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Revolutionizing Dairy Production: A Comprehensive Analysis of Industry 4.0-based Optimization Strategies in Yogurt Filling Systems

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Abstract

This study introduces a unique approach to yogurt and flavour-filling systems, presenting Case IV and a circular conveyor belt configuration. Unlike traditional linear setups, Case-IV revolutionizes yogurt and flavour-filling processes by optimizing processing time and space usage. The innovative system incorporates a Fanuc LR Mate 200ic robotic arm, NFC technology, and diverse conveyor belts, enhancing automation and energy efficiency, which are critical aspects of Industry 4.0. A mathematical model is developed, encompassing cup filling and shared movement along the conveyor belt. The model's results are compared with established methodologies, pushing the boundaries of efficiency and promoting sustainable production. Comparative analysis demonstrates the system's superior performance, showcasing its flexibility and adaptability to evolving production needs.

Keywords: *Fully Flexible Yogurt Filling Machine; Scheduling Problems; Advanced manufacturing; Combinatorial Optimization; Industrial Process Optimization*

1. Introduction

Production scheduling optimization is a practical lever for manufacturers: it improves throughput, cuts operating costs, and helps meet delivery targets by better aligning machines, labor, and materials. Prior research has shown that meaningful gains can come from both operational methods such as line balancing, Yama-zumi charts, and Takt time analysis in assembly lines (Sabadka, Molnár, Fedorko, & Jachowicz, 2017) and Lean/Kaizen/Standard Work initiatives that increase OEE (Santana, Afonso, Zanin, & Wernke, 2017) and advanced analytical tools, including well-designed PSO configurations for product line decisions (Tsafarakis, Marinakis, & Matsatsinis, 2011), digital twins that connect simulation to shop-floor automation (Jeon & Schuesslbauer, 2020), and mixed-integer optimization with Benders decomposition to support profit-maximizing production plans under customer-choice structures (Bertsimas & Mišić, 2019). AI-driven decision support has also been used to design industrial product portfolios (Tsafarakis, Saridakis, Baltas, & Matsatsinis, 2013), while generalized queuing network algorithms provide efficient evaluation and optimization capabilities for complex production lines (Spinellis, Papadopoulos, & Smith, 2000).

Within Industry 4.0 settings, parallel-machine scheduling is particularly important because systems must remain productive despite variability and disruption. Classical approaches such as implicit enumeration and constraint relaxation remain relevant (Cheng & Sin, 1990), but stronger exact methods e.g., branch-and-bound enhanced with dominance properties and bounding schemes can improve solution quality while reducing computation time (Yalaoui & Chu, 2002). Additional realism is captured through learning effects, where repeated processing reduces job times and associated energy and labor needs (Mosheiov, 2001). Because many variants are NP-hard, specialized algorithms are often necessary, including cutting-plane approaches grounded in polyhedral theory (Mokotoff, 2004) and hybrid intelligent algorithms for uncertain or fuzzy processing times that enable more adaptive scheduling decisions (Peng & Liu, 2004). More broadly, combinatorial optimization continues to underpin production planning and scheduling across domains, from flexible manufacturing flow shops (Crama, 1997) to air-traffic sequencing (Saraf & Slater, 2006), railway resource matching via network-flow methods (Matyukhin, Shabunin, Kuznetsov, & Takmazian, 2017), sim-heuristics for stochastic systems (Juan, Faulin, Grasman, Rabe, & Figueira, 2015), and swarm-intelligence variants for complex scheduling problems (Jiang & Zhang, 2018).

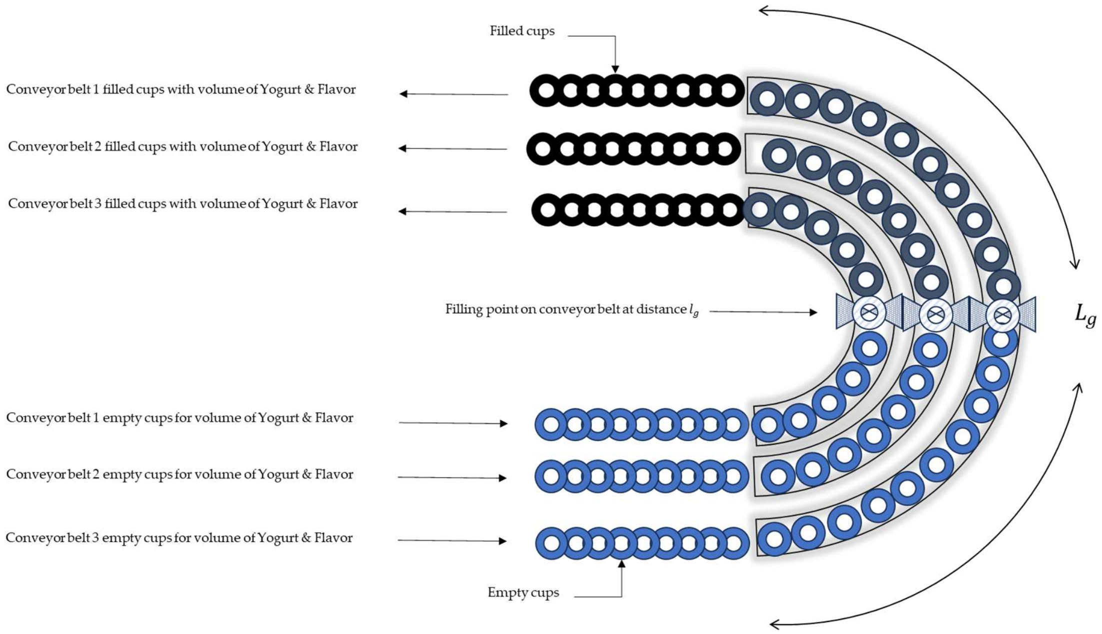
For food and dairy production, the need for optimized scheduling is even more pressing because it directly affects freshness, waste, and consistent product quality. Prior work on filling operations highlights benefits of integrating production planning, allocation, and sequencing (Masruroh, Fauziah, & Sulistyo, 2020), using efficient heuristics when exact solutions are impractical (Gellert, Höhn, & Möhring, 2011), and combining mathematical modeling with simulation to address uncertainty and dynamic conditions (Bilgen & Çelebi, 2013). Related process-industry studies (e.g., breweries) further demonstrate the value of MILP/MIP formulations coupled with heuristics under long lead times and parallel processing constraints (Baldo, Santos, Almada-Lobo, & Morabito, 2014; Georgiadis, Elekidis, & Georgiadis, 2021). In yogurt filling specifically, existing Industry 4.0-oriented models emphasize controllable variables such as conveyor speed, processing times, and valve feed rates (Salah, Khan, Ramadan, Ahmad, & Saleem, 2021; Salah, Khan, Ramadan, & Gjeldum, 2020), and show how alternative configurations such as consolidated filling points and dedicated nozzle designs can reduce processing time and improve efficiency (Chen et al., 2022; Cui, Zhang, & Luo, 2022; Salah, Alsamhan, Khan, & Ruzayqat, 2021).

Despite these advances, most yogurt-filling lines still rely on linear conveyor layouts that create start–stop behavior and entry-point waiting, increasing idle time for belts and filling equipment and weakening sustainability. Motivated by emerging evidence that circular conveyor layouts can better handle complex scheduling constraints and improve flow efficiency (Bock & Bruhn, 2021; Nielsen, Sung, El Yafrani, Kılıç, & Nielsen, 2023; Novak, Pikous, & Hanzalek, 2023; Vasilis, Nikos, Kosmas, & Dimitris, 2022; Winter, Musliu, Demirović, & Mrkvicka, 2019), this study proposes a novel circular conveyor belt configuration (Case IV) for yogurt filling. The system uses multiple nested circular belts with a three-point structure (entry–filling–exit) and removes entry waiting by enabling continuous order inflow. Building on prior models (Cases I–III) (Chen et al., 2022; Cui et al., 2022; Salah, Khan, et al., 2021), we develop a mathematical model for Case IV and benchmark its performance to identify the most effective yogurt-filling configuration. The study evaluates operational efficiency and throughput relative to traditional linear systems, while also considering space utilization, energy efficiency, resource optimization, and Industry 4.0 integration. Accordingly, this study addresses two research questions: (i) How does adopting a novel circular conveyor belt system for yogurt filling affect operational efficiency and throughput compared with traditional linear conveyor systems? (ii) Which yogurt-filling configuration delivers the best overall performance when space utilization, energy efficiency, resource optimization, and Industry 4.0 integration are considered? The remainder of the paper is organized as follows. Section 1 introduces the study and its motivation. Section 2 presents the problem description. Section 3 develops the proposed mathematical model, and Section 4 details the solution procedure. Section 5 reports empirical results for four different cases using the proposed framework. Finally, Section 6 concludes the paper and outlines directions for future research.

1. Problem Description

Industrial facilities often operate with limited or awkwardly shaped floor space, which can make traditional linear conveyor layouts difficult to install and inefficient to run. By contrast, circular conveyors can be arranged more compactly and adapted to tighter footprints, enabling better use of available space. Building on earlier yogurt-filling configurations (Cases I–III) that examined linear conveyors, single filling points, and floor-standing layouts, we note an important limitation: the start stop operating cycle in these systems increases idle time for both the conveyor and the filling nozzles, which can undermine efficiency and sustainability. To address this gap, Case IV departs from the established designs and introduces a U-shaped circular conveyor belt configuration.

As shown in Fig. 1, the proposed system consists of three nested U-shaped circular conveyor belts, integrated with entry points, filling nozzles, and exit points. The layout is designed to guide cups smoothly through the process and to support sorting based on predefined criteria. Empty cups enter at the designated entry points, travel to the filling stations, and then move to the exit points as filled products. Importantly, the belts enable shared movement of cups throughout the cycle, so cups progress continuously rather than waiting for discrete start–stop steps. In practice, a required number of cups is placed at the entry point of each belt, and each cup benefits from the coordinated motion of others helping reduce total order processing time.



2.1. Operational Dynamics

Case IV introduces a new approach by consolidating yogurt filling and three flavor-filling operations into a single station on a circular conveyor belt. Unlike the earlier cases, which relied on multiple filling points and linear layouts, this design creates a different operating flow and reduces unnecessary waiting and movement. The main goal of Case IV is to minimize the total processing time for a given set of orders, challenging conventional assumptions and placing efficiency at the center of the system design.

2.2. Robotic Automation and Continuous Operation

A key innovation in Case IV is the use of a robotic arm to place cups continuously onto the conveyor. Unlike the earlier setups, this approach removes the waiting time that typically occurs at entry points and helps maintain a steady flow of work. In addition, the study adopts a strict no-preemption policy during filling: once an order begins, it is completed without interruption. This creates a smoother and more consistent processing sequence, in contrast to the stop-and-go behavior and interruption points observed in Cases I and II.

2.3. Geometric Complexity and Varied Conveyor Belts

Case IV introduces a more complex geometry by using multiple circular conveyor belts, with smaller belts nested within the radius of a larger belt. This design differs from earlier cases, which relied mainly on linear layouts or single-belt configurations. Each circular belt in Case IV has its own characteristics such as different radii and belt lengths which adds flexibility to the system. As production demand changes, the layout can be adjusted quickly by adding or removing belt segments, allowing the line to scale up or down with minimal disruption.

2.4. Technological Advancements

The geometric constraints require that the width of the innermost circular conveyor belt be greater than the cup diameter, and that its length exceed three times the cup diameter. These design requirements add a practical engineering consideration that was not necessary in the earlier cases.

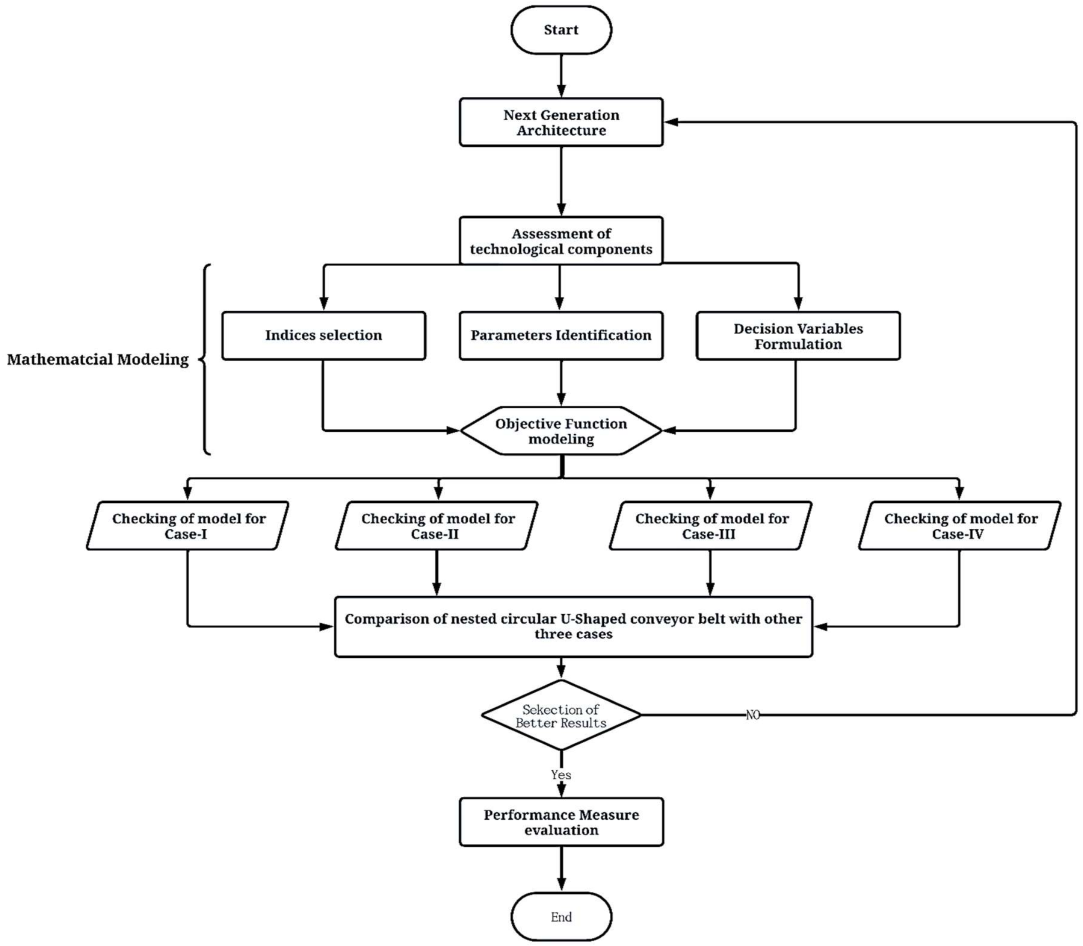


Fig. 1 Optimal solution algorithm.

The yogurt-filling production line has evolved substantially, moving toward a more advanced architecture that integrates modern technologies to improve both efficiency and precision. The design retains the core principles of a single filling point and full automation, following the approach proposed in (Chen et al., 2022), which helps keep the workflow smooth and straightforward. In addition, the use of Near Field Communication (NFC) as introduced in the earlier architecture supports faster and more reliable categorization and color recognition, enabling a more data-driven and responsive operation. Precision in loading and unloading is further strengthened through the Fanuc LR Mate 200ic robotic arm and the integration of all filling nozzles into a single unified head designed in SolidWorks (Chen et al., 2022). The system's control and communication layer is supported by the PN532 NFC/RFID controller breakout board and an FTDI chip, combined with Raspberry Pi and WAGO Programmable Field Controllers (PFCs) to ensure stable coordination across devices. A key addition in the proposed setup is the introduction of multiple circular U-shaped conveyor belts, including smaller belts embedded within larger-radius conveyors. This nested layout adds a new spatial dimension and improves the overall footprint and flow of the production line. Moreover, dedicated robotic arms at the entry and exit points enable continuous cup placement and removal, further increasing automation. Additional components such as a diaphragm pump, a pneumatic manipulator arm, and push-button controls enhance operational flexibility and precision (Chen et al., 2022). Overall, the proposed architecture combines established Industry

4.0 principles with new layout innovations, representing a meaningful step forward in yogurt-filling optimization. As illustrated in Fig. 3, the next-generation yogurt-filling line integrates circular conveyor belts and robotic arms to provide a flexible and efficient solution. Robotic arms are positioned strategically along the circular U-shaped conveyors to perform precise sorting and handling. Guided by the proposed model, the arms pick and place cups onto the appropriate conveyor belts and use sensors and actuators to ensure accurate placement on predefined paths.

3. Mathematical model

To support operational excellence in yogurt and flavor-filling systems, this study develops a mathematical model to guide process optimization. The model captures two core processes: cup filling and cup movement along the conveyor belt. Each cycle begins when a cup is placed at the entry point and ends when it exits the system after filling.

4.1. Indices

a	volume of yogurt	a = 1, 2... A
b	yogurt type	b = 1, 2... B
c	volume of flavor	c = 1, 2..., C
d	flavor type	d = 1,2..., D
e	total volume of yogurt and flavor(s)	e = 1, 2..., E
g	belt number in the system	g = 1, 2..., G
n	number of cups	n = 1, 2...., N

4.2. Process Parameters

L_g	The total length of the conveyor belt from entry to the exit point of belt 'g.'
l_g	Half of the total length of the conveyor belt, i-e. Entry to filling or filling to existing point of belt 'g.'
V_{abcdeg}	Volume of yogurt in a cup on a conveyor belt 'g'
v_{abcdeg}	Volume of flavor in a cup on a conveyor belt 'g'
d	The diameter of a cup 'n'
N_g	Possible number of cups 'n' in a queue on conveyor belt 'g'
S_{max}	Maximum allowable speed of the conveyor belts
T_{bg}	Idle time of the yogurt nozzle on a conveyor belt 'g'
T_{df}	Idle time of the flavor nozzle on a conveyor belt 'g'
t_{bg}	Yogurt filling time on a conveyor belt 'g'
t_{dg}	Flavor filling time on a conveyor belt 'g'
S_g	Actual speed of the conveyor belt 'g'
Δt_g	Time to reach filling point from entry point/or from filling point to exit point on conveyor belt 'g'
Δt_{gn}	Time taken to cover a distance equal to the diameter of a cup/job 'n' on a conveyor belt 'g'
ΔT_g	Total time taken from entry to exit without filling time on conveyor belt 'g'
$P_{abcdeg}(n)$	Processing time of job 'n' on a conveyor belt 'g'
P_g	Completion time of all cups assigned to conveyor belt 'g'
F_n	Maximum completion time of all cups assigned to the available conveyor belts 'g.'

4.3. Decision Variables

β_{abcdeg}	Feed rate of the yogurt valve on a conveyor belt 'g'
γ_{abcdeg}	The feed rate of the flavor valve on a conveyor belt 'g.'

As discussed in Section 2, the conveyor belts differ in both length and operating speed. As a result, the time required for cups to travel on each belt varies, and each belt's cup capacity depends on its respective length. The required process parameters can therefore be derived from the following equations:

$$S_g = min\left\{min\left[l_g\frac{\beta_{abcdeg}}{V_{abcdeg}}, l_g\frac{\gamma_{abcdeg}}{v_{abcdeg}}\right], S_{max}\right\} \quad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., e.g = 1, 2..., G} \tag{1}$$

$$\Delta t_g = \frac{l_g}{s_g} \quad \text{g = 1, 2..., G} \tag{2}$$

$$\Delta t_{gn} = \frac{d}{s_g} \quad \text{g = 1, 2..., G} \tag{3}$$

$$N_g = \frac{l_g}{d} \quad \text{g = 1, 2..., G} \tag{4}$$

Equation (1) defines the actual speed of the conveyor belt. Equations (2) and (3) compute (i) the time a cup needs to travel from the entry point to the filling station, or from the filling station to the exit point, and (ii) the time required to move a distance equal to one cup diameter, respectively. Equation (4) determines the maximum number of cups that can form a queue on a given conveyor belt.

Accordingly, the objective function is formulated to minimize the total time required to fill and transport cups, while allowing adjacent (back-to-back) cup entries to reduce idle time and waiting. This objective can be stated as follows:

$$Minimize: Z = \sum_a^A\sum_b^B\sum_c^C\sum_d^D\sum_e^E\sum_g^G\sum_n^N\left\{max\left(\frac{V_{abcdeg}}{\beta_{abcdeg}}, \frac{v_{abcdeg}}{\gamma_{abcdeg}}\right) + \frac{2l_g}{s_g} - [N_g - (n + x)]\frac{d}{s_g}\right\} \tag{5}$$

We observed that overall processing time can be reduced by minimizing the waiting time of cups at the entry point. In Case IV, cup movement is not constrained by entry delays; instead, yogurt and flavor filling is performed continuously at a single station while cups circulate on multiple conveyor belts of different lengths. The filling station is positioned equidistant from the entry and exit points of each conveyor belt. The objective function is therefore evaluated subject to the following equations and constraints to obtain the minimum processing time.

$$x = \begin{cases} N_g - 1 & if\ n = 1 \\ 0 & if\ N_g \geq n > 1 \\ 1 - N_g & if\ n > N_g \\ 2(1 - N_g) & if\ n > 2N_g - 1 \\ 3(1 - N_g) & if\ n > 3N_g - 2 \\ 4(1 - N_g) & if\ n > 4N_g - 3 \\ \vdots & \vdots \\ k(1 - N_g) & if\ n > kN_g - (k - 1) \end{cases} \quad \text{g = 1, 2..., G n = 1, 2...., N} \tag{6}$$

$$t_{bg} = \frac{V_{abcdeg}}{\beta_{abcdeg}} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{7}$$

$$t_{dg} = \frac{v_{abcdeg}}{\gamma_{abcdeg}} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{8}$$

$$\frac{\beta_{abcdeg}}{V_{abcdeg}} l_g \leq Maximum\ S_g \leq S_{max} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{9}$$

$$\frac{\gamma_{abcdeg}}{v_{abcdeg}} l_g \leq Maximum\ S_g \leq S_{max} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{10}$$

$$\beta_{abcdeg} \leq Maximum\ \beta_{abcdeg} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{11}$$

$$\gamma_{abcdeg} \leq Maximum\ \gamma_{abcdeg} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{12}$$

$$\frac{V_{abcdeg}}{\beta_{abcdeg}} = \frac{v_{abcdeg}}{\gamma_{abcdeg}} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{13}$$

$$l_g \geq d \qquad \text{g = 1, 2..., G} \tag{14}$$

$$\sum_{g}^{G}\sum_{n}^{N}\left(\frac{W_j}{\Delta t_{gn}} - \frac{t_{bfg}}{\Delta t_{gn}} - N_g\right) \geq D_{abcdeg} \qquad \text{a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G} \tag{15}$$

The objective function in Eq. (5) minimizes the total processing time required to fill each cup with yogurt and flavor, while also reducing waiting time. Equation (6) links the objective-function variable to the number of cups present on a given conveyor belt. Equations (7)–(8), adopted from Cui et al. (Cui et al., 2022), define the filling times for yogurt and flavor in a cup, respectively.

Constraints (9)–(13) are adapted from Chen et al. (Chen et al., 2022). Specifically, constraints (9) and (10) set the maximum allowable speed for each conveyor belt. Constraints (11) and (12) impose limits on the feed rates of the yogurt and flavor valves, respectively. Equation (13) enforces equality between yogurt and flavor filling times. Constraint (14) ensures that the conveyor belt length exceeds the cup diameter. Finally, constraint (15) represents the customer's allowable waiting time.

4. Solution Procedure

This study develops a structured order-handling plan that assigns customer orders based on machine availability and the maximum waiting time customers are willing to tolerate. To ensure stable and feasible operations, we define clear rules for minimum and maximum order sizes. Customers may select both the dairy-product volume per cup and the flavor volume, but these choices are constrained within allowable limits. The analysis focuses on Type-I dairy products, with the additional requirement that the dairy portion in each cup must exceed the flavor portion by a substantial margin. Under these conditions, the model determines the number of cups required for each order and the associated customer waiting time, while accounting for total volume requirements.

The problem is implemented and solved in Microsoft Excel using VBA, organized into 11 interconnected modules, each responsible for a specific part of the solution procedure. The algorithm was executed on a Core i5 (2.30 GHz) computer and completed within a practical runtime.

Table 1 summarizes five representative orders, each with specified dairy and flavor volume requirements. These inputs are used to parameterize and solve the mathematical models for Cases I–IV. Across all cases, the objective is to maximize conveyor-belt speed or equivalently, to minimize total processing time by identifying the optimal operating values derived from the data in Table 1.

Table 1 Yogurt and three flavor mixed orders percentage

Order No.	Total volume (ml)	Percentage in Total Volume (%)				Cups
	$V_{abcdeg} + v_{abcdeg}$	Yogurt	Flavor-I	Flavor-II	Flavor-III	
1	900	80	0	5	15	24
2	500	85	15	0	0	30
3	700	90	5	0	5	50
4	250	85	5	5	5	55
5	1400	80	10	5	5	20

Table 2 lists the system parameters that represent inherent and fixed characteristics of the production setup. These parameters remain constant throughout the analysis and play a crucial role in guiding the system toward an optimal solution. They also form the core architectural foundation of the proposed system.

Table 2 System parameters

Maximum speed of conveyor belts	S_{max}	10cm/sec
Total number of conveyor belts	g	3
Total length of conveyor belt '1'	L_1	90 cm
The total length of the conveyor belt is '2.'	L_2	80 cm
Total length of conveyor belt '3'	L_3	70 cm
Maximum allowable volume of a cup	V_{max}	1500 ml/cup
Minimum allowable volume of a cup	V_{min}	250 ml/cup
Available total volume of yogurt (type-I)	V_c	300 L
Available total volume of flavor (type-I, II & III)	v_c	15 L
Maximum feed rate of yogurt valve	β_{abcdeg}	150 ml/sec
Maximum feed rate of flavor valve	γ_{abcdeg}	50 ml/sec
The diameter of each cup	d	5 cm

Using the specified set of orders and fixed system parameters, we solve the mathematical models for Cases I–IV. For each case, the objective is to minimize processing time (or, equivalently, maximize conveyor-belt speed). The results for Cases I–III are reported in Tables 3–5 and are computed for three different conveyor-belt lengths.

In the reported results, *n* denotes the number of cups in an order; β and γ represent the feed rates of the yogurt and flavor nozzles, respectively; Sg is the conveyor-belt speed; and P(s) and Fn(s) correspond to the processing time per cup and the total completion time of an order.

Table 3. Solution of Case-I(a), Case-II(a), Case-III(a) for a given set of orders with l_g = 35.

		l_g = 35			Case-I (a)		Case-II (a)		Case-III (a)	
Orders	Cups(n)	β(ml/s)	γ(ml/s)	S_g (cm/s)	P (s)	F_n (s)	P (s)	F_n (s)	P (s)	F_n (s)
1.	24	150	37.5	7.291667	24	134.4	14.4	124.8	14.4	124.8
2.	30	121.428571	21.42857	10	17.5	119	10.5	112	10.5	112
3.	50	150	16.66667	8.333333	21	226.8	12.6	218.4	12.6	218.4
4.	55	60.7142857	10.71429	10	17.5	206.5	10.5	199.5	10.5	199.5
5.	20	150	37.5	4.6875	37.3333333	179.2	22.4	164.2667	22.4	164.2667

Table 4. Solution of Case-I(b), Case-II(b), Case-III(b) for a given set of orders with l_g = 40.

		l_g = 40			Case-I (b)		Case-II (b)		Case-III (b)	
Orders	Cups(n)	β(ml/s)	γ(ml/s)	S_g (cm/s)	P (s)	F_n (s)	P (s)	F_n (s)	P (s)	F_n (s)
1.	24	150	37.5	8.333333	24	134.4	14.4	124.8	14.4	124.8
2.	30	106.25	18.75	10	20	136	12	128	12	128
3.	50	150	16.66667	9.52381	21	226.8	12.6	218.4	12.6	218.4
4.	55	53.125	9.375	10	20	236	12	228	12	228
5.	20	150	37.5	5.357143	37.3333333	179.2	22.4	164.2667	22.4	164.2667

Table 5. Solution of Case-I(c), Case-II(c), Case-III(c) for a given set of orders with l_g = 45.

		l_g = 45			Case-I (C)		Case-II (C)		Case-III (C)	
Orders	Cups(n)	β(ml/s)	γ(ml/s)	S_g (cm/s)	P (s)	F_n (s)	P (s)	F_n (s)	P (s)	F_n (s)
1.	24	150	37.5	9.375	24	134.4	14.4	124.8	14.4	124.8
2.	30	94.44444	16.66667	10	22.5	153	13.5	144	13.5	144
3.	50	140	15.55556	10	22.5	243	13.5	234	13.5	234
4.	55	47.22222	8.333333	10	22.5	265.5	13.5	256.5	13.5	256.5
5.	20	150	37.5	6.026786	37.33333	179.2	22.4	164.2667	22.4	164.2667

In Cases I and II, a single conveyor belt of fixed length is used to process all cups. In Case III, multiple conveyor belts are employed, but they are all the same length. By contrast, Case IV uses three conveyor belts of different lengths, meaning the same cup can experience different travel and processing times depending on the belt assigned.

The Case IV results are reported in Tables 6–10, which show how each order is allocated across three conveyor belts with lengths of 35 cm, 40 cm, and 45 cm. For each order, the sequence number (S.N.) of cups assigned to each belt is provided in the first, third, and fifth columns of the tables. The corresponding processing time for each cup (n) on its assigned belt is given in the second, fourth, and sixth columns.

$$P_{abcdeg}(n) = \left\{\frac{V_{abcdeg}}{\beta_{abcdeg}} + 2\Delta t_g - [N_g - (n+x)]\Delta t_{gn}\right\}$$

a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G (16)

$$P_g = \sum_{n}^{N} P_{abcdeg}(n)$$

a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G (17)

$$F_n = \max\{P_1, P_2, P_3, \dots, P_g\}$$

a = 1, 2... A b = 1, 2... B c = 1, 2..., C d = 1,2..., D e = 1, 2..., E g = 1, 2..., G (18)

Cups are initially placed at rest at the entry point of each conveyor belt. However, as explained in Section 2, the combination of continuous placement and shared cup movement removes entry waiting time in Case IV. Before assigning cups to specific conveyor belts based on the required yogurt and flavor volumes, we first compute the processing time of each cup on each belt using Eq. (16), subject to the constraints in Eqs. (6)–(14). Equation (16) gives the processing time of the *n*th cup on a conveyor belt.

As shown in Table 6, the first cup on each belt requires more time than the second cup. This occurs because of the adjacent movement mechanism: once the first cup begins moving, subsequent cups benefit from the relative motion of preceding cups and therefore do not start from complete rest. In other words, shared movement during the entry phase helps reduce the effective processing time for later cups.

After assigning cups to conveyor belts and computing their individual processing times, we sum the processing times on each belt using Eq. (17) to obtain the total time required by each belt to process its assigned cups. The final order completion time, Fn, is then defined as the maximum of these belt-specific totals i.e., the time taken by the slowest (most loaded) belt. This overall completion time is computed using Eq. (18), which selects the maximum completion time among the three conveyor belts.

Table 6. Order number 1 with the number of cups, n=24

Belt 1(S.N)	$P_{abcde1}(n)$	Belt 2(S.N)	$P_{abcde2}(n)$	Belt 3(S.N)	$P_{abcde3}(n)$
3	14.4	2	14.4	1	14.4
4	10.66666667	5	10.8	6	10.97142857
7	11.2	8	11.4	9	11.65714286
10	11.73333333	11	12	12	12.34285714
13	12.26666667	14	12.6	15	13.02857143
16	12.8	17	13.2	18	13.71428571
19	13.33333333	20	13.8	21	14.4
23	13.86666667	24	14.4	22	10.97142857
P_1	100.2666667	P_2	102.6	P_3	101.4857143

As shown in Table 6, the total completion times (Pg) for the cups assigned to conveyor belt 1 (P1), conveyor belt 2 (P2), and conveyor belt 3 (P3) are 100.27 s, 102.60 s, and 101.49 s, respectively. The overall order completion time (Fn) is the maximum of these three values. Since P2 is the largest, Order 1 is completed in 102.60 s.

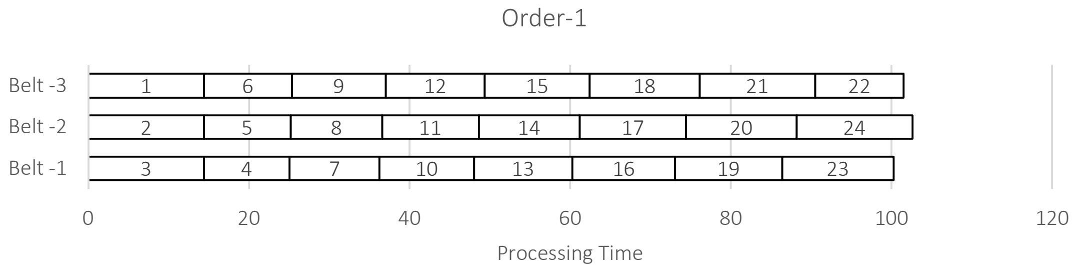


Fig. 3 Order 1 cups sequence on belts

To sequence cups efficiently, we assign them to conveyor belts based on (i) the earliest availability and (ii) the shortest processing time. For each order, the first cup is assigned to the belt with the shortest processing time, the second cup to the belt with the second-shortest time, and the third cup to the belt with the third-shortest time. If two or more belts have the same processing time, any of the tied belts may be selected.

As processing continues, each belt's available time is updated by adding the processing time of the newly assigned cup. The next cup is then assigned to the belt that becomes available the earliest, and this cycle continues until the required number of cups for the order is completed.

To visualize these assignments, Figs. 4–8 present Gantt-style charts where the title indicates the order number, the square blocks represent processing intervals, and the numbers inside the blocks indicate cup sequence. The y-axis denotes the belt number, while the x-axis shows processing time. For example, Fig. 4 indicates that Belt 2 has the longest workload among the belts for Order 1; therefore, Order 1 completes when Belt 2 finishes processing its assigned cups.

For Order 2, Table 7 shows that the first cup can be processed with different times across the three belts. Following the assignment rule, the first cup is allocated to Belt 3 (shortest processing time), the second to Belt 2, and the third to Belt 1. After updating belt availability across the full assignment sequence, the completion times are P1 = 107.5 s, P2 = 104 s, and P3 = 101 s. The order completion time is the maximum of these values, so Order 2 completes in 107.5 s. Figure 5 visually confirms this result, showing that Order 2's completion time is driven by the final cup processed on Belt 1.

Table 7. Order number 2 with number of cups, n=30

Belt 1(S.N)	$P_{abcde1}(n)$	Belt 2(S.N)	$P_{abcde2}(n)$	Belt 3(S.N)	$P_{abcde3}(n)$
3	13.5	2	12	1	10.5
6	10	5	9	4	8
9	10.5	8	9.5	7	8.5
12	11	11	10	10	9
15	11.5	14	10.5	13	9.5
18	12	17	11	16	10
22	12.5	20	11.5	19	10.5
25	13	23	12	21	8
29	13.5	27	9	24	8.5
		30	9.5	26	9
				28	9.5
P_1	107.5	P_2	104	P_3	101

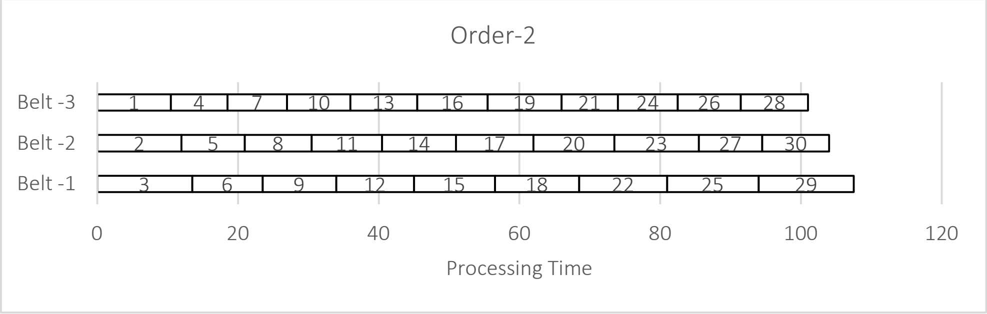


Fig. 4 Order 2 cups sequence on belts.

Table 8 shows a clear cyclic pattern in processing times across the three conveyor belts for Order 3. On Belt 1, the processing time observed for the first cup reappears when the cup index n reaches 9, and the same repeating behavior is visible on Belts 2 and 3. This repetition reflects the model's structure and indicates that cups benefit from shared movement on the conveyor belt rather than starting from rest each time.

For Order 3, the total completion times for the cups assigned to conveyor belt 1 (P1), conveyor belt 2 (P2), and conveyor belt 3 (P3) are 188.0 s, 186.375 s, and 187.8 s, respectively.

Table 8. Order number 3 with several cups, n=50.

Belt 1(S.N)	$\boldsymbol{P_{abcde1}(n)}$	Belt 2(S.N)	$\boldsymbol{P_{abcde2}(n)}$	Belt 3(S.N)	$\boldsymbol{P_{abcde3}(n)}$
3	13.5	2	12.6	1	12.6
6	10	4	9.45	5	9.6
9	10.5	7	9.975	8	10.2
12	11	10	10.5	11	10.8
15	11.5	13	11.025	14	11.4
18	12	16	11.55	17	12
21	12.5	19	12.075	20	12.6
24	13	22	12.6	23	9.6
27	13.5	26	9.45	25	10.2
30	10	29	9.975	28	10.8
33	10.5	31	10.5	32	11.4
36	11	34	11.025	35	12
39	11.5	37	11.55	38	12.6
42	12	40	12.075	41	9.6
45	12.5	43	12.6	44	10.2
48	13	47	9.45	46	10.8
		49	9.975	50	11.4
P_1	188	P_2	186.375	P_3	187.8

Fig. 5 It shows allocating the cups of Order-3 on each conveyor belt, which indicates that the maximum processing time for cups on conveyor Belt-1 is.

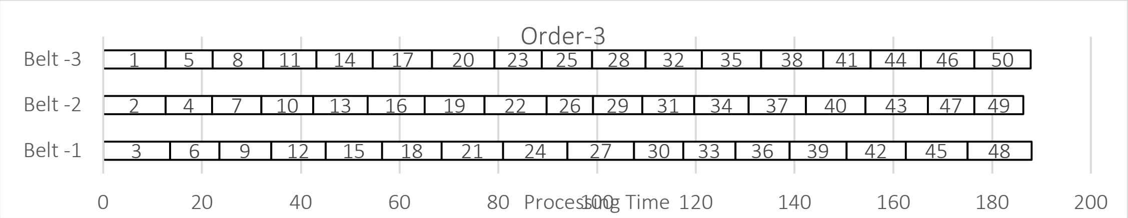


Fig. 5 Order 3 cups sequence on belts.

Table 9 shows that the first cup in Order 7 can be processed with different times depending on the conveyor belt selected. Following the established assignment rule, we allocate the first cup to Belt 3 because it offers the shortest processing time. The second and third cups are then assigned to Belt 2 and Belt 1, respectively.

After updating belt availability throughout the assignment sequence, the completion times for conveyor belt 1 (P1), conveyor belt 2 (P2), and conveyor belt 3 (P3) are 188.0 s, 187.5 s, and 193.5 s, respectively. Since the overall order completion time is the maximum of these values, Order 7 completes in 193.5 s.

Table 9. Order number 4 with the number of cups, n=55.

Belt 1(S.N)	$P_{abcde1}(n)$	Belt 2(S.N)	$P_{abcde2}(n)$	Belt 3(S.N)	$P_{abcde3}(n)$
3	13.5	2	12	1	10.5
6	10	5	9	4	8
9	10.5	8	9.5	7	8.5
12	11	11	10	10	9
15	11.5	14	10.5	13	9.5
19	12	17	11	16	10
22	12.5	20	11.5	18	10.5
25	13	23	12	21	8
29	13.5	27	9	24	8.5
33	10	30	9.5	26	9
36	10.5	32	10	28	9.5
39	11	35	10.5	31	10
43	11.5	38	11	34	10.5
46	12	41	11.5	37	8
49	12.5	44	12	40	8.5
52	13	48	9	42	9
		51	9.5	45	9.5
		54	10	47	10
				50	10.5
				53	8
				55	8.5
P_1	188	P_2	187.5	P_3	193.5

Within the provided Fig. 6, the distribution cups across belts highlight Belt-3 as a primary contributor to the order's completion time.

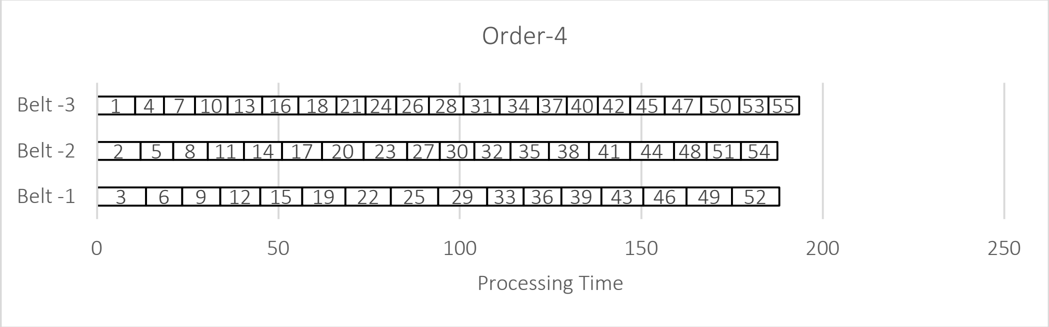


Fig. 6 Order 4 cups sequence on belts.

Table 10 summarizes the cup-allocation strategy for Order 10. Because the initial cups have identical processing times across the belts, the first cup is assigned to Belt 3. As the sequence progresses, cup assignments follow the same selection rule to balance workload and minimize processing time; for example, cup 4 is assigned to Belt 1 because it offers the shortest processing time at that point. Using this criterion, the full set of 20 cups is distributed across the three belts. The resulting completion times for conveyor belt 1 (P1), conveyor belt 2 (P2), and conveyor belt 3 (P3) are 134.4 s, 137.2 s, and 118.4 s, respectively. The overall completion time of Order 10 is determined by the maximum of these values; therefore, Order 10 completes in 137.2 s (Belt 2).

Table 10 Order number 5 with the number of cups, n=20.

Belt 1(S.N)	$P_{abcde1}(n)$	Belt 2(S.N)	$P_{abcde2}(n)$	Belt 3(S.N)	$P_{abcde3}(n)$
3	22.4	2	22.4	1	22.4
4	16.59259259	5	16.8	6	17.06666667
7	17.42222222	8	17.73333333	9	18.13333333
10	18.25185185	11	18.66666667	12	19.2
13	19.08148148	14	19.6	15	20.26666667
16	19.91111111	17	20.53333333	18	21.33333333
19	20.74074074	20	21.46666667		
P_1	134.4	P_2	137.2	P_3	118.4

Fig. 7 illustrates that belt 1 holds the highest processing time for Order-10 and correspondingly represents the workload distribution among the belts.

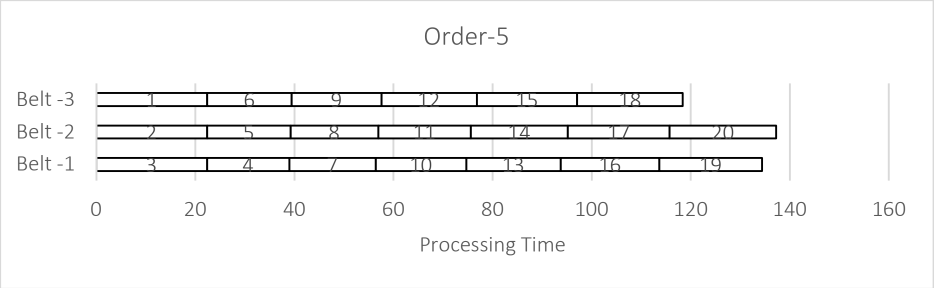


Fig. 7 Order 5 cups sequence on belts.

We adopt a dispatching strategy that assigns cups to conveyor belts in a way that minimizes idle time and maximizes utilization of both the conveyor belts and the filling nozzles. Under this rule, the first cup of each order is sent to the belt with the shortest processing time among all available belts. Subsequent cups are then allocated dynamically to the belts that offer the best combination of earliest availability and shortest processing time.

By continuously updating belt availability and applying this selection logic, the system balances the workload across belts, reduces waiting, and achieves a lower overall completion time for each order consistent with the results reported in Table 11.

Table 11 The optimal solution for a set of 13 orders following Case-IV.

Order	Cups	β_{abcde1}(ml/s)	β_{abcde2}(ml/s)	β_{abcde3}(ml/s)	S_1 (cm/s)	S_2 (cm/s)	S_3 (cm/s)	$P_{abcdeg}(n)$	F_n (S)
1.	24	150	150	150	7.29166666	8.33333333	7.29166666	14.4	114.666666
2.	30	121.428571	106.25	121.428571	10	10	10	10.5	89.0952381
3.	50	150	150	150	8.333333333	9.523809524	8.333333333	12.6	187.8
4.	55	60.7142857	53.125	60.7142857	10	10	10	10.5	106.78125
5.	20	150	150	150	4.6875	5.35714285	4.6875	22.4	159.6

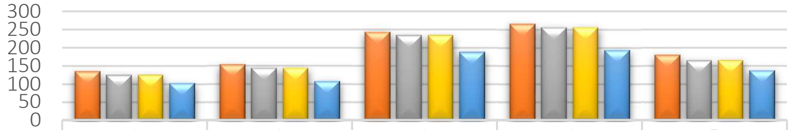
The results in the tables confirm that all configurations satisfy the model constraints and that the nozzle feed rates remain within their allowable limits. In Case I, the processing times for configurations (a), (b), and (c) are 16.2517 min, 15.2067 min, and 14.4317 min, respectively. In Case II, the corresponding processing times are 15.3928 min, 14.3911 min, and

13.6494 min. Case III yields the same processing times as Case II for configurations (a), (b), and (c): 15.3928 min, 14.3911 min, and 13.6494 min, respectively.

In contrast, Case IV, which operates three conveyor belts of different lengths concurrently, achieves the lowest processing time of 12.1467 min.

5. Results and Discussion

Exploring different configurations under identical operating conditions helps reveal how conveyor-belt design affects process efficiency. Figure 9 compares order processing times across the four cases using conveyor belts of the same length.



	1	2	3	4	5
🟧 Case-I (a)	134.4	153	243	265.5	179.2
▨ Case-II (a)	124.8	144	234	256.5	164.2666667
🟨 Case-III (a)	124.8	144	234	256.5	164.2666667
🟦 Case-IV	102.6	107.5	188	193.5	137.2

Fig. 8 Processing time (seconds) of orders from Case-I(a), II(a), III(a) & Case-IV

Our results highlight clear differences in order processing times across the proposed cases. Processing time is reported in seconds and shows that Case I consistently requires more time than Case II. Cases II and III exhibit similar processing times, largely because Case III is constrained by its multi-flavor filling setup for a single cup. As shown in Figure 11, Case IV consistently outperforms Cases I–III, indicating superior operational efficiency in order processing.

	1	2	3	4	5
🟧 Case-I (C)	134.4	119	226.8	206.5	179.2
▨ Case-II (C)	124.8	112	218.4	199.5	164.2666667
🟨 Case-III (C)	124.8	112	218.4	199.5	164.2666667
🟦 Case-IV	102.6	107.5	188	193.5	137.2

Fig. 9 Processing time (seconds) of orders from Case-I(c), II(c), III(c) & Case-IV

	a	b	c
🟧 Case-I(a,b,c)	16.25166667	15.20666667	14.43166667
▨ Case-II(a,b,c)	15.39277778	14.39111111	13.64944444
🟨 Case-III(a,b,c)	15.39277778	14.39111111	13.64944444
🟦 Case-IV	12.14666667	12.14666667	12.14666667

Fig. 10 Processing time (seconds) of orders from Case-I(b), II(b), III(b) & Case-IV.

Figures 10 and 12 indicate a clear pattern: processing time increases as conveyor-belt length increases. Figure 12 compares total order completion times across the four cases for the corresponding belt lengths. In Case I, configurations (a), (b), and (c) require 16.25 min, 15.21 min, and 14.43 min, respectively. Case II shows the same overall trend, with completion times of 15.39 min, 14.39 min, and 13.65 min for configurations (a), (b), and (c). Notably, Case III produces identical processing times to Case II across all three configurations, suggesting that the system behaves similarly under the multi-flavor filling condition considered.

In contrast, Case IV which uses three conveyor belts of different lengths operating concurrently achieves a substantially shorter processing time of 12.15 min. Overall, these results reinforce a consistent takeaway: conveyor layout and belt length meaningfully shape throughput and efficiency, and the proposed circular configuration (Case IV) delivers the best performance among the evaluated alternatives.

6. Conclusions

This study examined alternative machine configurations for a dairy filling system with the goal of reducing processing time, using space more efficiently, and strengthening automation and data exchange (Chen et al., 2022; Cui et al., 2022; Salah, Alsamhan, et al., 2021; Salah, Khan, et al., 2021). The proposed mathematical model for the modified configurations consistently outperformed earlier models, offering a clear analytical foundation for improving conveyor-belt performance, an ongoing challenge in many production environments (Chen et al., 2022; Cui et al., 2022). At the core of this work was a sustainability-driven objective: to minimize the total time required to fill cups with different dairy products and flavors while operating within practical constraints (Chen et al., 2022; Cui et al., 2022). To achieve this, the model adjusts key controllable parameters, particularly conveyor-belt speed and valve feed rates, while respecting their maximum allowable limits (Chen et al., 2022; Cui et al., 2022).

Across the linear conveyor designs, the progression from Case I (two filling points) to Case II (single filling point) and Case III (dedicated filling point for each flavor) produced only modest changes in processing time (Chen et al., 2022; Cui et al., 2022; Salah, Khan, et al., 2021). In contrast, the move to Case IV, a system of multiple circular conveyor belts with continuous cup placement and coordinated movement of adjacent cups delivered a substantial reduction in processing time (Bock & Bruhn, 2021; Nielsen et al., 2023; Novak et al., 2023; Vasilis et al., 2022; Winter et al., 2019). This improvement supports more sustainable operations and provides greater flexibility to respond to changing production requirements (Bock & Bruhn, 2021; Novak et al., 2023). Based on these results, Case IV was selected as the preferred configuration for order processing.

The findings offer several practical implications for yogurt manufacturers. First, they show that meaningful efficiency gains can be achieved by redesigning machine configurations to improve space utilization and reduce cycle time, especially when paired with Industry 4.0 capabilities such as automation and real-time data exchange (Chen et al., 2022; Salah, Khan, et al., 2021; Salah et al., 2020). Second, the mathematical modeling framework developed here provides a practical decision-support basis for conveyor system improvement, helping address a common bottleneck in filling operations (Chen et al., 2022; Cui et al., 2022). Importantly, reducing processing time and resource consumption aligns with environmental goals while also creating opportunities for cost savings and higher throughput (Santana et al., 2017).

Beyond time savings, Case IV also enhances operational agility, allowing the system to adapt more readily to shifts in product mix and demand (Bock & Bruhn, 2021; Nielsen et al., 2023). At the same time, this study has limitations. For example, automatic decision-making for cup sequencing on the conveyor belts was not fully addressed. Future work could extend the proposed framework by integrating deep learning or neural-network-based decision support to improve sequencing decisions and further reduce processing time (Jeon & Schuesslbauer, 2020).

Author Contributions

All authors contributed equally to formal analysis, data acquisition, methodology, manuscript drafting, and reviewing and editing all sections. The authors have read and agreed to the final version of the manuscript.

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