, while the values of the remaining secondary objective are represented by greyscale colors. it appears that solution number 93 might be the optimal choice among these 125 alternatives. However, it should be noted that this selection is based solely on the authors' judgment. In actual practice, the decision maker has to select the most suitable solution from this set.

Tables 8 and 9 present the harvesting plan from days 1 to 7 and from days 8 to 14, respectively. These tables detail which worker is assigned to which rice field on a given day, specifying the type of rice stalk they work with during each period. In both tables, the "U" stands for upright rice stalk, "L" stands for lodged rice stalk, "I" stands for inundated rice stalk, and "-" means rest periods or breaks from harvesting. For instance, on day one, worker 1 is assigned to four periods, harvesting upright, lodged, inundated, and upright rice stalks during periods 1, 2, 3, and 4, respectively. The result can be illustrated with the following examples. Worker number 5, a 32-year-old male with normal BMI, is assigned to all 56 jobs without assigned breaks. He works in 31 periods in upright fields, 15 in lodged fields, and 10 in inundated fields, resulting in an average risk load of 5.33. Worker number 25, a 60-year-old female with an obese BMI, is assigned to 33 out of 56 jobs with 23 assigned breaks. She works in 22 periods in upright fields, 11 in lodged fields, and none in inundated fields, resulting in an average risk load of 5.92. It is clear that the female worker, due to her individual characteristics, is assigned to less demanding jobs and fewer jobs overall than the male worker. Both workers share the workload and are not permitted to exceed the maximum risk load. However, the male worker can earn more income than the female worker.

6. CONCLUSION

This study focuses on the harvesting process of the second-generation rice seed, known as registered rice seed, of the photoperiod-sensitive variety. The optimal harvesting period of this rice variety spans only 14 days; any delay beyond this timeframe results in rice quality that does not meet the standard required by the RSC, a government unit responsible for rice seed production. Furthermore, manual harvesting is necessary to maintain the purity of the seeds. Consequently, a group of rice field owners, members of the RSC engaged in rice seed production, must hire manual harvesters concurrently. Rice fields have three distinct categories of rice stalks: upright, lodged, and inundated. Each type demands different working postures, depending on the difficulty level faced by the workers. In rice growing, including harvesting, farmers are commonly

Table 7. The value of the secondary objective functions solved by the AUGMECON

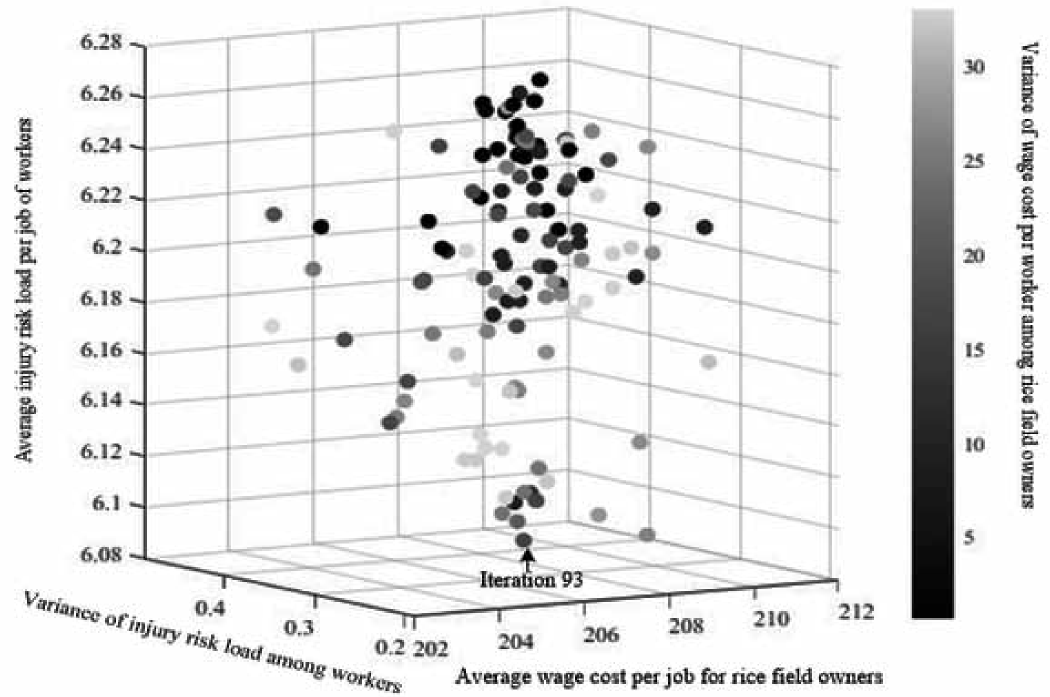
Iteration	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	Iteration	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$
1	*Infeasible*	*Infeasible*	*Infeasible*	*Infeasible*	63	6.138	0.364	205.126	16.772
2	*Infeasible*	*Infeasible*	*Infeasible*	*Infeasible*	64	6.139	0.373	205.466	25.408
3	*Infeasible*	*Infeasible*	*Infeasible*	*Infeasible*	65	6.149	0.390	207.703	33.040
4	6.179	0.391	209.362	25.280	66	6.208	0.436	210.334	0.712
5	6.199	0.397	207.624	32.754	67	6.219	0.405	210.113	8.623
6	6.235	0.302	208.410	0.710	68	6.213	0.389	208.189	17.407
7	6.194	0.296	209.466	8.865	69	6.116	0.356	208.448	24.302
8	6.186	0.229	205.240	16.917	70	6.104	0.370	207.979	32.255
9	6.178	0.199	205.292	27.008	71	6.249	0.426	209.161	0.697
10	6.180	0.202	203.257	31.667	72	6.099	0.397	208.748	8.357
11	6.238	0.369	209.440	0.690	73	6.103	0.360	208.478	16.391
12	6.199	0.392	210.173	8.957	74	6.106	0.366	208.325	24.302
13	6.237	0.296	206.747	17.204	75	6.107	0.389	209.349	32.087
14	6.189	0.303	207.853	25.763	76	6.252	0.436	208.839	0.702
15	6.187	0.347	207.720	32.420	77	6.257	0.415	209.257	8.563
16	6.236	0.413	208.696	0.702	78	6.238	0.424	207.555	16.496
17	6.221	0.398	209.250	8.864	79	6.241	0.382	208.740	24.271
18	6.253	0.293	206.816	17.581	80	6.245	0.427	206.555	32.651
19	6.214	0.191	207.621	27.143	81	6.201	0.426	210.401	0.712
20	6.190	0.224	206.460	32.883	82	6.181	0.368	208.253	8.960
21	6.255	0.393	208.638	0.697	83	6.213	0.394	209.150	17.881
22	6.221	0.203	209.101	8.892	84	6.232	0.381	208.233	24.353
23	6.195	0.415	210.332	16.891	85	6.120	0.410	208.346	32.930
24	6.195	0.365	209.649	26.304	86	6.199	0.415	207.435	0.712
25	6.163	0.251	210.216	31.662	87	6.169	0.436	209.079	8.616
26	6.218	0.410	208.231	0.703	88	6.166	0.420	205.247	17.532
27	6.235	0.420	209.466	8.823	89	6.188	0.360	208.867	27.038
28	6.190	0.382	206.243	18.043	90	6.146	0.366	207.987	32.109
29	6.249	0.328	209.109	26.011	91	6.241	0.426	209.449	0.696

continued on following page

Table 7. Continued

Iteration	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	Iteration	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$
30	6.204	0.310	209.640	32.149	92	6.104	0.380	208.775	11.091
31	6.239	0.421	209.318	0.705	**93**	**6.084**	**0.396**	**208.944**	**16.469**
32	6.180	0.378	208.193	8.510	94	6.169	0.376	207.669	25.679
33	6.197	0.310	206.202	16.836	95	6.179	0.362	209.669	33.028
34	6.250	0.311	207.116	25.077	96	6.237	0.415	210.328	0.709
35	6.202	0.313	209.272	32.468	97	6.201	0.418	209.352	11.091
36	6.227	0.397	209.346	0.693	98	6.198	0.418	210.023	16.469
37	6.213	0.306	208.328	8.940	99	6.092	0.390	210.580	27.991
38	6.232	0.313	208.248	17.787	100	6.125	0.415	208.332	32.963
39	6.177	0.312	205.021	25.159	101	6.231	0.432	209.586	0.696
40	6.189	0.309	209.193	32.719	102	6.196	0.396	208.419	8.652
41	6.245	0.408	209.050	0.702	103	6.186	0.426	207.244	16.819
42	6.218	0.313	210.211	8.793	104	6.144	0.398	208.793	27.156
43	6.239	0.311	209.137	17.493	105	6.186	0.429	208.472	32.829
44	6.128	0.307	209.787	27.274	106	6.217	0.363	203.479	0.709
45	6.226	0.307	208.796	32.948	107	6.185	0.375	209.341	8.596
46	6.202	0.489	208.686	0.695	108	6.184	0.437	207.423	16.854
47	6.214	0.391	208.251	8.538	109	6.141	0.410	206.442	26.453
48	6.241	0.381	209.619	17.101	110	6.162	0.380	203.306	31.884
49	6.243	0.308	209.992	26.970	111	6.246	0.465	209.519	0.690
50	6.119	0.411	208.749	33.074	112	6.192	0.378	209.157	8.691
51	6.234	0.415	208.384	0.711	113	6.146	0.434	207.031	17.264
52	6.185	0.391	208.852	8.913	114	6.144	0.385	208.583	25.839
53	6.222	0.397	207.773	16.408	115	6.120	0.369	207.258	32.324
54	6.252	0.412	208.919	26.905	116	6.236	0.415	209.669	0.703
55	6.240	0.378	209.575	31.942	117	6.197	0.421	207.669	8.695
56	6.254	0.409	209.475	0.695	118	6.093	0.383	208.522	20.945
57	6.235	0.399	209.381	8.557	119	6.097	0.380	208.102	24.386
58	6.218	0.414	203.456	18.179	120	6.117	0.401	207.669	32.324
59	6.201	0.361	203.255	24.375	121	6.261	0.419	209.815	0.712
60	6.175	0.409	203.310	33.052	122	6.218	0.427	209.088	8.829
61	6.233	0.403	209.122	0.695	123	6.188	0.420	209.860	16.532
62	6.193	0.394	208.449	8.806	124	6.179	0.422	208.847	27.109
					125	6.087	0.349	210.848	26.120

Figure 3. Three-dimensional graph of Pareto optimal solution



challenged by ergonomic issues caused by improper working postures and repetitive movements. Prolonged subjection to such work can lead to various bodily discomforts, and eventually to WMSDs. Medication treatment is not the best solution, due to the unexpected side effects. Thus, management is an effective way to prevent WMSDs from chronic pain or injury. This research employs an ergonomic assessment tool, REBA, to evaluate worker injury risk scores. Normally, each risk score provides a recommended action to prevent the injury of workers. These risk scores are adjusted on the basis of the individual age, gender, and BMI of workers and are termed "risk loads." This research aims to develop a harvest plan that minimizes and balances worker injury risk load per job while also optimizing wage costs per job for rice field owners. This problem is complex because of the high number of rice fields and of workers and the varying working conditions and high number of working periods. This problem is a decision-making problem with numerous feasible solutions. To find the optimal solution, a multi-objective optimization model with four objectives was developed and solved by the AUGMECON method, yielding 125 alternative solutions. The selected solution optimizes the primary objective of minimizing the average risk load per job for workers, while the secondary objectives align approximately in the middle values. This solution represents a well-balanced compromise. The resulting solution indicates a rotation of 30 workers from three locations, working across different rice stalk types in different fields over four daily periods for 14 days, along the entire harvesting timeframe. The significant constraints include limiting a worker's total risk load during consecutive periods to comply with the RSC. Secondly, if a worker's total risk load exceeds the maximum limit when continuing work in the next period, this worker is required to take a break in that period to protect against fatigue-related injuries or discomfort.

Table 8. Harvesting plan during days one to seven

Worker no.	Day																											
	1				2				3				4				5				6				7			
1	1				2				1				3				2				1				2			
	U	L	I	L	L	U	I	U	U	L	U	U	I	U	L	U	U	U	L	U	I	U	U	U	U	L	U	I
2	1				1				5				1				3				3				4			
	U	L	U	I	I	U	L	U	U	U	L	U	U	U	I	U	I	U	L	L	U	L	U	I	U	L	-	I
3	2				4				2				5				1				4				1			
	U	L	I	-	U	L	U	I	L	U	U	L	I	U	U	L	U	U	I	-	U	U	L	U	U	L	-	I
4	4				3				3				4				1				3				5			
	U	L	U	I	U	U	L	U	U	L	U	I	U	U	L	U	L	U	I	U	L	U	U	I	U	U	L	U
5	1				5				3				2				3				5				2			
	U	L	I	U	L	U	I	U	U	U	L	U	I	U	L	L	U	U	I	U	U	U	L	L	L	U	L	U
6	3				1				5				4				2				1				1			
	I	U	L	L	U	L	I	U	U	I	U	I	U	L	U	L	U	I	U	I	U	L	L	U	L	L	U	I
7	5				3				1				3				3				5				1			
	U	I	U	L	U	I	U	L	I	U	U	L	U	L	U	L	U	U	I	U	U	I	U	L	U	U	U	I
8	2				1				3				2				2				3				2			
	L	U	U	I	U	L	U	I	U	U	L	L	I	U	L	U	U	I	U	L	U	I	U	L	U	I	U	U
9	3				3				2				3				4				2				5			
	U	L	L	L	I	-	L	L	U	L	U	L	U	U	L	U	U	U	I	U	U	L	U	U	U	I	U	U
10	1				4				1				1				5				4				3			
	U	I	L	U	U	I	U	U	U	L	I	U	L	U	L	U	U	L	L	U	I	U	U	L	I	U	U	L
11	4				5				2				1				3				3				2			
	I	U	U	L	U	L	U	I	L	U	I	U	U	L	U	I	U	L	U	I	L	U	I	U	U	U	I	U
12	4				2				4				1				2				3				1			
	U	U	L	-	U	L	U	I	U	U	L	L	I	U	L	I	U	U	U	I	U	U	I	U	L	U	I	U
13	2				1				5				4				3				4				3			
	-	L	L	I	L	U	I	U	U	U	U	I	I	U	U	I	I	U	L	U	U	I	U	U	U	L	U	U
14	5				3				1				5				1				2				1			
	-	L	U	U	I	-	U	I	U	I	U	U	U	L	U	L	U	I	U	U	I	U	U	I	L	U	-	U
15	4				2				2				1				3				1				2			
	L	U	-	-	U	L	U	-	U	-	U	L	U	-	U	U	I	-	U	L	U	-	U	-	-	U	U	U
16	3				5				4				2				4				1				5			
	U	L	I	U	U	L	U	U	U	L	-	I	L	U	L	-	I	-	L	U	L	U	I	U	L	U	-	L
17	2				3				2				4				2				4				1			
	I	U	U	I	U	I	U	I	U	L	U	I	U	L	U	L	U	L	U	U	U	L	L	U	L	U	I	L
18	4				4				1				3				1				2				2			
	U	U	I	U	I	U	U	L	L	U	L	U	I	U	-	U	U	L	L	U	U	I	U	L	L	U	U	L
19	5				1				5				1				2				1				4			
	L	-	U	I	L	U	I	U	I	U	U	L	L	U	U	I	I	U	U	U	U	I	U	U	-	L	U	I
20	4				3				3				3				1				3				4			
	L	U	U	I	U	L	U	I	U	U	L	U	U	U	L	U	I	U	L	U	U	U	L	U	U	U	L	-

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Table 8. Continued

Worker no.	Day																											
	1				2				3				4				5				6				7			
21	2				2				4				1				1				1				2			
	U	L	I	U	I	U	I	U	I	U	U	L	I	U	L	U	L	U	L	U	I	U	L	U	L	L	I	-
22	3				4				4				1				3				2				3			
	L	U	U	I	U	L	U	I	U	L	U	I	L	U	-	I	U	L	U	U	U	I	U	L	U	L	U	U
23	4				5				3				2				2				3				4			
	L	U	U	-	U	U	L	-	I	U	L	-	L	U	I	U	U	L	U	L	U	L	U	I	U	L	U	I
24	5				1				4				2				5				1				3			
	I	-	-	-	-	-	-	I	U	L	U	-	U	-	-	U	-	-	L	U	U	-	-	-	I	-	L	U
25	2				2				5				1				5				5				4			
	U	-	U	-	-	-	U	-	-	-	-	U	-	-	U	-	L	U	L	-	U	L	U	-	U	L	U	L
26	1				4				1				3				5				5				5			
	U	L	U	I	U	L	U	I	U	L	L	U	I	U	I	-	I	U	L	U	L	-	I	U	U	U	L	U
27	5				5				5				5				3				5				4			
	-	L	U	I	I	U	U	I	U	L	U	I	U	L	U	I	U	I	U	I	-	L	U	I	U	L	L	U
28	4				1				1				4				4				3				5			
	I	-	U	-	U	L	U	I	U	L	-	I	L	-	L	U	U	L	-	I	L	U	I	-	U	L	L	U
29	1				1				5				4				5				3				5			
	U	L	L	U	L	U	U	L	U	L	U	I	L	L	I	-	U	L	I	-	U	L	U	U	U	L	U	I
30	4				1				1				3				4				3				5			
	U	L	I	U	U	L	U	L	U	L	U	I	I	U	L	U	U	L	U	I	U	L	U	I	L	U	I	U

This solution has the potential to promote the sustainability of farming communities, with a particular focus on improving the health and well-being of farmers. In rice farming, work assignments may be gender based; however, regardless of gender, the nature of work often involves repetitive tasks over long periods. These conditions pose a risk of WMSDs for both men and women. Women not only have agricultural duties, but also manage household responsibilities, resulting in extended working hours and limited time for rest and recovery. The Implementation of a gender-sensitive approach to managing WMSD risks in rice farming can mitigate health disparities and contribute to sustainability by enhancing the overall well-being of farming communities. Healthy rice farmers can work more efficiently and produce higher yields while maintaining high quality. However, excessive weight places additional stress on the musculoskeletal system, increasing the risk of injuries and stress during work-related activities. Rice farmers with a high BMI may experience reduced mobility and reduced physical fitness, which can decrease work efficiency and productivity. They may also require more frequent breaks, which impact overall performance. Furthermore, older rice farmers may face a higher risk of developing WMSDs because of age-related changes in musculoskeletal health. Effective risk management strategies can reduce the occurrence of WMSDs and help to maintain and even improve farmers' productivity, thus contributing to the sustainability of their agricultural operations. Moreover, preventing WMSDs can reduce the need for medication to manage pain and discomfort among rice farmers, leading to decreased healthcare costs. Such prevention benefits individual farmers and also contributes to the sustainability of healthcare systems.

While this research has made significant contributions, several limitations and suggestions for future research should be noted. First, there is room for improvement through meta-heuristic approaches

Table 9. Harvesting plan during days eight to 14

Worker no.	Day																											
	8				9				10				11				12				13				14			
1	3				1				2				1				5				5				1			
	L	U	L	-	U	U	I	U	I	U	L	U	I	U	L	U	U	I	U	I	U	L	U	U	U	L	U	I
2	3				3				1				3				5				1				5			
	U	L	U	I	L	U	I	U	U	L	U	I	L	U	L	U	U	L	U	L	U	I	U	U	I	U	U	L
3	1				4				5				5				5				5				4			
	U	L	L	U	U	U	I	U	U	L	U	L	U	L	U	I	I	U	L	U	U	I	U	L	U	L	U	I
4	5				2				1				2				5				3				1			
	I	U	U	L	I	U	U	L	U	L	U	I	L	U	U	I	U	U	I	U	U	U	I	-	I	U	L	U
5	2				3				3				5				3				5				4			
	U	L	U	I	U	L	U	I	L	U	I	U	U	L	U	I	U	I	U	U	U	L	U	I	U	L	U	U
6	4				5				4				3				4				3				5			
	U	I	U	L	U	U	U	I	U	I	U	L	U	L	U	L	I	U	I	U	I	U	I	U	I	U	U	L
7	4				4				1				1				1				5				4			
	U	L	L	U	U	L	U	L	U	U	I	U	U	U	I	U	U	L	L	U	U	I	U	U	U	I	U	L
8	1				2				2				2				5				4				5			
	I	U	L	U	U	I	U	L	L	U	I	U	L	U	I	U	U	L	I	U	U	L	U	I	L	U	I	U
9	2				1				3				3				5				5				1			
	U	U	-	U	L	U	U	I	U	U	L	U	U	U	I	U	U	I	U	I	U	I	U	U	U	I	U	I
10	5				5				5				1				3				3				4			
	U	L	U	U	U	L	L	U	U	L	U	I	I	U	L	U	U	I	U	U	I	U	L	U	U	I	U	L
11	4				1				4				5				2				5				5			
	U	I	U	L	I	U	L	U	I	U	U	L	I	U	L	U	U	U	U	I	U	I	U	U	U	L	U	I
12	2				3				2				3				4				3				4			
	L	U	I	U	U	I	U	L	U	U	L	U	U	L	U	I	I	U	U	U	U	L	L	U	U	U	L	U
13	3				2				3				4				2				5				5			
	I	U	L	U	L	U	I	U	L	U	I	U	U	L	I	U	U	U	I	U	U	U	L	U	I	U	U	L
14	1				1				1				2				5				5				1			
	I	U	I	U	L	U	I	U	L	U	U	I	U	U	L	L	U	L	U	U	I	U	U	L	U	L	U	I
15	1				3				4				4				1				1				1			
	-	U	U	-	-	I	U	-	U	-	U	-	-	L	U	L	-	U	-	-	-	-	-	U	-	U	U	-
16	4				5				5				1				2				1				4			
	U	I	U	L	U	U	L	U	U	L	U	U	U	I	U	L	U	I	U	U	U	L	L	U	U	L	U	I
17	3				3				5				2				4				1				4			
	I	U	U	U	I	U	L	U	L	U	I	U	U	I	U	L	U	L	U	I	L	L	U	I	I	U	U	U
18	4				2				1				3				1				4				5			
	U	L	U	L	U	L	U	I	U	L	U	I	U	U	I	U	U	L	U	I	U	L	U	I	U	I	U	L
19	3				3				3				2				4				1				1			
	U	I	U	L	U	L	U	U	L	U	L	U	L	U	L	U	U	I	U	U	U	L	I	U	I	U	U	L
20	2				4				2				4				2				5				4			
	I	-	L	U	I	-	L	U	L	U	I	U	U	I	-	U	U	U	I	U	U	U	I	U	U	U	L	U

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Table 9. Continued

Worker no.	Day																											
	8				9				10				11				12				13				14			
21	4				5				3				3				4				5				5			
	U	U	I	U	U	I	U	U	U	I	U	L	U	I	U	L	U	U	U	I	L	U	U	I	L	U	I	U
22	3				2				2				2				5				4				5			
	U	I	U	L	U	L	U	I	U	I	L	U	U	L	L	U	U	U	I	U	U	I	U	L	U	I	U	I
23	5				1				4				1				3				1				1			
	L	U	I	U	L	U	U	I	L	U	I	U	U	I	U	L	U	I	U	L	U	U	I	U	L	U	L	U
24	1				4				4				4				3				5				5			
	U	-	U	U	U	-	U	U	U	U	-	-	U	-	U	L	U	-	U	U	U	-	-	U	I	-	L	U
25	3				2				2				3				1				1				4			
	L	U	-	-	-	-	-	U	-	U	L	-	U	L	L	U	-	U	U	-	U	-	U	U	U	L	U	L
26	1				5				4				2				5				1				5			
	I	U	U	L	U	L	U	I	U	I	U	L	L	U	U	I	U	L	U	I	L	U	I	U	-	L	U	I
27	5				2				3				5				3				4				1			
	U	U	U	I	L	-	-	I	U	L	L	U	U	L	L	L	I	U	U	I	I	U	I	-	U	L	U	I
28	5				5				3				1				4				1				5			
	U	L	U	U	U	L	-	I	L	-	U	U	U	L	U	L	I	-	-	I	L	U	I	-	U	L	U	-
29	3				1				4				5				3				1				1			
	-	I	L	U	I	U	L	U	-	I	L	U	L	-	I	U	I	-	U	U	U	U	I	U	U	L	U	I
30	3				1				5				5				5				1				5			
	I	U	L	-	L	U	L	U	U	L	U	I	-	L	L	-	-	-	I	U	I	U	U	L	I	U	L	U

to harvest workforce planning, which would reduce computational time. Second, the proposed model for rice seed harvesting planning is a deterministic model. It could be improved by considering factors of uncertainty involved in planning. Third, a sensitivity analysis should be conducted on significant parameters, such as demand, costs, and the maximum allowable risk load, among others. This analysis is necessary to compare solutions and can help in recommending valuable strategies to the RSC. Last, the model could be applied and/or adapted for various other crops that require manual harvesting or other manual processes. Other countries' governmental units responsible for managing crops that require manual labor could apply this model to plan for the mutual benefit of all stakeholders across the agricultural sector.

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