Proceedings of the 3rd GCC International Conference on Industrial Engineering and Operations Management
Tabuk, Saudi Arabia, February 2-4, 2026

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/GC03.20260155
Published: February 2, 2026

Optimization of Coffee Roasting Operations: A Case Study of Saudi Roastery

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Abstract

Coffee roasting represents a rapidly growing market where operational efficiency is essential for sustaining profitability and product quality. Despite its economic significance, the operational-level challenges of roasting and packaging have received limited attention in the literature. To fill the gap, this research presents a mixed-integer linear programming (MILP) model to address the challenges of optimizing coffee production planning. The proposed model determines optimal daily production schedules and best quantities to roast, package, store, and dispatch. The objective is to maximize overall profitability while satisfying key operational constraints, including production capacity, inventory limitations, and demand requirements. In addition, this research includes the shelf-life constraint to reduce waste and guarantee product quality and freshness which is critical in the coffee market. To reflect the real-life case and give the model more flexibility, shortages are allowed and back-ordered later with specific cost. The research validates the model through a real-world case study conducted in a Saudi Arabian coffee roastery.

Keywords
Supply chain management; production planning; food and beverages industry; Optimization; Mixed-integer linear programming.

1. Introduction
Coffee is considered one of the top consumed beverages globally, and the coffee market has increased yearly. According to (Grand View Research, 2024), the market size of coffee was estimated at USD 269.27 billion in 2024 and is expected to reach USD 369.46 billion by 2030. Although coffee has a substantial economic scale and impact, there is a significant disparity between its academic focus and commercial importance. The coffee products go through several stages before reaching the final customer. It begins with the cultivation stage, followed by harvesting, which occurs in specific seasons. Once harvested, the processing stage starts to prepare green beans for the roasting stage, typically by drying and fermenting them. The fermented beans then moved to the production line, where they are roasted and packaged. The coffee is roasted following specific profiles that ensure the same taste for all the batches of one coffee type.

Coffee supply chain faces several challenges that complicate planning. The coffee is mainly shipped by sea which leads to unpredictable lead time due to vessel queuing time at ports, global shortages of containers, and weather conditions. Moreover, Coffee products have a short shelf life, and their quality is extremely sensitive to the warehouse environment as well as the storage period. Most of the roasters distribute their products through wholesale channels rather than selling directly to end consumers. Since products remain in the wholesale distribution chain for an extended period before reaching consumers, wholesalers consistently demand freshly roasted products with the most recent production dates. Finally, the variation of coffee types and varied sizes makes it hard to have enough stock of each type due to space limitations. The quantity produced must be suitable with demand; overproduction leads to an increase in waste and holding costs, and underproduction results in unmet demand and unsatisfied customers. Therefore, those challenges necessitate advanced production planning and scheduling.

In the coffee production process, several types of coffee are roasted on specialized roasting machines using predefined profiles. After roasting, the coffee is either packaged immediately or stored as work-in-progress (WIP) inventory for a limited number of days and then packaged later once needed. The packaged coffee is then used to meet daily demand or stored as finished goods (FG) inventory, subject to time limits that vary by product size. Each coffee type is assigned to a designated roasting machine, and the total quantity roasted on each machine must not exceed its capacity. Moreover, daily packaging quantities must stay within the packaging capacity, and the quantity of coffee used to meet demand must not exceed the daily preparation capacity. Due to storage space limitations, daily WIP and FG inventories are also subject to warehouse space limitations. The demand is either covered on the same day or considered as a shortage that could be covered in the future, and the shortage cost is calculated based on the shortage quantity and the time before it is fulfilled. The roasted coffee beans stored in WIP and FG inventories are limited to a specific time to avoid expiration. The production problem consists of **R** roasters, **I** coffee types, and **J** packaging sizes. This research proposes a mathematical model aiming to determine the optimal daily roasting and packaging quantities that maximize the total profit, while satisfying all operational constraints. For more details about the production process, the process map of production for the real case is shown in Figure 1. Based on demand profile for the coming couple of weeks, the decision maker should decide the quantity to be roasted, the quantity to be packaged, and when and how much of the demand should be covered.

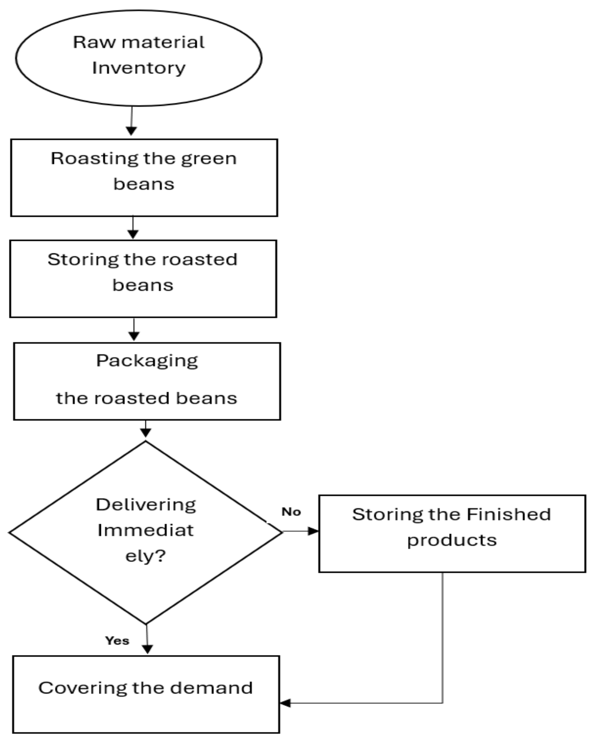

Figure 1. Real case production process map

1.1 Research Objectives

1) Highlight relevant research work in the same field.
2) Identifying coffee roasting system configuration.
3) Build a mathematical model based on the system configuration to support decision makers to optimize the coffee production operations.

4) Conduct a sensitivity analysis and compare the model result with the actual values.

2. Literature review

The problem of optimizing food production has been heavily studied in recent years, aiming to reduce costs and enhance productivity. Gameiro (2016) studied the problem of broader agricultural supply chains and presented a linear programming model (LP) for resource optimization at the farm level and a MILP model to optimize the supply chain network. Angizeh et al. (2020) proposed a mixed-integer linear programming (MILP) model to minimize the production cost by optimizing the operational schedule for the beverages production lines. Georgiadis et al. (2020) introduced a real case of a Spanish canned fish production plant. They developed a mixed-integer linear programming model to enhance the makespan by optimizing the weekly schedules. In the same context, Handayani et al. (2021) proposed a case study of Indonesian canned fish food industry, they developed a mixed-integer linear programming model to minimize the total production cost, distribution cost, and carbon emissions while increasing the traceability. Nwoke (2025) presented a multi-objective optimization approach to increase machine efficiency and minimize quality problems and manufacturing costs in beverage industry.

Although several studies focused on the food industry and applied optimization models to reduce production cost and enhance the system's efficiency, coffee production optimization was not studied enough, and most of the studies focused on the stage of cultivation. For example, Al-Abdulkader et al. (2018) studied the problem of optimizing coffee cultivation in Saudi Arabia and developed an LP model to maximize the net economic return, considering local demand, cultivation area, and international trade. Achmad and Ahmad (2023) developed an LP model to optimize the resource allocation of coffee farming to maximize monthly profits and output. Sakamoto et al. (2023) also developed an LP model to optimize the coffee green beans supply chain. The model consists of a multi-objective optimization to minimize the supply chain cost and reduce the environmental impact. Their paper studied a case of Brazilian coffee exported to the US. Fitra et al. (2024) presented a case study in Malang, Indonesia, and used the WaNuLCAS model to optimize coffee yields in agroforestry systems. Chen et al. (2024) proposed a statistical optimization model and response surface methodology to find the best schedule for the fertigation (nutrients, water), aiming to maximize yield while minimizing fertilizer and water use.

Few papers focused on the coffee roasting stage such as Oliveira et al. (2016) who proposed a mixed integer programming model to optimize the daily production with the objective to minimize the holding cost, penalty cost for late delivery, and silo loading cost. Giraldo (2020) developed an LP model to optimize roasting costs considering mass loss and degassing time constraints. Anjanni (2024) developed an LP model to maximize profit by optimizing the coffee production quantities. The paper analyzed a case study of the Komocha coffee home industry. In recent years, some papers have studied sustainability in coffee industry. For example, Tsai et al. (2025) studied the problem of optimizing energy efficiency and carbon emissions in coffee production. Activity-Based Costing was developed to maximize profit and minimize carbon emissions and energy use. Although previous research has studied coffee production optimization, critical operational challenges such as batch-based manufacturing, products shelf life, and supply chain shortages are still underexplored.

3. Methods

To achieve the research objectives, the system configuration was identified as shown in Figure 1. Moreover, the mathematical model will be built based on the system configuration and several operational constraints with objective of maximizing the profit. Once the mathematical model is ready, data will be collected and cleaned to get the values of the parameters such as machines and warehouses capacities, raw materials and production costs, and weekly demand. The model will be then solved using GAMS software to find the optimal production quantities. A sensitivity analysis is going to be conducted to discover any improvement opportunities and increase resource utilization. The key assumptions adopted in the model are listed below followed by model notations. The proposed model depends on several assumptions for simplification and computational tractability purposes. Firstly, the demand, production costs, and system capacities are assumed to be deterministic and known for the whole week. Secondly, all resources are available and reliable, and loading and unloading times are calculated in the process time. Thirdly, the production operation occurs only in the morning shift and maintenance is done at night out of the working shift. Finally, Shortages are allowed and backordered. The sets, parameters, and variables of the model are shown in Table 1.

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Table 1. Notations used in the optimization model

Sets			
r	roaster {1,2,..,R}	J	coffee bags size {1,2,..,J}
i	coffee type {1,2,..,I}	t	Time {1,2,..,T}
Parameters			
CR_{ir}	Assigning parameter which is 1 if item i can be done on roaster r 0 otherwise	D_{ijt}	Demand of coffee type i size j at time t
C_r	Capacity of roaster r	crm_{ij}	Cost of raw material of type i size j
CP	Packaging capacity for one unit of time	c_r	Cost of roasting on batch on roaster r
Cd	Capacity of preparation for one unit of time	cp	Cost of packaging one item
Cf	Capacity of FG inventory	cs	Cost of shortage of one item for one unit of time
Cw	Capacity of WIP inventory	ch	Cost of holding one item for one unit of time
p_{ij}	Price of one item type *i* size *j*	B_r	Batch size for roaster r
M	Large number		
Variables			
Decision variables		**Auxiliary variables**	
X_{irt}	Number of batches from item i roasted on roaster *r* at time t	RMI_{it}	Raw material inventory of item i at time t
PC_{ijt}	Number of items type i size j packaged at time t	W_{it}	WIP inventory of item i at time t
FD_{ijt}	Number of item i size j at time t dispatched immediately	FI_{ijt}	FG inventory of item i size j at time t
FS_{ijt}	Number of item i size j at time t stored in FG inventory	z	Objective function value
FSD_{ijt}	Number of item i size j at time t dispatched from stock	SV_{ijt}	Number of salvaged items from type i size j at time t
S_{ijt}	Number of shortages from item i size j at time t		

The model consists of an objective function and several operational constraints as explained below. The objective function is to maximize the profit as formulated in Equation (1). The profit is equal to total revenue minus total costs. The costs included are total packaging cost, total roasting cost, total shortage cost, total FG holding costs, total WIP holding costs, total storing cost, and total salvage cost.

$$Max\ z = \sum_i \sum_j \sum_t \left(p_{ij} - cp - crm_{ij}\right) * \left(FD_{ijt} + FSD_{ijt}\right) - \sum_r \sum_i \sum_t c_r X_{irt} - \sum_i \sum_j \sum_t cs\, S_{ijt} - \sum_i \sum_j \sum_t ch\, FI_{ijt} - \sum_i \sum_t ch\ W_{it} - \sum_i \sum_j \sum_t 0.5 FS_{ijt} - \sum_i \sum_j \sum_t 0.25 p_{ij} SV_{ijt} \quad (1)$$

To ensure the result is feasible, the model consists of the following set of constraints as explained below.

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Roaster's capacity constraint: ensure the roasted beans do not exceed the roaster capacity.

$$\sum_{i} X_{irt} \leq C_r \qquad \forall r \; \forall t \tag{2}$$

Packaging and preparation Constraint: the packaged and the roasted coffee at time *t* is within the packaging and preparation capacity.

$$\sum_{i}\sum_{j} PC_{ijt} \leq \; CP \;\; \forall t \tag{3}$$

$$\sum_{i}\sum_{j} (FD_{ijt} + FSD_{ijt}) \; \leq \; Cd \;\; \forall t \tag{4}$$

Assigning constraint: ensure the coffee is only roasted on the designated machine.

$$X_{irt} \leq (M)CR_{ir} \quad \forall i \; \forall r \; \forall t \tag{5}$$

RM update constraint: the roasted beans at time *t* do not exceed the row material quantity, and the next day's inventory equals today's inventory minus today's roasted beans.

$$RMI_{it} = RMI_{it-1} - \sum_{r} B_r X_{irt} \qquad \forall i \; \forall t \tag{6}$$

WIP update constraint: the packaged items at time *t* do not exceed the available roasted beans, and the WIP inventory is updated after packaging.

$$W_{it} = W_{it-1} + \sum_{r} B_r X_{irt} - PC_{i1t} - 0.25\, PC_{i2t} - 0.09\, PC_{i3t} \; \forall i \; \forall t \tag{7}$$

FI update constraint: the dispatched quantity at time *t* is less than or equal to the finished good quantities, and the FI is updated after dispatching and storing new quantities.

$$FI_{ijt} = FI_{ijt-1} + FS_{ijt} - FSD_{ijt} - SV_{ijt} \quad \forall i, \forall j, \forall t \tag{8}$$

Demand balance constraint: the demand at time t and cumulative uncovered demand from the previous day are equal to the dispatched quantity plus the shortage at time t.

$$D_{ijt} + S_{ijt-1} = FD_{ijt} + FSD_{ijt} + S_{ijt} \qquad \forall i, \forall j, \forall t \tag{9}$$

Expiration constraint: for product quality purposes, the stored finished goods of type two have 4 days as storage limit and then it will be salvaged if it is not dispatched to a customer within 4 days. On the other hand, the WIP must be packed within 3 days from roasting to avoid expiration.

$$FS_{i2t} = \sum_{t}^{t+4} FSD_{i2t} + SV_{i2t} \; \forall i, \forall t \tag{10}$$

$$W_{it} \leq \sum_{t}^{t+3} (PC_{i1t} + PC_{i2t} + PC_{i3t}) \;\; \forall i, \forall t \tag{11}$$

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Packaging constraint: the packaged quantity is either stored or dispatched immediately to customers.

$$PC_{ijt} = FS_{ijt} + FD_{ijt} \quad \forall i, \forall j, \forall t \tag{12}$$

Warehouses' capacity constraints: ensure the stored WIP and FG do not exceed their inventory spaces.

$$\sum_i W_{it} \leq Cw \quad \forall t \tag{13}$$

$$\sum_i (FI_{i1t} + 0.31FI_{i2t} + 0.52FI_{i3t}) \leq Cf \quad \forall t \tag{14}$$

Domain constraints

$$X_{irt} = \{0,1,2,..N\}, PC_{ijt} \geq 0, \; FS_{ijt} \geq 0, FD_{ijt} \geq 0, FSD_{ijt} \geq 0, S_{ijt} \geq 0, W_{it} \geq 0, FI_{ijt} \geq 0, RMI_{it} \geq 0, SV_{ijt} \geq 0 \tag{15}$$

4. Data Collection

Historical company data was analyzed to find all required parameters for the model, and variables values are collected for the designated period to be compared with the outcomes of the model. All recorded data are scaled for sake of confidentiality. The model will be tested in a one-week period. The model required initial values for inventories at time 1, for example the WIP inventories for items from 1 to 7 are (0,0,0,211,102,0,374) respectively. The initial values of the FG inventory for items 1 to 7 size 1 is (0,0,0,7,7,0,10) respectively, for size 2 (0,0,0,295,445,0,304), and for size 3 (1000,0,1000,1000,1000,1000,1000). Moreover, the model required the assigning parameter values for example items (1,3,4,5,7) are only roasted on roaster number 4, and items (2,6) are roasted only on roasters (3,2) respectively. Each roaster has a daily capacity and the number of batches roasted on each roaster must not exceed its limit, for example the capacities for roasters (1,2,3,4,5,6) are (27,27,27,27,27,27,30) respectively. The packaging and preparation processes are limited with specific number of items due to workforce limitation, the items packaged daily must not exceed 12 K items and the prepared items must not exceed 30 K items. Moreover, the WIP and FG inventories have limited spaces which are 25000 items and 30000 items respectively. To evaluate the model outcomes, the actual production data for whole week was recorded based on the previous parameters and capacities. Table 2 shows an example of the variable's recorded values for item type 1 for all the three sizes at day 2.

Table 2. Variables recorded values.

I	J	T	FI_{ijt}	PC_{ijt}	D_{ijt}	FSD_{ijt}	FD_{ijt}	S_{ijt}	FS_{ijt}
1	1	2	0	1	1	0	1	0	0
1	2	2	0	50	116	0	50	66	0
1	3	2	1000	0	3	3	0	0	0

After collecting the required data, the total costs, revenue, and profit were calculated. Table 3 shows a summary of scaled calculated values, and the profit for that week was 3110328.969SR.

Table 3. Total costs and revenue during a week of operation.

Total holding cost	211,256.5 SR
Total packaging cost	113,158 SR
Total shortages cost	2,990 SR
Total roasting cost	41,450 SR
RM cost	1,915,438 SR
Total revenue	5,394,621.213 SR
Total profit	3,110,328.969 SR

5. Results and Discussion

The same Initial values, parameters were used in the mathematical model to find the optimal values, the model was built and solved using GAMS software. As a result of the proposed model, the profit is increased by 47,621 SR, which is 1.5% in only one week.

5.1 Numerical Results

In this section, some parts of the solution will be highlighted and discussed to give some insights that are of interest to the decision makers. The solution confirms that items were roasted only if there is no available finished good to cover the demand. Table 4 shows all the roasted batches on the roasters, roasters 4 and 6 were the most utilized roasters followed by roaster 3. Roaster 6 reached its upper limit 3 consecutive days, roasters 3 and 4 reached their limits only one day and the others were below the limit for all the days. This can show that the assignment of the items was not balanced for all roasters, and this may lead to delay covering the demand even though we have enough capacity in general. This issue can be solved by reassigning the items.

Table 4. Number of roasted batches.

	Time(t)						Capacity (Batch)	Utilization
Roaster	**2**	**3**	**4**	**5**	**6**	**7**		
1	2	16	2	15	11	15	162	38%
2					1		162	1%
3	1	0	1	14	30	10	180	31%
4	10	27	19	16	27	9	162	67%
5	0	1	5	4	15	6	162	19%
6	21	30	30	30	29	12	180	84%

Following the roasting stage, roasted beans are moved to the packaging stage where they are transformed to the final products. Here, the items are packaged into different sizes based on the demand which drives the daily packaging schedule. Table 5 shows an example of the packaging schedule for the first 7 items.

Table 5. Packaging schedule

		Time(t)					
Item(I)	**Size(J)**	**2**	**3**	**4**	**5**	**6**	**7**
1	**1**	1			9	2	10
1	**2**	51		33	5	29	
4	**1**	98	17	16		46	
4	**2**		225	95	25	67	42
5	**1**	67	23	106	22	137	5
5	**2**	124	267	161	54	76	62
7	**1**	424	455	265	328	291	210
7	**2**	619	841	258	250	590	532

A comparison with the actual values shows that the proposed model reduces the total inventories for the whole week. For example, total WIP inventory for all days is 14570 Kg compared with actual values of 41659 Kg which decreased by 65%. Moreover, total packaged items are 52733 items compared with actual values of 56579 items which decreased by 6%. Total FG inventory for all days is 150821 items compared with actual values of 156256 items which decreased by 3.4%.

5.2 Graphical Results

The results show a low utilization of production capacity and storage spaces which indicate idle resources within the system. The utilization rates of the WIP inventory space and packaging stage are shown in Figure 2 and 3. Figure 2 shows that the number of packaged items for all sizes remained below the packaging capacity. Figure 3 shows that, the WIP peak value did not exceed 15% of the available capacity which is 25000 items.

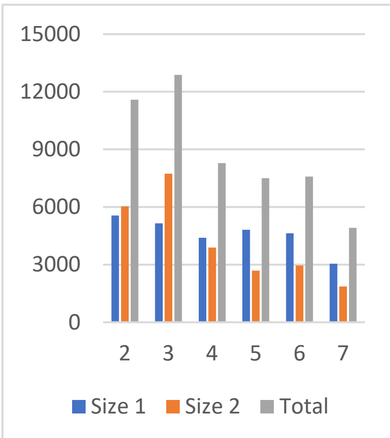

Figure 2. Packaged Items.

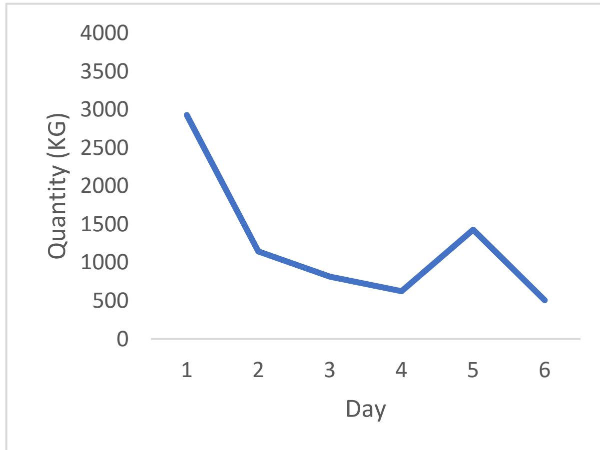

Figure 3. WIP inventory.

Figure 4 shows daily dispatched items, in the first two days the number of dispatched items reached 50% of the capacity then decreased to stay below 30% for the remaining days. Figure 5 shows the FG inventory where it starts with about 30000 items and decreased daily to end up below 20000.

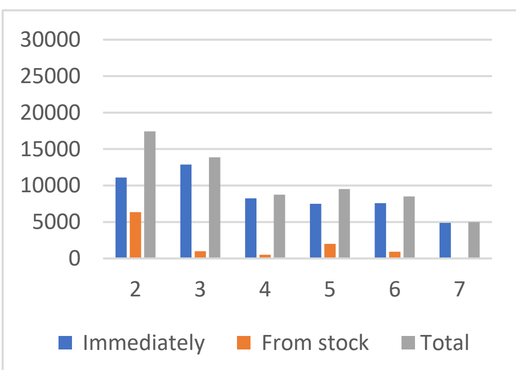

Figure 4. Dispatched Items.

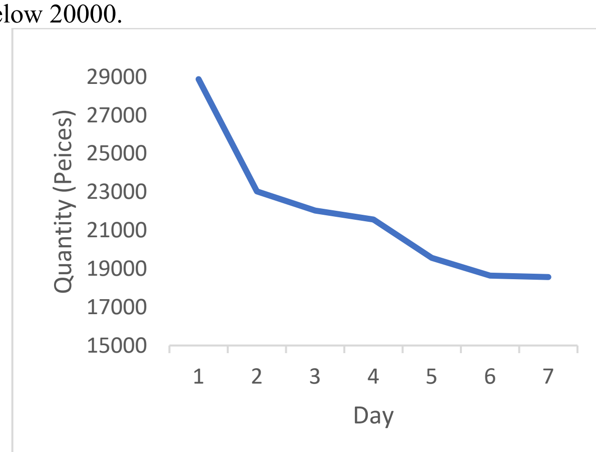

Figure 5. FG inventory.

5.3 Proposed Improvements

The model results shows a significant improvement in the profitability due to a major reduction in the total costs comparing with the actual values. Table 6 shows a scale summary of all costs, revenue, and profit for both real life case recorded data and model results to highlight the improvement that was made by using the proposed model. It can be shown that all costs were decreased except packaging cost. In general, total costs were decreased by 51259 SR and revenue decreased 3637.314 SR. In results the profit increased by 47621.86 SR.

Table 6. summary of scaled costs and profit

Cost/ Price	Model (SR)	Real case (SR)	Difference (SR)	Percentage
Packaging cost	126,072	113,158	12,914	11.41%
Roasting cost	25,500	41,450	-15,950	-38.48%
Shortage cost	1,605	2,990	-1,385	-46.32%
FG holding cost	150,821	156,256	-5,435	-3.48%
WIP holding cost	14,570.17	41,659.5	-27,089.33	-65.03%
Storing cost	301	13,341	-13,040	-97.74%
RM cost	1,914,163.9	1,915,437.744	-1,273.844	-0.07%
Revenue	5,390,983.899	5,394,621.213	-3,637.314	-0.07%
Profit	3,157,950.829	3,110,328.969	47,621.86	1.53%

5.4 Validation

Before it is put into use, The model will undergo validation using some scenarios with sample inputs and expected outputs.

Case 1 model input data:
For first case, all the initial values of the inventories are assumed to be zero except the raw material inventory to be 20000 kg for all items; to force the model to roast and package the demand quantity only. The demand for item 1 size 1 at time 2 is equal to 400 pieces and zero for the others. Moreover, item 1 can be only roasted on roaster 1.
Model output:

Since the demand for item 1 size 1 at time 2 is 400, and it can be roasted only on roaster 1 then we expect the system to roast the same quantity or more based on the batch size. The number of roasted batches of item 1 at time 2 is 3 and zero for others. We expect the raw material inventory to be updated after the roasted quantity, which is 3 multiply by the batch size 140. The initial value of item 1 is 20000 and the result values for item 1 for all t are (20000,19580,19580,19580,19580,19580,19580). To cover the demand the roasted quantity should be packaged and dispatched at time 2. The packaged and dispatched quantities for time 1 to 7 are (0,400,0,0,20,0,0) and (0,400,0,0,0,0,0) respectively. Since the roasted beans are related to the batch size, we expect to have remaining quantity after covering the demand thus those quantities are either stored as WIP or packaged and stored as FG. The WIP, stored quantities and FG inventories are (0,20,20,20,0,0,0), (0,0,0,0,20,0,0), and (0,0,0,0,20,20,20) respectively. As shown that the FG inventory update is equal to accumulated stored quantities because there is no quantity dispatched from stock. Since all the demand is covered then we don't have any shortages or dispatching from stock thus the values of S and FSD are all zero.

Case 2 input data:
For second scenario all the input parameters are the same except for the inventory's initial values, raw material initial values are all zeros except for item 1 400, and the WIP initial value of items 1 size 1 is 400. Her we force the system to cover the demand from WIP inventory only without roasting any additional quantity. FG inventory initial values are all zero.

Output data
The demand here is 400 for item 1 size 1 at time 2 and we expect to cover this quantity from WIP inventory, thus the system should not roast any new quantities. Therefore, the RM inventory update and number of roasted batches for item 1 for all times are (400,400,400,400,400,400,400) and (0,0,0,0,0,0,0) respectively. Since the demand for item 1 size 1 at time 2 is 400 then we expect to pack all quantities at time 2, then the packaged quantities of item 1 size 1 and WIP inventory update for item 1 are (0,400,0,0,0,0,0) and (400,0,0,0,0,0,0). This packed quantity should be dispatched to cover the demand, thus we the dispatched quantities from item 1 size 1 for all times are (0,400,0,0,0,0,0). Since all

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the demand covered immediately there are no items to be stored, no shortages, and the FG inventories for all items for all times are zero. Case one and two show that the model results were the same as expected, thus the model is valid and can be used for larger numbers.

6. Conclusion

This research has developed and implemented a Mixed-Integer Linear Programming (MILP) model to address the challenges associated with coffee roasting operational planning. The objective is to maximize the total profit while meeting all operational constraints. The model yielded in a significant improvement in profitability. The primary source of this improvement was the reduction of total costs, basically in the holding and roasting costs. The model results highlight the major contribution of the initial weekly inventory to the total holding cost, identifying an opportunity for improvement. The study shows the importance and power of optimization modelling as a support for decision makers. This work can be extended by considering the environmental impact by decreasing the emissions. Moreover, including a strategic level planning for deciding the quantity of raw material to be purchased each season or year to be integrated with operational level planning

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