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Development of Green Product Processes in Textile Industry Using Mathematical Modeling and NSGA-II Metaheuristic Algorithm: A Case Study in Oyaz Industrial Group

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ABSTRACT

The development of green product processes is a strategic approach to minimize the impact of organizational supply chain on the environment while simultaneously expanding its economic performance. To achieve this task, it is crucial to emphasize aspects related to performance in optimizing resource utilization and implementing sustainability principles within an organizational domain. To this end, a multi-objective mixed-integer linear programming model is presented in this study with the objective of minimizing the production time of textiles, transportation costs, and inventory of the products, as well as minimizing the environmental effects of the processes of developing green products. In this model, the constraints and problem parameters are deterministic and solved using weighted sum methods, utilizing real data obtained from the "Oyaz" industrial group. By solving the model, an optimal combination for the values of the objective functions is obtained both collectively and separately. Furthermore, the capability of the proposed model is evaluated for solving large-scale instances using the NSGA-II algorithm. This metaheuristic method has demonstrated satisfactory capabilities compared to the mathematical model because of the slight difference in modeling errors while confirming the accuracy of the developed mathematical model, proving the accuracy and efficiency of the NSGA-II algorithm. Consequently, the sensitivity analysis examines the influence of changing key parameters, such as the maximum storage capacity of production centers, on the decisions of the proposed model. This parameter change is determined through consultation with experts in the textile field. Based on the results obtained, changing the maximum storage capacity has a considerable impact on fibers and cotton. Additionally, if the capacity is changed to the maximum possible value, it has the greatest impact on the purifiers.

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1. INTRODUCTION

Global competition in an ever-changing environment has led organizations to recognize the importance of flexibility and demonstrate thoughtful and timely responses (1). In order to survive nowadays, organizations need to globalize and have a presence in this vast arena, even if they aim to have a national or regional presence, they must think globally (2). Therefore, considering green product design is of great importance and became a key issue in both industry and commerce. Green product design means creating products that have a smaller impact on the environment and natural resources throughout their life cycle (3). Furthermore, green product design should strive to reduce the consumption of natural resources, energy, and water during production, use, and disposal. This includes the use of recycled materials, optimization of the production process, and increased energy efficiency (4). In addition, green product design should contribute to the preservation and protection of the environment and prevent air, water, and soil pollution. This includes

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reducing the emission of greenhouse gases, using clean technologies, and proper waste management. In addition to environmental considerations, green product design can have an impact on economic and social aspects. For example, green product design can help increase the efficiency and profitability of businesses (5). Green products can lead to cost savings and increase competitiveness due to the reduction of resource consumption, production and maintenance costs, and improve efficiency. Additionally, green products can have a positive impact on society and contribute to the health and well-being of individuals (6). This includes using materials harmless to human health, designing recyclable products, and reducing product hazards for users. Therefore, green product design considers a proper combination of environmental, economic, and social factors, ultimately benefiting both society and the environment. With the changes in climate and the need for global sustainability, the importance of focusing on green product design is increasing day by day (7).

Mathematical modeling is a powerful tool for developing green product processes in the textile industry, which has various benefits. For example, mathematical modeling helps optimize green product manufacturing processes in the textile industry and minimize resource consumption including water, energy, and recycled materials (8). By optimizing resource consumption, the textile industry can increase its green and sustainable achievements while reducing production costs. Furthermore, it can identify important features and factors that affect product quality and aim to improve it (9). By improving product quality, the textile industry can increase customer satisfaction and enhance its competitiveness in the market (10). Mathematical modeling also helps the textile industry identify and manage various risks associated with green product activities (11). Using mathematical modeling, the effects of changes in different conditions can be simulated, and appropriate solutions for risk management can be provided. Moreover, mathematical modeling assists the textile industry in improving decision-making processes (12). With the use of mathematical modeling, complex problems in this industry can be analyzed, and optimal solutions can be proposed. Considering these benefits, mathematical modeling can significantly contribute to the development of green product processes in the textile industry, as well as environmental sustainability and the improvement of performance in the textile industry (13).

Based on the information mentioned above, the main objective of this research is to provide a mathematical model for optimizing cost and time in the process of developing green products in the textile industry, particularly in Oyaz industrial group. Therefore, the most significant contribution of this research is to propose a multi-objective linear programming model with the aim of minimizing time, cost, and the environmental impacts of the process of developing green products in the textile industry. In this model, the constraints and problem parameters are deterministic and have been solved using the weighted sum method. Since the model may encounter disruptions in dealing with large-scale issues, metaheuristic methods have been used to cope with this situation.

The remainder of the article is organized in as follows: In second section, a literature review of previous research has been provided. In the third section, mathematical modeling and a metaheuristic approach to solving the problem are demonstrated. In the fourth section, the results of applying the problem to a case study of Oyaz industrial group are presented. Finally, in the fifth section, a general conclusion is provided along with recommendations for future research.

2. LITERATURE REVIEW

In this section of research, we have focused on reviewing past studies on the development of Green Product Processes. To this end, Zindani et al. (14) have presented a decision-making framework that makes decisions by modeling the settings of experts using fuzzy sets in a fuzzy environment. This proposed decision-making framework has been examined for identifying the optimal set of process parameters (weight percentage and duration of chemical purification) according to technical, environmental, and economic conditions. The validity, accuracy, and robustness of the ranking have been evaluated through sensitivity analysis and solving previous case studies. This decision-making framework provides a tool for inferring a set of desirable parameters for green composites from agricultural waste, which can be used to examine the possibilities of designing green products and ultimately achieving sustainable goals. Barros(15) investigated the relationship between the circular economy and sustainable jobs in a systematic study and identified the drivers involved.

These drivers include strategic planning, cost management, circular supply chain management, quality management, environmental management, process management, logistics and reverse logistics, service management, and research and development. In addition, the key impact of changes in product development by the circular economy, which helps management achieve greater business sustainability, was presented. Based on the results obtained, adopting a circular economy-based mindset may enable the achievement of sustainable results. Kong and Liu (16) created a new system to justify economic, environmental, and social indicators in their study. According to the evaluation framework, a directed distance function based on the measurement model has been adopted to measure the sustainability of port cities in terms of external impact and internal interaction. For this purpose, nine port cities in China have been selected as the research domain. Lavuri et al. (17)conducted a study on green factors influencing the purchase of organic products (implication of sustainable development). In this research, they created consumer orientation towards environmentally friendly products, which is considered a social challenge, in the natural components of their products. Furthermore, this study examined how green factors influence customers' intention to purchase organic products. They demonstrated that the mediating role of trust and attitude is crucial in ensuring customers' sustainable orientation towards organic products. Dzikriansyah et al. (18) have addressed the role of green supply chain management practices on environmental performance in small and medium-sized companies in Indonesia in this article. The results indicate that internal factors such as strategic orientation and internal environmental management do not drive companies to consider green supply chain management. Among these, external factors, such as government regulations, play a significant role in adopting green supply chain management. Furthermore, it demonstrates that adopting green supply chain management influences the environmental performance of companies. The findings also establish that internal factors have no impact on environmental performance through green supply chain management. Chakraborty et al. (19) examined the internal factors related to the green supply chain using a structural interpretive modeling approach. In this study, eight factors have been identified that can be controlled within the organization. Among these eight factors, senior management commitment is the most important factor for the highest driving force. The reverse logistics process comes next, followed by storage and materials management at a high level. Soufi et al. (20) have examined the factors influencing the green supply chain in the construction industry of Iran in this study. For this purpose, a descriptive and applied method has been used in this research. The participating experts in the study are senior managers of the construction sector in the municipality of Rasht, Iran, who have relevant academic qualifications and suitable experiences in urban and industrial construction. The experts participated in both qualitative and quantitative stages of the research, which involved examining the factors extracted from the literature and ranking them in ascending order. In the quantitative stage, the step-wise weight assessment ratio analysis (SWARA) was conducted as a new multi-criteria decision-making method to evaluate the drivers of green supply chain acceptance using MATLAB software. Yousaf et al. (21) have investigated the mediating roles influencing the green supply chain in relation to environmental sustainability and environmental performance for small companies. The results of this research are useful for managers who intend to manage their companies sustainably, as they need to understand the mediating roles influencing green supply chains. Wu et al. (22) presented a green supply chain model composed of a capital-constrained manufacturer and a retailer to study the impact of the application of blockchain technology on the manufacturer’s financing strategy. Zhu et al. (23) introduced a green sensitivity into the green supply chain system and establish an evolutionary game model between enterprises and consumers. Abbas et al. (24) investigated the complex association that exists between information technology capabilities, green supply chain integration and green innovation on organizational performance in the manufacturing industry. Yang et al. (25) proposed a green product supply chain comprising one dominant manufacturer and one retailer, where the manufacturer can invest to improve a product's green level, and the retailer can make regular-sale promotional efforts.

Based on the accepted reviews in theoretical and empirical studies, a research gap has been observed in the field of providing a mathematical model for optimizing the green product development process, which has not been addressed so far. Therefore, the innovation and contribution of this research are as follows:

1. Simultaneous consideration of cost and time in the green product development process using multi-objective mathematical modeling.
2. Providing a comprehensive model for green product development by formulating its flow through mathematical programming.
3. Utilizing metaheuristic methods to solve the proposed model in large computational dimensions.

Table 1 categorized the literature review related to this work.

TABLE 1. Literature review

References	Research objective			
	Cost	**Time**	**Environment**	**Competitive Advantage**
[14]	*	*		
[15]		*	*	
[16]			*	*
[17]	*			*
[18]		*	*	
[19]	*	*	*	
[20]				*
[21]		*	*	
[22]	*			*
[23]		*	*	
[24]	*			*
[25]		*	*	*
Current research	*	*	*	*

3. RESEARCH METHODOLOGY

In the present research, a multi-objective model has been proposed for green product production in the textile industry for producing decorative fabrics. The components of this model include manufacturer, supplier, and consumer. As evident from the mentioned components, a green supply chain network has been considered in which the manufacturer is obliged to use environmentally friendly materials such as cotton, hemp, and bamboo in the production of decorative fabrics, as well as controlling chemical wastewater discharge to the environment. Therefore, in this research, we intend to design and optimize a logistics network to save costs in transportation and inventory while considering environmental factors for a decorative fabric manufacturer in the production and supply of green products. In fact, we aim to provide strategic planning for the supply chain from production to distribution of textile products in the form of a network. Figure 1 illustrates the green product production chain.

3. 1. Mathematical Modeling

In this section, all the symbols used to describe sets, parameters, and variables of the problem are explained in Table 2.

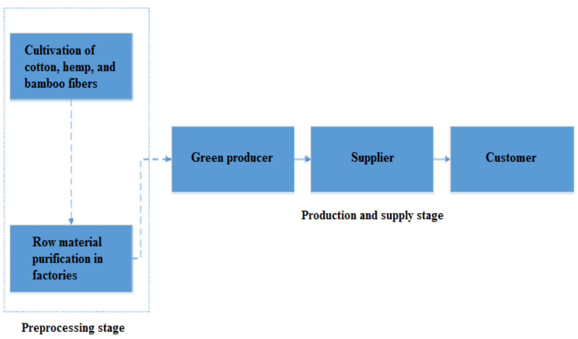

Figure 1. Supply Chain Structure

TABLE 2. Notation for Sets and Indices in the Mathematical Model

Symbol	Explanation
Sets	
I	Set of fields required for the production of environmentally friendly raw materials (cotton, hemp, and bamboo) $\mathbf{1},\dots,\boldsymbol{I}$
J	Set of purifiers in factories $\mathbf{1},\dots,\boldsymbol{J}$
P	Set of environmentally friendly raw materials $\mathbf{1},\dots,\boldsymbol{P}$
T	Set of periods $\mathbf{1},\dots,\boldsymbol{T}$
D	Set of suppliers $\mathbf{1},\dots,\boldsymbol{D}$
S	Set of storage warehouses $\mathbf{1},\dots,\boldsymbol{S}$
C	Set of consumers $\mathbf{1},\dots,\boldsymbol{C}$
H	Set of factories $\mathbf{1},\dots,\boldsymbol{H}$
Indices	
$i \in I$	Index related to the set of fields
$j \in J$	Set of purifiers
$p \in P$	Set of raw materials
$t \in T$	Set of periods
$d \in D$	Set of suppliers
$s \in S$	Set of storage warehouses
$c \in C$	Set of consumers
$h \in H$	Set of factories

TABLE 3. Notation for Parameters and Variables of the Mathematical Model.

Symbol	Explanation
Parameters	
$capacity_i$	Maximum capacity of field "i"
Cx_{ijt}	Cost of transferring raw materials from the field "i" to purifier "j" at time "t"
Cyj_{jhpt}	Cost of transferring raw materials from purifier "j" to factory "h" at time "t"
Cyd_{dcpt}	Cost of transferring decorative textiles from supplier "d" to consumer at the time "t"
Cyh_{hdpt}	Cost of transferring decorative textiles from manufacturer "h" to supplier at the time "t"
Cds_{dst}	Cost of transferring textiles from distributor "d" to warehouse "s"
Csd_{sdt}	Cost of transferring textiles from warehouse "s" to distributor "d"
γds_{dst}	Percentage of transfer of textiles from distributor "d" to warehouse "s"
γsd_{sdt}	Percentage of transfer of textiles from warehouse "s" to distributor "d"
CI_{jt}	Cost of importing raw materials to purification center "j" at time "t"
CIc_{ctp}	Cost of consuming textiles at consumer centers "c" at the time "t"
CId_{dtp}	Cost of consuming textiles at distribution centers "d" at the time "t"
CIh_{htp}	Cost of consuming raw materials at production centers "h" at the time "t"
λ_{ip}	Percentage of product quantity "p" (environmentally friendly raw materials) from the input of field "i"
Dh_{htp}	The demand of factory centers "h" for environmentally friendly raw materials "p" in period "t"
$CIhm_{im,h,t}$	Cost of transferring raw materials from import centers "i_m" to production center "h" at the time "t"
CI'_{jt}	Cost of purchasing imported materials to purification center "j" at the time "t"
CIh'_{htp}	Cost of textile production at production centers "h" at the time "t"

Variables	
x_{ijt}	The amount of transfer of raw materials from the field "i" to purifier "j" at time "t"
yh_{jhpt}	The amount of transfer of organic cotton from purifier "j" to manufacturer "h" at time "t"
$y'h_{jhpt}$	The amount of transfer of hemp from purifier "j" to manufacturer "h" at time "t"
$y''h_{jhpt}$	The amount of transfer of bamboo from purifier "j" to manufacturer "h" at time "t"
ds_{dst}	The amount of transfer of textiles from distributor "d" to warehouses.
sd_{sdt}	The amount of transfer of textiles from warehouse "s" to distributor "d"
II_{jt}	The inventory level of imported raw materials from the field to purification center "j" at time "t"
Id_{dtp}	The inventory level of textiles in distribution centers "d" at time "t"
Ih_{htp}	The inventory level of textiles in refinery centers "h" at the time "t"
Ic_{ct}	The inventory level of textiles in warehouse centers "s" for consumption at the time "t"
II'_{jt}	The amount of purchased raw materials for purification center "j" at time "t"
Ih'_{htp}	The production quantity of textiles in production centers "h" at time "t"
$Ihm_{im,h,t}$	The amount of imported raw materials from import centers "i_m" to production center "h" at the time "t"
tx_{htp}	The duration of textiles manufacturing in the factory.

3. 1. 1. Objective Function and Constraints Taking the above factors into consideration, a mathematical model of linear programming has been developed in a deterministic form to represent the mathematical modeling of the problem in the following equations.

$$A=\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}x_{ijt}.Cx_{ijt}+\sum_{j\in J}\sum_{d\in D}\sum_{p\in P}\sum_{t\in T}(yh_{jhpt}+y'h_{jhpt}+y''h_{jhpt}).Cyj_{jhpt}$$
$$+\sum_{j\in J}\sum_{d\in D}\sum_{p\in P}\sum_{t\in T}(yh_{jhpt}+y'h_{jhpt}+y''h_{jhpt}).Cyh_{hdpt}+\sum_{j\in J}\sum_{d\in D}\sum_{p\in P}\sum_{t\in T}(yh_{jhpt}+y'h_{jhpt}+y''h_{jhpt}).Cyd_{dcpt} \quad (1)$$
$$+\sum_{j\in J}\sum_{c\in C}\sum_{p\in P}\sum_{t\in T}ds_{dst}.Cds_{dst}+\sum_{j\in J}\sum_{c\in C}\sum_{p\in P}\sum_{t\in T}sd_{sdt}.Csd_{sdt}$$

$$B=\sum_{j\in J}\sum_{t\in T}CI'_{jt}.II'_{jt}+\sum_{j\in J}\sum_{t\in T}CI_{jt}.II_{jt}+\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}CIh'_{htp}.Ih'_{htp}+\sum_{c\in C}\sum_{t\in T}\sum_{p\in P}CIc_{ctp}.Ic_{ctp}$$
$$+\sum_{d\in D}\sum_{t\in T}\sum_{p\in P}Id_{dtp}.CId_{dtp}+\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}Ih_{htp}.CIh_{htp}+\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}CIh_{im,htp}.Ih_{im,htp} \quad (2)$$

$$C=\sum_{i\in I}\sum_{p\in P}\lambda_{ip}.(yh_{jhpt}+y'h_{jhpt}+y''h_{jhpt})+\gamma_{sdt}.(\sum_{j\in J}\sum_{t\in T}CI'_{jt}.II'_{jt}+\sum_{j\in J}\sum_{t\in T}CI_{jt}.II_{jt}$$
$$+\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}CIh'_{htp}.Ih'_{htp}+\sum_{c\in C}\sum_{t\in T}\sum_{p\in P}CIc_{ctp}.Ic_{ctp}+\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}Ih_{htp}.CIh_{htp}+\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}CIh_{im,htp}.Ih_{im,htp}) \quad (3)$$

$$D=\gamma_{dst}.(\sum_{d\in D}\sum_{t\in T}\sum_{p\in P}Id_{dtp}.CId_{dtp}) \quad (4)$$

$$F=tx_{hpt}.(\sum_{h\in H}\sum_{t\in T}\sum_{p\in P}Dh_{htp}) \quad (5)$$

Equation 1 calculates the cost of transferring raw materials and decorative textiles. For this purpose, it calculates the costs of transferring from the purification center to the factory, from the factory to the supplier, and then from the supplier to the consumer. It also takes into account the costs of transferring from the warehouse to the manufacturer and the supplier. Equation 2 calculates the inventory cost of decorative textiles. To this end, the inventory of raw materials for entering the purification center, as well as the inventory of the factory warehouse, and then the inventory of the supplier's warehouse is calculated. Equation 3 calculates the level of environmental pollution in production centers. Equation 4 calculates the level of environmental pollution in distribution centers. In addition, in Equation 5, the duration of textile production is considered. In general, the objective functions considered in mathematical modeling in this study are expressed as transportation costs of textiles (A) and inventory costs (B). Additionally, the level of environmental pollution in production centers (C) the level of environmental pollution in distribution centers (D), and the duration of textile production (F). To overcome the weaknesses of methods when the number of objectives exceeds two, considering the homogeneity of some objectives with each other such as objectives (A), (B), (C), and (D), the sum of these objectives is considered as the final goal, and the problem is transformed into a three-objective problem. Given the mentioned cases above, the sum of Equations 1 and 2 is considered F1, the sum of Equations 3 and 4 is considered F2 and the final objective function is $E = 0.33*F1 + 0.33*F2 + 0.33F$.

$$\sum_{j\in J} x_{ijt} \leq capacity_i \qquad \forall i \in I, t \in T \qquad (6)$$

$$II_{jt} = II_{jt-1} + \sum_{i\in I} x_{ijt} - \sum_{i\in I}\sum_{p2\in P} yh_{jhpt} - \sum_{c\in C}\sum_{p1\in P} yh'_{jhpt} - \sum_{h\in H}\sum_{p3\in P} yh''_{jhpt} \qquad \forall i \in I, t \in T \qquad (7)$$

$$\sum_{i\in I}\sum_{p\in P}(yh_{jhpt} + y'h_{jhpt} + y''h_{jhpt}) \leq \sum_{i\in I} \lambda_{ip}.x_{ijt} \qquad \forall j \in J, t \in T, p2 \in P \qquad (8)$$

$$\sum_{i\in I} \lambda_{ip}.x_{ijt} \geq D_{htp} \qquad \forall j \in J, t \in T, p3 \in P \qquad (9)$$

$$Id_{dtp} = \sum_{s\in S} \gamma sd_{st} sd_{sdt} - \sum_{s\in S} \gamma ds_{st}.ds_{dst} \qquad \forall d \in D, t \in T, p2 \in P \qquad (10)$$

$$Ih_{htp} = Ih_{h,t-1,p} + \sum_{h\in H}\sum_{t\in T} Ihm_{im,ht} \qquad \forall d \in D, t \in T, p2 \in P \qquad (11)$$

Constraint 6 ensures that the maximum amount sent from the field to the purifiers is considered. Constraint 7 indicates the inventory level of raw material input from the purifiers. Constraint 8 guarantees that the amount of raw materials to be sent from purifiers "j" to manufacturers should not exceed the maximum desired input of the processed product. Constraint 9 ensures that the quantity of produced textiles to be sent to other distributors meets the required demand for the desired product. Constraint 10 calculates the quantity of textiles available at distribution centers. In constraint 11, the quantity of produced textiles available for supply centers is calculated.

3. 2. Solution Approach: NSGA-II

In this paper, the NSGA-II metaheuristic algorithm has been used to solve the model. One of the positive aspects of this algorithm is that, unlike some other algorithms that only search the solution space in one direction, it simultaneously searches for solutions in multiple directions (24). Another positive feature of this algorithm is its lack of dependence on the continuity and convexity of the objective function. The performance of the NSGA-II algorithm is described below according to the semicode.

//Start
Step 1: Generate an initial population
Begin loop /* *Loop until a termination condition is met*/*
Step 2: Evaluate the fitness of a subset of individuals from the population
Step 3: Select pairs of the fittest individuals for reproduction
Step 4: Create offspring using a crossover operator
Step 5: Introduce genetic variation in the offspring using a mutation operator
Step 6: Replace some of the least fit individuals in the current population with the new offspring
End loop
Finish//.

Also, the flowchart for its implementation is shown in Figure 2.

4. FINDINGS

4.1. Case Study: Oyaz Textile Group

Jahan Orum Oyaz Company, in the textile industry of the country, was established in 2018 as a young but rich and prosperous company, benefiting from the valuable experience of more than 23 years of continuous presence and activity in the country's textile industry. With relentless efforts and the collaboration of experienced and creative entrepreneurs, relying on their long and valuable experience and private sector investment, the factory of this company was established at the beginning of the road, utilizing the maximum long-term experiences of the board of directors and investors and with sufficient knowledge of the characteristics and conditions of domestic and regional markets. It covers an area of 45,500 square meters and has a nominal production capacity of 33 million and 600 thousand

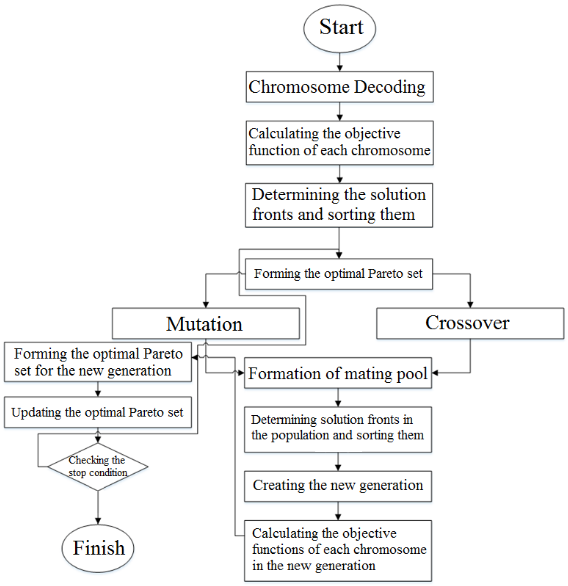

Figure 2. Flowchart of the NSGA-II Algorithm Execution

square meters. After 18 months of construction, it became operational to make positive and effective contributions towards the development of the country and the realization of the valuable aspirations of the esteemed Supreme Leader, including production growth and support for Iranian labor and capital.

Jahan Orum Oyaz is proud to have successfully prevented the outflow of 50 million dollars in currency through its dynamic investments and become a successful regional and global business. In doing so, it contributes to improving the economic indicators of our beloved country, such as Gross Domestic Product and employment. The textile industry is considered one of the most environmentally hazardous industries in the world. Environmental issues arise during certain production processes in the textile industry and directly affect the final product.

4. 2. Practical Numerical Results In this section, by considering the specified items in Table 3 as predetermined parameters of the programmed optimization problem for controlling the considered parameters, it is calculated in a small-scale problem as indicated below. The mentioned problem has been executed using GAMS software for the values of the sets specified in Table 4. The feasibility of this problem in this section has been demonstrated by determining a set of solutions based on solving the model in this way.

In this case, the cost of transferring raw materials from the field "i" to purifier "j" at the time "t" (x_{ijt}) is calculated according to Table 5.

Based on the calculated results, the total amount of raw material transfer costs, including (fibers, cotton, hemp, and bamboo) is shown in Table 5. The cost of

TABLE 4. Defined Sets for the Problem in Small-Scale

Defined Sets	Value
Field sets for raw material production	$i_1; i_2; i_3$
Purification sets in factories	$j_1; j_2$
Environmentally friendly raw material sets	Cotton, fiber, hemp, and bamboo
Time periods	$t_1; t_2; t_3$
Factories	$h_1; h_2$
Distributors	$d_1; d_2; d_3$
Warehouses	$s_1; s_2$

transferring raw materials from field "i_1" to the first purification center is zero in the first period. Additionally, this value is zero from the second and third centers to the first and second purification centers in all periods. Furthermore, the highest amount of fluid transfer in the third period from the first field to the first center is equal to 106.080. Moreover, Table 6 displays the inventory value of raw materials transferred from the field to purification center "j" at time "t" (II_{jt}).

Based on the results obtained, the value of ($IIjt$) indicates that the inventory of raw materials, (including cotton, hemp, flax, and bamboo) entering both purification centers in the first period is equal to zero. Furthermore, the inventory of the purification center in the second period is also equal to zero. In contrast, the inventory of the purification center in the third period is 20.749, which is the highest inventory value during the period. In Table 7, the transfer values of organic cotton from purification center "j" to manufacturer "h" at the time "t" is represented as the variable (yh_{jhpt}). The transfer value of hemp from purification center "j" to the manufacturer at the time "t" is represented by a variable ($y'h_{jhpt}$). Similarly, the transfer value of bamboo from the

TABLE 5. Optimal Value of x_{ijt}

From \ To	j_1			j_2		
	First Period	**Second Period**	**Third Period**	**First Period**	**Second Period**	**Third Period**
i_1	0	71.489	106.080	85.355	76.101	18.449
i_2	0	0	0	0	0	0
i_3	0	0	0	0	0	0

TABLE 6. Values of II_{jt}

Purification Center	First Period	Second Period	Third Period
j_1	0	0	20.749
j_2	0	7.906	13.601

purification center "j" to the manufacturer "h" at time "t" is represented by variable ($y''h_{jhpt}$). Additionally, the transfer value of fibers from the purification center "j" to manufacturer "h" at time "t" is represented by variable ($y'''h_{jhpt}$).

The amount of raw materials from the import centers (i_m) to the production center "h" at the time (t), denoted as (im_{imdt}), is according to Table 8.

According to the calculated results, the amount of imported raw materials to the first and second factories in the second period is zero. Furthermore, the amount of imported raw materials sent to the first and second factories in the first period have the highest quantity among them, with the highest entry of raw materials from the import section related to the first factory in this period, which is equal to 55.886. Finally, in Table 9, the values of transferring textiles from the warehouse "s" to the distributor "d", (sd_{sdt}), are shown.

By calculating the values above, the value of the objective function is determined according to Table 10. Considering that the problem in this dissertation is multi-objective, it has been calculated using the weighted sum method. The optimum value of the objective function depends on the weights assigned to the objective functions. Since the form of the objective function in the weighted sum problem is represented as ($w_1 f_1 + w_2 f_2 + w_3 f_3$) and the sum of weights is equal to one ($\sum w_i = 1$), different combinations of coefficients can be considered, as shown in Table 9.

TABLE 7. Optimal Values of yh_{jhpt}, $y'h_{jhpt}$, $y''h_{jhpt}$, $y'''h_{jhpt}$.

Raw Materials	From \ To	First Period		Second Period		Third Period	
		h_1	h_2	h_1	h_2	h_1	h_2
(yh_{jhpt})	j_1	0	0	22	0.070	0	12
	j_2	7	19.342	0	15.577	0	0
($y'h_{jhpt}$)	j_1	0	15	22	0.863	0	14
	j_2	7	16.324	0	15.577	0	0
($y''h_{jhpt}$)	j_1	0	10.214	22	0.070	0	12
	j_2	9	17.247	0	17.542	0	0
($y'''h_{jhpt}$)	j_1	0	0	28	0.956	0	24
	j_2	5	12.254	0	19.247	0	0

TABLE 8. Values of ihm_{imdt}

from-to	First Period	Second Period	Third Period
$i_1 \to h_1$	55.886	0	48.150
$i_1 \to h_2$	51.886	0	9.150
$i_2 \to h_1$	0	0	0
$i_2 \to h_2$	39.902	0	0

TABLE 9. Values of sd_{sdt}

from-to	First Period	Second Period	Third Period
$s_1 \to d_1$	0	0	0
$s_1 \to d_2$	0	0	0
$s_1 \to d_3$	0	0	0
$s_2 \to d_1$	112.960	0	0
$s_2 \to d_2$	86.760	0	0
$s_2 \to d_3$	234.104	0	0

TABLE 10. Examination of the Value of the Objective Function for Different Weights

Raw	w_1	w_2	w_3	Value of the Objective function
1	0.1	0.7	0.2	35996.988
2	0.2	0.7	0.1	57969.729
3	03	0.5	0.2	76014.309
4	0.5	0.4	0.1	92482.238
5	0.3	0.2	0.5	108570.220
6	0.6	0.2	0.2	12815.680
7	0.7	0.1	0.2	134993.518
8	0.2	0.4	0.4	128171.356
9	0.5	0.3	0.2	161349.194

Based on the obtained results, it can be observed that the value of the objective function is strongly dependent on the weight of the first objective. With an increase in its value, the objective function also increases. On the other hand, the higher the weight of the second objective function, the lower the value of the objective function.

4. 3. Tuning Parameters of NSGA-II In order to design experiments in the NSGA-II algorithm, initially, three different levels are defined for its parameters (low with code 1, medium with code 2, and high with code 3). Then, pre-defined experiments in this algorithm are executed for all possible combinations. The suggested values for the parameters of this algorithm are according to Table 11.

Then, using the L9 design, various experiments were conducted on Taguchi and each one was executed with the NSGA-II algorithm. The results of the execution are presented in Table 12. In this table, all possible cases are shown for different levels considered for the factors of the NSGA-II algorithm. For example, in the first experiment, all factors participate at their lowest level. In the second experiment, the factor "PS" is at its lowest level, while other factors are at their average level. Similarly, other possible cases are completed based on the permutation rule in the statistics. By running each experiment and calculating the value of the MID index, the desired response level is estimated using this index.

TABLE 11. Parameters and Their Levels for the NSGA-II Algorithm

Parameters	Values of Each Level		
	Level 1	Level 2	Level 3
Population size (PS)	50	100	200
Crossover rate (CR)	0.5	0.7	0.9
Mutation rate (MR)	0.2	0.3	0.5
Maximum iterations (Max_iter)	100	150	200

TABLE 12. Variable Response Values in the Taguchi design

Execution Number	Parameters of the Algorithm				MID index
	Max_iter	MR	CR	PS	
1	1	1	1	1	0.543
2	2	2	2	1	0.612
3	3	3	3	1	0.537
4	3	2	1	2	0.491
5	1	3	2	2	0.576
6	2	1	3	2	0.637
7	2	3	1	3	0.599
8	3	1	2	3	0.973
9	1	2	3	33	0.642

By providing the MINITAB software with these outputs, the S/N chart is presented in Figure 3. Based on the calculated signal-to-noise ratio for all levels considered for each factor, the lower the value for aspecific level, the corresponding level is selected for that factor. As shown in Figure 3, the minimum value of signal-to-noise ratio occurs for the factor PS at its high level with code 3. Therefore, the value considered for this parameter in the NSGA-II algorithm is 200. Additionally, the minimum value of the signal-to-noise ratio for the CR index corresponds to the medium level with code 2 for this factor. Hence, the factor CR will have a value of 0.7 in the algorithm. Furthermore, the minimum value for the MR factor corresponds to its low level with code 1. Thus, this factor will have a presence in the algorithm with a value of 0.2. Finally, the Max_iter factor has a lower value in terms of noise when it is at its high level with code 3. Therefore, this factor will have a value of 200 in the algorithm.

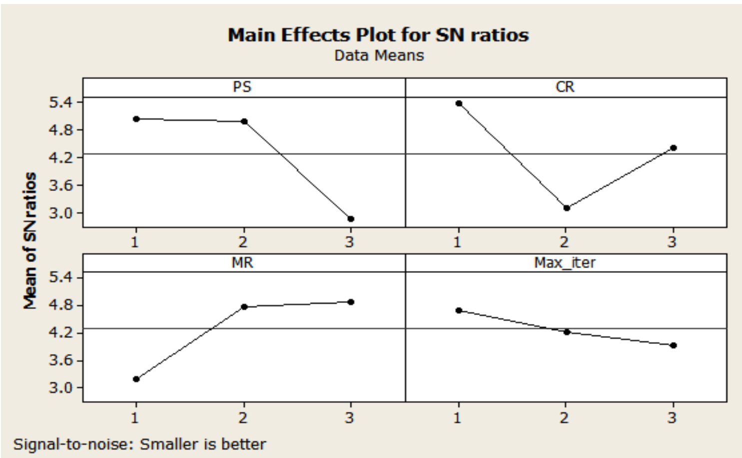

Figure 3. MINITAB Output for the Taguchi Method in the NSGA-II Algorithm

Based on the output provided in the above chart, the optimal value for each parameter is specified in Table 12, and other examples are executed with these values of parameters of the algorithm. The optimal values of the parameter are presented in Table 13.

TABLE 13. Optimal Values of Variables in NSGA-II

Parameters	Optimal Values
Population size (PS)	200
Crossover rate (CR)	0.7
Mutation rate (MR)	0.2
Maximum iterations (Max_iter)	200

4. 4. Comparison Between Deterministic and Metaheuristic Method In this section of the research, experiments have been conducted to compare the exact solution with a metaheuristic algorithm on small, medium, and large scales according to Table 14. The numerical sample scales are indicated in this table. As it is evident, there are 10 numerical samples. Samples 1 to 4 correspond to small scales, samples 5 to 8 correspond to medium scales, and samples 9 to 10 correspond to large scales. Naturally, as the scales of the problem increase, the number of problem nodes also increases. These experiments are based on the initial assumptions of the model, which include fields for raw material production, purifiers in manufacturing factories, suppliers, consumers, time periods, and storage warehouses.

TABLE 14. Scales of Numerical Samples

Scales	Samples	Fields	Purifiers	Consumers	Periods	Suppliers	Storage Warehouses
Small	Sample 1	1	1	1	1	1	1
	Sample 2	2	2	1	1	2	2
	Sample 3	2	2	1	1	3	2
	Sample 4	2	3	1	1	4	3
Medium	Sample 5	3	3	2	2	3	3
	Sample 6	3	3	2	2	4	3
	Sample 7	4	4	2	2	4	3
	Sample 8	4	4	2	2	3	4
Large	Sample 9	5	5	3	3	4	4
	Sample 10	6	6	4	4	5	5

TABLE 15. Comparative Results of Solving in Small and Medium Scales

Column	GAMS			Solution Time	NSGA-II			Solution Time	Errors		
	f_1	f_2	f_3		f_1	f_2	f_3		ARE_1	ARE_2	ARE_3
1	509	284.9	1	10	509	284.9	1	5	0	0	0
2	541	300.2	37	12	542	300.2	35	7	0.001	0	0.05
3	649	302.1	49	15	650	303.3	46	12	0.001	0.003	0.06
4	691	320.3	99	17	693	321.9	94	15	0.002	0.004	0.05
5	1454	629	1021	20	1457	631.9	998	18	0.002	0.004	0.02
6	1568	737.5	1413	25	1572	740.4	1398	22	0.002	0.003	0.01
7	1600	804.6	2934	35	1604	806.3	2905	33	0.002	0.002	0.009
8	1909	983.3	7371	50	1911	987.6	7370	45	0.001	0.004	0.0001
9	-	-	-	-	2502	1000.65	76	50	-	-	-
10	-	-	-	-	3546	1125.5	82	55	-	-	-
Mean Errors in Each Objective Function									0.01	0.002	0.018

Table 15 displays the results of solving the model in small, medium, and large sizes. The first four samples correspond to the average model solutions in the small case, the next four samples correspond to the average model solutions in the medium size, and the last two samples are related to the large-scale problem. The last two samples are placed on a large scale because the mathematical model is unable to solve and provide answers for the objective function value. In Table 14, the exact solution results are compared with the results of the NSGA-II method. In the error column, three relative absolute errors are calculated using the formula ($\frac{|mathematical\ model - metaheuristic\ model|}{mathematical\ model}$) developed by Abolghasemian and Darabi (26) which has been recommended by other researchers (27-30). Based on this formula, we can calculate the error between two sets of results. If the calculated computational error between the two sets of data is less than 0.05, the error between the two sets of data will be negligible. Therefore, in this case, we can have confidence in the results of the metaheuristic model in solving large-scale problems. Considering the small difference in the error of the modeling methods and the confirmation of the accuracy of the developed mathematical model, the accuracy and efficiency of the NSGA-II algorithm are proven, and we can rely on NSGA-II for solving large-scale problems. The solution results indicate that as the dimensions of the problem increase, the complexity of the problem increases in both computational methods. This is because the solution time varies and increases from one problem to another. However, the solution time by the NSGA-II metaheuristic algorithm is significantly lower compared to the deterministic method. Therefore, based on the results in Table 14, we can trust the NSGA-II algorithm for solving large-scale problems and predict satisfactory performance.

4. 5. Sensitivity Analysis In this section, the impact of changing key parameters such as the maximum storage capacity of production centers on the decisions of the proposed model is examined. This parameter change has been determined in consultation with experts in the textile field. As shown in Figure 4, changing the maximum storage capacity has a significant impact on fibers and cotton. Figure 4 shows the amount of parameter change for different values in each product.

Also, it is necessary to mention that changing the key parameter affects all examined objective functions. For this purpose, the value of the objective function is calculated for each center. Considering the results of the objective functions, the effect of the maximum capacity parameter was ignored. In Figures 5, 6, and 7, the impact of the maximum capacity parameter on transportation costs, inventory costs, and environmental pollution is shown, respectively. According to Figure 5, if the capacity is changed to the maximum possible value, it has the greatest impact on the purifiers. The minimum impact occurs when the capacity increases to 20,000 in which case the least effect is placed on the fields.

According to Figure 6, if the capacity is changed to its maximum possible value, it will have the greatest impact on the purifier. The least impact resulting from a change in capacity occurs when the capacity increases by 50,000. In this case, the minimum inventory cost is incurred in the storage warehouses.

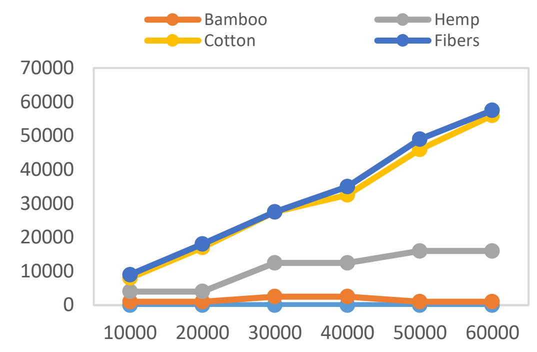

Figure 4. Change of Capacity Parameter in Relation to the Quantity of Textile Raw Materials

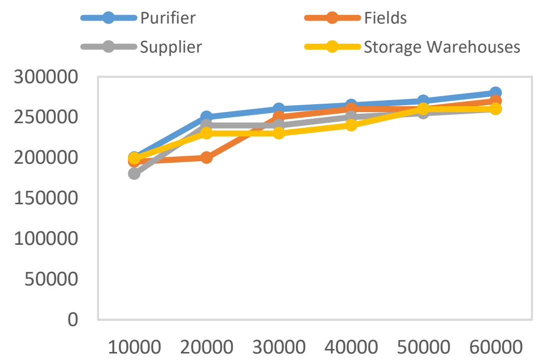

Figure 5. The Effect of Capacity on Transfer Costs

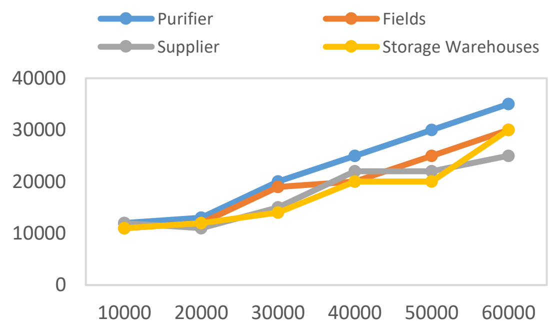

Figure 6. The Effect of Capacity on Inventory Cost.

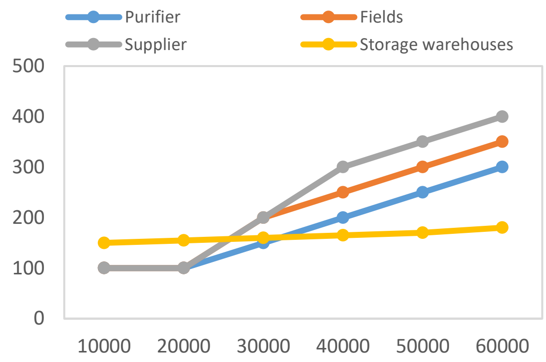

Figure 7. The Effect of Capacity on Pollution Level.

According to Figure 7, if the capacity is changed to its maximum value, suppliers will have the greatest impact on pollution. The least impact resulting from a change in capacity occurs when the capacity increases by 10,000 units. In this case, suppliers will make a significant contribution to pollution.

5. MANAGERIAL INSIGHT

The managerial insight gained from the current research can be summarized as follows:

1. Enhanced Environmental Sustainability: By incorporating green product processes, organizations like OYAZ Industrial Group can actively contribute to environmental sustainability. Mathematical modeling and the NSGA-II algorithm provide a systematic approach to identify the most effective and eco-friendly practices, helping reduce energy consumption, waste generation, and emissions.

2-. Optimized Resource Allocation: The utilization of mathematical modeling and the NSGA-II algorithm allows managers to optimize resource allocation within the textile production processes. This can lead to improved efficiency, lowered costs, and minimized material waste through better planning and scheduling.

3. Competitive Advantage: Adopting green product processes can give OYAZ Industrial Group a competitive advantage in the textile industry. By focusing on sustainability, they can attract environmentally conscious customers while complying with regulations and demonstrating corporate social responsibility.

4. Decision Support System: The integration of mathematical modeling and the NSGA-II algorithm creates a decision support system for managerial decision-making. It provides insights into the trade-offs between different objectives, such as cost, environmental impact, and production efficiency. This empowers managers to make informed decisions aligned with their sustainability goals.

5. Continuous Improvement: The application of mathematical modeling and the NSGA-II algorithm enables OYAZ Industrial Group to continuously improve their green product processes. Through iterative optimization, managers can identify bottlenecks, inefficiencies, and areas for further enhancement, allowing for ongoing process optimization and refinement.

6. CONCLUSION

In this study, a mathematical modeling method for producing green textiles in a textile company has been presented, focusing on the importance of a green supply chain and reducing environmental pollution. Based on the mathematical modeling proposed for the development of green product processes in the textile industry, it can be concluded that the use of mathematical modeling methods and techniques in the textile industry enables the improvement and optimization of the processes of green product production. Mathematical modeling, using mathematical concepts and computational algorithms, helps analyze and improve process performance.

Therefore, considering the aforementioned points and their significance in this research, a multi-objective mixed-integer linear programming model has been presented with the objective of minimizing production lead time, transportation and inventory costs, and minimizing environmental impacts in the processes of developing green products. In this model, the problem's constraints and parameters are deterministic and have been solved deterministically using weighted sum methods, utilizing real data obtained from the industrial group Oyaz. Furthermore, to evaluate the capability of the proposed model in solving larger instances, the NSGA-II metaheuristic method has been employed. This metaheuristic method has demonstrated desirable performance compared to the mathematical model, as the small difference in modeling errors confirms the accuracy of the developed mathematical model, and the performance and efficiency of the NSGA-II algorithm are proven, making it reliable for solving problems on large scales as well. Finally, the impact of changing key parameters such as the maximum storage capacity of production centers on the decisions of the proposed model has been examined through sensitivity analysis. This parameter change has been determined based on consultation with experts in the textile industry. Based on the results obtained, changing the maximum storage capacity has a significant impact on fibers and cotton. Additionally, if the capacity is changed to the maximum possible value, it will have the greatest impact on the purifiers. The least impact occurs when the capacity increases by 20,000 units, in which case the minimum impact is placed on the fields. Furthermore, if the capacity is changed to the maximum possible value, it will have the greatest impact on the inventory of the purifiers. The least impact occurs when the capacity increases by 50,000 units, in which case the minimum cost is incurred in the storage warehouses. Finally, if the capacity is changed to the maximum possible value, the suppliers in the chain will have the greatest pollution impact. The least impact occurs when the capacity increases by 10,000 units, in which case the suppliers will make a significant contribution to pollution. It is recommended to use a robust planning approach in the developed model for further research. Additionally, metaheuristic methods should be used to assess the capabilities of the model in small, medium, and large scales.

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Persian Abstract

چکیده

توسعه فرآیند محصول سبز یک رویکرد استراتژیک برای به حداقل رساندن اثر زنجیره تأمین سازمانی بر محیط زیست و در عین حال گسترش عملکرد اقتصادی آن است. در انجام این کار، ابعاد متمرکز بر عملکرد در بهینه سازی مصرف منابع و تحقق مفاهیم پایداری در یک زمینه سازمانی ضروری هستند. برای این منظور در این مطالعه یک مدل برنامه ریزی خطی عدد صحیح مختلط چند هدفه با هدف حداقل سازی زمان تولید منسوجات و هزینه های حمل و نقل و موجودی محصول و همچنین کمینه کردن آثار زیست محیطی در فرآیند توسعه محصول سبز در ارائه شده است. در این مدل، محدودیت ها و پارامترهای مساله از نوع قطعی هستند که با استفاده از روش های مجموع وزن دار شده حل شده اند که برای این منظور از داده های واقعی بدست آمده از گروه صنعتی ایاز استفاده شده است. با حل مدل یک ترکیب بهینه برای مقدار توابع هدف به طور ترکیبی و مجزا بدست آمده است. علاوه بر این برای سنجش قابلیت مدل پیشنهادی برای حل نمونه های بزرگ تر از روش فراابتکاری NSGA-II استفاده شده است. این روش فراابتکاری در مقایسه با مدل ریاضی قابلیت مطلوبی را از خود نشان داده است. زیرا، اختلاف کم در خطای روش های مدلسازی ضمن تأیید صحت مدل ریاضی توسعه داده شده، صحت عملکرد و کارایی الگوریتم NSGA-II اثبات می‌شود و می‌توان برای حل مسائل در ابعاد بزرگ نیز به NSGA-II اعتماد کرد. سرانجام، تأثیر تغییر پارامترهای کلیدی مانند حداکثر ظرفیت ذخیره سازی مراکز تولیدی بر تصمیمات مدل پیشنهادی از طریق تحلیل حساسیت بررسی شده است. این تغییر پارامتر با استفاده از مشاوره با کارشناسان حوزه نساجی مشخص شده است. براساس نتایج بدست آمده تغییر حداکثر ظرفیت ذخیره سازی تأثیر قابل توجهی بر روی الیاف و پنبه دارد. همچنین، در صورت تغییر ظرفیت به حداکثر مقدار ممکن، بیشترین تأثیر را بر روی تصفیه کننده ها می گذارد.