Single Product Capacitated Lot Sizing combined with the Single Row Facility Layout Problem

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Abstract: This study addresses the Single-Product Capacitated Lot Sizing Problem (SP-CLSP) in conjunction with the Single-Row Facility Layout Problem (SRFLP) by proposing a mathematical model. To minimize total costs associated with a single product across all periods (including setup, inventory holding, production, and material handling), this model will determine optimal production quantities (lot sizes) for each period. Furthermore, it will identify an optimal facilities layout that minimizes material handling costs specifically based on those lot sizes. The model incorporates constraints for production capacity, single-product inventory balance, setup times, and machine-position assignments. Binary variables represent machines setup, machine assignments to specific positions in the layout, and potentially machine orientation if relevant. The model is illustrated with several example problems. CPLEX software is used to solve the Mixed-Integer Programming formulation, determining the optimal production quantities for each period and the machine layout that best suits these quantities. This integrated model allows for the simultaneous optimization of lot sizes and machine layouts for a single product, aiming to reduce total costs and improve production efficiency.

Keywords: Lot sizing, Single-Product Capacitated Lot Sizing Problem, Facility Layout Problem, Single Row Facility Layout Problem.

1. INTRODUCTION

The Single-Product Capacitated Lot Sizing Problem (SP-CLSP) is a fundamental optimization problem in production planning and inventory management. It involves determining how much of the product to produce in each period of a finite planning horizon, subject to production capacity constraints. The goal is to minimize the total costs, which typically include setup costs, inventory holding costs, and production costs.

The Single Row Facility Layout Problem (SRFLP) is another fundamental optimization problem in facility design. It deals with arranging facilities (or machines) with specific lengths along a straight line (single row) in a way that minimizes the total material handling cost.

Traditionally, lot sizing and Facility Layout Problem (FLP) have been treated as independent decisions. However, recent research has proposed conceptual frameworks that integrate these aspects. Despite these advancements, a critical gap remains in developing practical methods for simultaneous optimization. This would enable manufacturers to achieve significant gains in efficiency and cost reduction.

In this article, section 2 provides a comprehensive literature review, followed by section 3 which presents the problem description and the corresponding mathematical model. The model, formulated using Mixed Integer Programming (MIP), considers various factors impacting production costs. These factors include setup costs, production costs, and inventory holding costs. Additionally, the model incorporates facility and position dimensions, traffic intensity based on production quantities per period, and the distance between positions within the facility. This mathematical model aims to simultaneously determine optimal production quantities (lot sizes) for each period and a facilities layout that minimizes material handling costs based on those lot sizes. section 4 showcases the model's effectiveness through the evaluation of several practical examples. Finally, the article concludes in section 5 by summarizing the key findings and outlining potential future research directions.

2. LITERATURE REVIEW

2.1 Lot sizing

The lot sizing problem is a well-studied topic in inventory management and production planning. Previous research has focused on various aspects of this problem:

Lot sizing models

Researchers have developed different models to address the lot sizing problem, including the single-item lot sizing problem (Suzanne et al., 2020), the multi-level lot sizing problem (Qin et al., 2024), and the capacitated lot sizing problem (Ramya et al., 2019). These models consider factors such as production capacity, setup costs, and multi-stage production processes.

Solution approaches

Researchers have proposed various solution methods for lot sizing problems, including exact methods such as mathematical programming (Qin et al., 2024), as well as heuristic approaches like subgradient optimization (Muthuraman & Venkatesan, 2017) and coefficient-modification heuristics (Liang et al., 2022). These methods aim to find efficient and effective solutions for lot sizing decisions.

Practical applications

Lot sizing problems have been studied in the context of various industries, such as manufacturing, supply chain management, and inventory control. Researchers have explored how lot sizing decisions can be optimized to reduce costs and improve efficiency in real-world settings (Bányai, 2024), (Ullah & Parveen, 2010).

Overall, the lot sizing problem remains an active area of research, with scholars continuing to develop new models, solution methods, and practical applications to address the challenges faced by organizations in managing their inventory and production processes.

2.2 Facility Layout Problem

The Facility Layout Problem (FLP) is a well-studied topic in operations management, with a focus on optimizing the arrangement of facilities, departments, and equipment within a given space to improve efficiency and productivity. Two specific variants of the FLP that have received significant attention in the literature are the Dynamic Facility Layout Problem (DFLP) and the Single Row Facility Layout Problem (SRFLP).

Dynamic Facility Layout Problem

The DFLP addresses the challenge of designing a facility layout that can adapt to changes in production requirements, product mix, or other factors over time (Pérez-Gosende et al., 2021), (Herrera-Granda et al., 2022). This is in contrast to the traditional static FLP, which assumes a fixed layout. The DFLP aims to find the optimal sequence of layouts that minimizes the total material handling costs over the planning horizon. Approaches to solving the DFLP include mathematical programming models, heuristic algorithms, and metaheuristics (Pérez-Gosende et al., 2021) Herrera-Granda et al., 2022).

Single Row Facility Layout Problem

The SRFLP focuses on arranging facilities or departments in a single row, with the objective of minimizing the total weighted distance between adjacent facilities (Meshram & Dalu, 2014), (Albán Palango et al, 2022). This problem is particularly relevant in situations where the physical layout of a facility is constrained, such as in a long and narrow building. The SRFLP has been shown to be NP-hard, and various solution methods have been proposed, including exact algorithms, heuristics, and metaheuristics (Meshram & Dalu, 2014), (Albán Palango et al, 2022).

The literature on the DFLP and SRFLP highlights the importance of these variants in addressing the practical challenges faced by organizations in designing and managing their facility layouts. The research in this area has contributed to the development of more efficient and adaptable facility layouts, leading to improved operational performance and cost savings.

2.3 Lot Sizing and Facility Layout Optimization

Lot sizing and facility layout optimization are two important but separate problems in production planning. Lot sizing determines the optimal production quantities for each product, while facility layout optimization arranges the physical layout of production departments and equipment to minimize material handling costs.

While lot sizing and facilities layout problems have been studied extensively, there is limited research on the integration of these two problems. Integrating lot sizing and facility layout optimization can lead to significant cost savings and improved operational efficiency. Previous research has identified several key approaches to address this combined problem:

Integrated Lot Sizing and Facility Layout Models

A few articles have looked at integrating these two problems to achieve better overall optimization. One conceptual framework proposes a 4-phase model to integrate unequal-area facility layout planning (UAFLP) with flowshop group scheduling (FSGSP), which includes lot sizing decisions. The goal is to jointly optimize layout, scheduling and lot sizes to reduce waste like excess inventory and material handling in a lean manufacturing environment (Cáceres-Gelvez et al., 2022).

(Yang et al., 2023) developed mathematical models to jointly optimize lot sizing and facility layout decisions. An approach that combines facility layout optimization and spatially differential parking pricing to improve the efficiency of parking lots has been presented. The authors demonstrate the effectiveness of this joint optimization approach through a case study and show that it can lead to significant improvements in parking lot performance compared to traditional approaches.

Heuristic and Metaheuristic Optimization Techniques

Researchers have applied various heuristic and metaheuristic methods to solve the integrated lot sizing and facility layout problem. For example, (Nordin et al., 2023) reviewed the use of genetic algorithms and other meta-heuristics to optimize dynamic single-row facility layout problems, which can be combined with lot sizing considerations.

Simulation-Based Optimization:

Some studies have used simulation models coupled with optimization algorithms to find the best lot sizing and facility layout decisions. This approach allows for the consideration of complex real-world constraints and dynamics that may be difficult to capture in analytical models (Yang et al., 2023)

Incorporating Flexibility and Reconfigurability

To address changing production requirements, researchers have explored facility layout designs that allow for easy reconfiguration, such as modular or reconfigurable manufacturing systems. Integrating these flexible layout approaches with lot sizing can enhance the responsiveness and efficiency of the overall system (Salimpour & Azab, 2021).

However, the literature on combining lot sizing and facility layout is still quite limited, most articles focus on one problem or the other and more research is needed to develop practical methods for simultaneously optimizing lot sizes, production schedules, and facility layouts to improve manufacturing efficiency and reduce costs.

In summary, the key to optimizing lot sizing in conjunction with facility layout is to develop integrated models and solution approaches that consider the interdependencies between these two critical operational decisions. By adopting a holistic perspective, organizations can achieve significant improvements in inventory management, material handling costs, and overall production efficiency.

3. PROBLEM DESCRIPTION

This model considers several resources (machines) on which only one type of product is manufactured during several periods *t*. The periods have limited capacities C_t which is assumed in units of time and it can vary from one period to another and the product is composed of one or more levels, with a determined demand d_t during each period. The product has a production coefficient a_t or consumption capacity to be produced. The unit of time is discrete and the time horizon is limited. When the product needs to be manufactured, the resource must be configured for that product in the same time period, which consumes system capacity. The product has a launch cost SC_t and a setup time ST_t as well as a production cost PC_t in each period. Backorders and lost sales are not permitted. Capacity per period is consumed by setup time and production time.

The excess quantity produced can be stored, resulting a storage cost h_t except in the last period when all units in the inventory must be consumed. Assuming b_t a large number, not limiting the achievable production quantities during period *t*. The routing of the product in each period is considered variable and it's determined by a binary variable R_{jkt} which takes the value of 1 if the product passes through machines *j* and *k* on period *t*, and 0 otherwise.

The quantity produced during each period is represented by Q_t, and the inventory at the end of the period is represented by I_t.

The model also takes into account the assignment of facilities to positions. Assuming that we have N installations where each installation is assigned to a specific position of length $long_p$ and width $larg_p$, and each installation can be placed at any position in each period.

Since the facilities are predetermined and fixed, we also assume that the distance between each pair of positions is known. Let d_{pq} represent the distance between positions *p* and *q*, where 1 ≤ p, q ≤ P. Each facility *j* has a specified length l_j and width w_j, and is connected to all other machines by a traffic intensity defined from the quantity produced in each period and which is equal to $R_{jkt}Q_t$. The cost of simultaneously assigning facility j to position p and facility k to position q is equal to $R_{jkt}Q_t d_{pq}$.

We introduce binary decision variables Y_t which takes the value 1 if a product launch is carried out in period *t* and 0 otherwise, x_{jp}, which takes the value 1 if machine *j* is assigned to position *p*, and 0 otherwise and v_j which take the value 1 if department *j* is placed vertically and 0 otherwise.

We use a mixed integer programming formulation for this problem. The main objective of this model is to determine the production quantity of the product in each period while minimizing the sum of setup, storage, and production costs over all periods. Additionally, it aims to define the optimal machine layout based on the total quantity of the product transported between each pair of machines and the distance between each pair of positions according to formula (1).

$$Z = \min \sum_{t=1}^{T} SC_t . Y_t + \sum_{t=1}^{T} h_t . I_t + \sum_{t=1}^{T} Q_t . PC_t + \sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{k=1}^{M}\sum_{p=1}^{P}\sum_{q=1}^{P} R_{jkt.} Q_t . d_{pq} . x_{jp} . x_{kq} \quad (1)$$

Subject to

$$I_{t-1} + Q_t = d_t + I_t \qquad \forall\, t \quad (2)$$

$$a_t Q_t + ST_t Y_t \leq C_t \qquad \forall\, t \quad (3)$$

$$Q_t \leq b_t Y_t \qquad \forall\, t \quad (4)$$

$$Q_t \geq 0, Y_t \geq 0 \; and \; I_t = 0 \qquad \forall\, t \quad (5)$$

$$Y_t \in \{0,1\} \qquad \forall\, t \quad (6)$$

$$\sum_{p=1}^{P} x_{jp} = 1 \qquad \forall\, 1 \leq j \leq M, \; \forall\, 1 \leq t \leq T \quad (7)$$

$$\sum_{j=1}^{M} x_{jp} = 1 \qquad \forall\, 1 \leq p \leq P, \; \forall\, 1 \leq t \leq T \quad (8)$$

$$\sum_{j=1}^{M} (l_j v_{jt} + w_j(1 - v_{jt})) x_{jpt} \leq larg_p \qquad \forall\, 1 \leq p \leq P, \; \forall\, 1 \leq t \leq T \quad (9)$$

$$\sum_{j=1}^{M} (l_j(1 - v_{jt}) + w_j v_{jt}) x_{jpt} \leq long_p \qquad \forall\, 1 \leq p \leq P, \; \forall\, 1 \leq t \leq T \quad (10)$$

$$x_{jp} \in \{0,1\} \qquad \forall j, \forall p \quad (11)$$

$$v_j \in \{0,1\} \qquad \forall j \qquad (12)$$

$$R_{jkt} \in \{0,1\} \qquad \forall j, \forall k, \forall t \qquad (13)$$

Constraint (2) represents the inventory balancing constraint. Constraint (3) states that the total capacity consumed (production + changeover time) cannot exceed the system capacity in period t. Constraint (4) indicates that a product cannot be produced in period t only if a setup is made before the start of production. Constraint (5) is a non-negativity constraint for Q_t and Y_t and it indicates the initial inventory value of the product. Constraint (6) indicates that the decision variable Y_t is a binary variable. Constraint (7) guarantees that each department is assigned to exactly one location while constraint (8) guarantees that only one department is assigned to each position. Constraints (7) and (8) together define an assignment of departments to locations. Constraints (9) and (10) ensure that the dimensions of the facility must not exceed the dimensions of the position to which it will be assigned, whether placed vertically or horizontally.
Constraints (11), (12), and (13) guarantee that the variables x_{jp}, v_j and R_{jkt} are binary.

4. PERFORMANCE EVALUATION

To validate our mathematical model, we will use several practical examples to test its performance under real-world conditions.

4.1 Example with two periods and three machines

Table 1 presents data related to the mathematical model, which considers product demand for two different periods.

Table 1. Data for an example of 3 machines and 2 periods

	Period 1	Period 2
d_t	100	200
h_t	30	30
SC_t	1000	1000
ST_t	1	1
C_t	1000	1000
PC_t	1	1
a_t	1	1
b_t	10000	10000
Routing	M2>M3>M1	M2>M1

Suppose that the product can pass through three machines with specific dimensions (Fig. 1) that they must be assigned to three designated positions of different dimensions (Fig. 2).

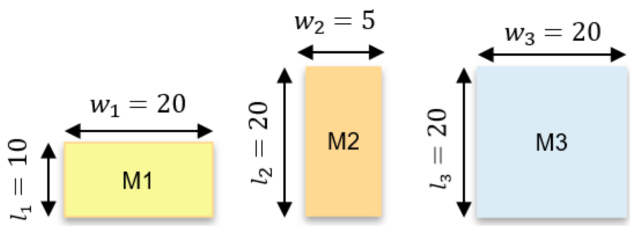

Figure 1. Machine dimensions.

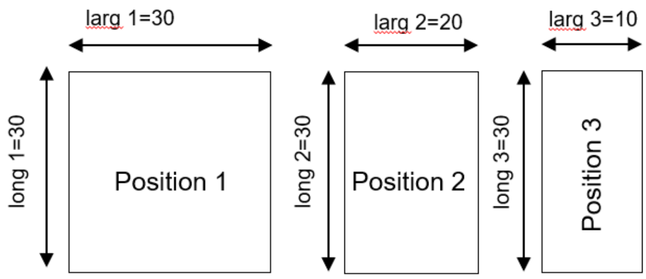

Figure 2. Position dimensions.

The distance between the pairs of facilities is given by:

$$d_{pq} = \begin{pmatrix} 0 & 10 & 20 \\ 10 & 0 & 10 \\ 20 & 10 & 0 \end{pmatrix}$$

After running this model on CPLEX, it gave us the quantities to produce during period 1 and period 2 which are equal to Q1=200 and Q2=100 respectively. This implies producing all the demand in each period rather than storing any inventory. The model likely prioritizes this approach because the setup cost associated with starting production in each period is lower compared to the cost of storing inventory.

Based on the model's solution, the total product flow through the machine pairs across all periods will be:

$$f_{jk} = Q_t R_{jkt} = \begin{pmatrix} 0 & 200 & 100 \\ 0 & 0 & 100 \\ 0 & 0 & 0 \end{pmatrix}$$

Based on the model solution for producing Q1=200 units in period 1 and Q2=100 units in period 2, the optimal machine layout obtained by CPLEX is shown in Figure 3.

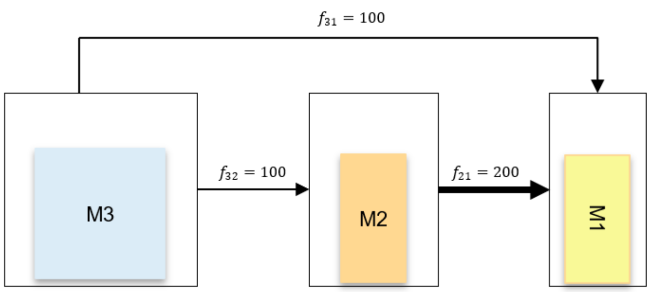

Figure 3. Optimal machine layout given by CPLEX.

The objective function value obtained by CPLEX for this layout (Fig. 3) is 7300. The CPLEX program positioned machines with the highest flow (machines 1 and 2) close together, suggesting frequent cooperation. Conversely, machine 3, which has less frequent interaction with machine 1, is placed further away. This strategy of grouping frequently used machines together should improve overall system performance by reducing material handling time and cost.

4.2 Example with five periods and five machines

Table 2 presents data related to the mathematical model, which considers product demand for five different periods and eight machines.

Table 2. Data for an example of 5 machines and 5 periods

	Period 1	Period 2	Period 3	Period 4	Period 5
d_t	100	100	100	100	100
h_t	3	3	3	3	3
SC_t	1000	1000	1000	1000	1000
ST_t	1	1	1	1	1
C_t	151	51	101	101	101
PC_t	1	1	1	1	1
a_t	1	1	1	1	1
b_t	10000	10000	10000	10000	10000
Routing	M4>M5>M1	M4>M1>M3	M2>M4>M5	M2>M4>M1>M3	M4>M5>M1

Suppose that the product can pass through five machines with specific dimensions (Fig. 4) that they must be assigned to five designated positions of different dimensions (Fig. 5).

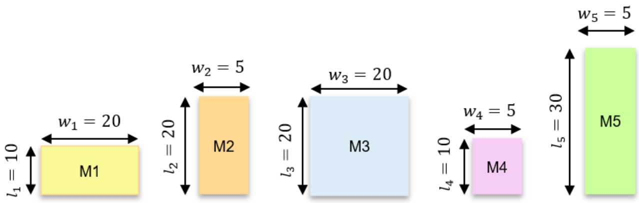

Figure 4. Machine dimensions.

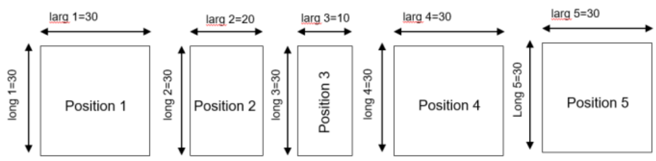

Figure 5. Position dimensions.

The distance between the pairs of facilities is given by:

$$d_{pq} = \begin{pmatrix} 0 & 10 & 20 & 30 & 40 \\ 10 & 0 & 10 & 20 & 30 \\ 20 & 10 & 0 & 10 & 20 \\ 30 & 20 & 10 & 0 & 10 \\ 40 & 30 & 20 & 10 & 0 \end{pmatrix}$$

After running this model on CPLEX, it gave us the quantities to produce during each period which are equal to $Q_1 = 150$, $Q_2 = 50$, $Q_3 = 100$, $Q_4 = 100$ and $Q_5 = 100$.

To meet the demand for period 2 while considering limited production capacity, the program has prioritized producing 150 units in period 1. Even though a production run is planned for period 2, 50 units will be stored from period 1 to ensure fulfillment of the period 2 order.

Based on the model's solution, the total product flow through the machine pairs across all periods will be:

$$f_{jk} = Q_t R_{jkt} = \begin{pmatrix} 0 & 0 & 150 & 0 & 0 \\ 0 & 0 & 0 & 200 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 150 & 0 & 0 & 0 & 350 \\ 250 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Based on the model solution for the quantity produced in each period, the optimal machine layout obtained by CPLEX is shown in Figure 6.

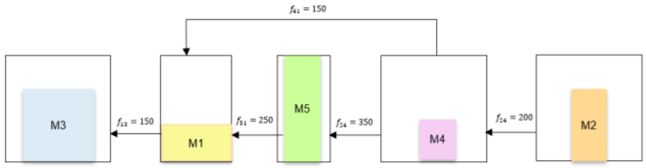

Figure 6. Optimal machine layout given by CPLEX.

The objective function value obtained by CPLEX for this layout (Fig. 6) is 18150. The CPLEX program achieved an optimal machine layout by prioritizing the placement of machines with high product flow close together (ex, machine 4 and machine 5). Conversely, machines with low product flow were positioned farther apart (ex, machine 2 and machine 3).

4.3 Example with five periods and eight machines

Table 3 presents data related to the mathematical model, which considers product demand for five different periods and eight machines.

Table 2. Data for an example of 8 machines and 5 periods

	Period 1	Period 2	Period 3	Period 4	Period 5
d_t	100	100	100	100	100
h_t	3	3	3	3	3
SC_t	1000	1000	1000	1000	1000
ST_t	1	1	1	1	1
C_t	151	51	101	101	101
PC_t	1	1	1	1	1
a_t	1	1	1	1	1
b_t	10000	10000	10000	10000	10000
Routing	M4>M5>M1	M4>M1>M3	M2>M4>M5	M2>M4>M1>M3	M4>M5>M1

Suppose that the product can pass through three machines with specific dimensions (Fig. 7) that they must be assigned to three designated positions of different dimensions (Fig. 8).

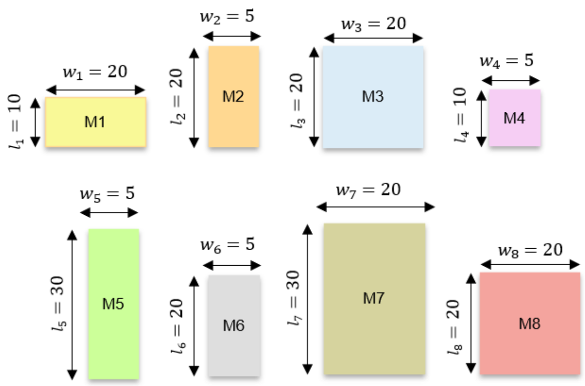

Figure 7. Machine dimensions.

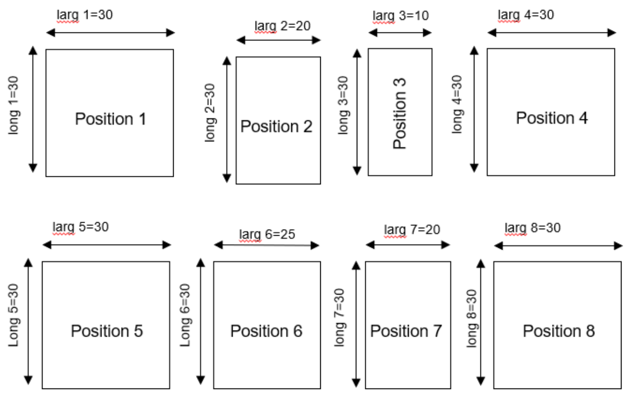

Figure 8. Position dimensions.

The distance between the pairs of facilities is given by:

$$d_{pq} = \begin{pmatrix} 0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 \\ 10 & 0 & 10 & 20 & 30 & 40 & 50 & 60 \\ 20 & 10 & 0 & 10 & 20 & 30 & 40 & 50 \\ 30 & 20 & 10 & 0 & 10 & 20 & 30 & 40 \\ 40 & 30 & 20 & 10 & 0 & 10 & 20 & 30 \\ 50 & 40 & 30 & 20 & 10 & 0 & 10 & 20 \\ 60 & 50 & 40 & 30 & 20 & 10 & 0 & 10 \\ 70 & 60 & 50 & 40 & 30 & 20 & 10 & 0 \end{pmatrix}$$

After running this model on CPLEX, it gave us the quantities to produce during each period which are equal to $Q_1 = 150$, $Q_2 = 50$, $Q_3 = 100$, $Q_4 = 100$ and $Q_5 = 100$. These quantities were chosen for the same reason explained in Example 2.

Based on the model's solution, the total product flow through the machine pairs across all periods will be:

$$f_{jk} = Q_t R_{jkt}$$
$$= \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 250 & 0 & 0 \\ 0 & 0 & 0 & 0 & 350 & 0 & 50 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 50 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 350 & 0 \\ 0 & 0 & 100 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 350 \\ 350 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Based on the model solution for the quantity produced in each period, the optimal machine layout obtained by CPLEX is shown in Figure 9.

The objective function value obtained by CPLEX for this layout (Fig. 9) is 24650. Remarkably, the optimal machine layout in this case, like in the previous examples, efficiently minimizes material handling costs.

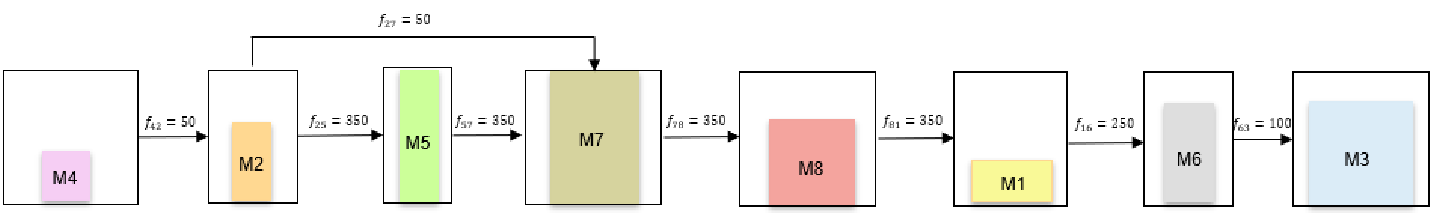

Figure 9. Optimal machine layout given by CPLEX.

6. CONCLUSIONS

The integrated model presented in this article addresses the critical gap in simultaneously optimizing lot sizing and facility layout decisions. By formulating the problem as a mixed-integer programming model, the approach determines the optimal production quantities (lot sizes) for each period and the corresponding machine layout that minimizes material handling costs.

The model is able to jointly optimize lot sizing and facility layout, leading to significant cost savings and improved operational efficiency compared to treating these decisions independently. The optimal machine layouts group frequently interacting machines closer together, reducing material handling time and costs. This layout strategy aligns well with the production quantities determined by the model. The mathematical model incorporates realistic constraints such as production capacity, setup times, and machine-position assignments. The examples demonstrate the model's ability to handle varying numbers of machines, periods, and product routing scenarios.

Looking ahead, there are several promising research directions to build upon this work:

Extending to Multi-Product Scenarios: Expanding the model to handle multiple products with different production requirements and interdependencies would enhance its applicability to more complex manufacturing environments.

Incorporating Flexibility and Reconfigurability: Developing facility layout designs that allow for easy reconfiguration to adapt to changing production needs could further improve the model's responsiveness and efficiency.

Exploring Advanced Solution Techniques: Investigating the use of heuristic and metaheuristic optimization methods, as well as simulation-based approaches, could lead to more efficient solution algorithms for larger-scale problems.

Validating with Real-World Case Studies: Applying the integrated model to real manufacturing facilities and comparing the results to current practices would provide valuable insights and opportunities for further refinement.

By addressing these research directions, the integrated lot sizing and facility layout optimization approach can be further enhanced to deliver even greater benefits to manufacturing organizations in terms of cost reduction, productivity improvement, and overall operational excellence.

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