Project Report of Master of Engineering

Modeling of Optimal Facility Layout considering Stocker and Pillar Structure in the Display Industry

디스플레이 산업의 스토커와 기둥 구조를 고려한 설비 최적 배치 모델링

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Abstract

In the display manufacturing system, the optimal facility layout can maximize productivity with minimal investment cost by efficiently utilizing a fabrication (FAB) area. Because the project period is insufficient to analyze all scenarios of the new layout, industrial engineers are instead arranging facilities based on past experience and their planning rules. The aim of this study is to design the optimal facility layout automatically for processes and automated material handling systems, such as stockers and vehicles, that can satisfy the material handling cost while avoiding overlap with pillars. We developed a mathematical programming model and found an optimal layout with CPLEX optimization software that minimizes the material handling cost for test instances. The optimal results showed great effects in transportation time and the distance, the traffic volume, and the material handling investment costs. This indicates that there is a possibility of obtaining an optimal layout within a reasonable time frame when planning a new factory and suggests that engineers can make more objective and reliable decisions through given results.

Keywords : Facility layout problem (FLP), Display manufacturing system, Hybrid layout, Mixed integer linear programming (MILP), Automated material handling system

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Chapter 1

Introduction

1.1 Background of Study

Recently, the global display market is so large that people carry or have more than one portable computer, such as a smart phone, tablet, or laptop. In addition, the market is still expanding as customers increase the need for innovative new products or for existing products that perform more powerfully. Accordingly, the display industry is continuously working on projects such as establishing new display factories and improving existing factories to provide high-quality products in a timely fashion, while simultaneously producing many kinds of products. Since most displays visually communicate certain objects, photos, and moving images to people, standards for product and process quality are very high, so they are produced in clean rooms with very little finely suspended dust in the air, as in semiconductor factories [1]. However, the initial investment cost of building a new display FAB is more than several billion dollars. Hence, when designing layout, FAB area efficiency and productivity should be considered, as well as efficient and continuous manufacturing operations in the future [2]. However, due to the lack of a planning period to analyze all layouts, most engineers design layouts based on past experience and engineer rules. Therefore, a solution that automatically analyzes all layouts and proposes optimal layouts and performance indicators is essential. This will give engineers time to focus more on decision-making and will have the effect of improving productivity and reducing investment costs. The arrangement of process facilities and automated material handling systems (AMHSs) in a specified space under constraints is called a facility layout problem (FLP), and its purpose is to minimize material handling costs and maximize productivity [3].

1.2 Literature Review

An optimal facility layout contributes to reducing transportation distance and time between facilities and improving manufacturing productivity [4]. In addition, an efficient facility arrangement in manufacturing systems can reduce investment costs such as construction and equipment costs, and in particular, it can reduce manufacturing operation costs by at least 10% [5]. Moreover, Asef et al. [6] agreed that improving facility layout and process flow can decrease manufacturing costs by around 20%. Hence, FLP is one of the most important considerations when planning a new FAB. In the display industry, layout design is specifically significant because very large facilities are connected to AMHSs such as stockers and vehicles, making reconfigurations difficult once the facilities are arranged. In recent decades, researchers have been designing FLPs by considering not only overlap among facilities but safe distances and aisles [7]. We received insights from previous studies that solved FLPs through many methodologies, such as mathematical programming and heuristic algorithms. For example, Chen et al. [8] proposed an optimal facility layout to minimize the production cost in an automated guided vehicle (AGV)-based system, and Chae et al. [3] proposed an optimal multi-bay type layout in which rail and facilities are connected. Also, Pourvaziri et al. [4] designed an FLP to control aisle structure and facility rotation. As such, most FLP studies are undertaken to design the optimal layout considering the picked up and dropped off (PD) points of the facility and the AMHS while checking the overlap of the facilities. Tubaileh et el. [9] designed the optimal layout considering the AGV path connected to PD points of different rectangular facilities. They studied an optimal arrangement that minimizes AGV transportation distances in single and multi-row setups. The display FLP includes the methodology, objective function, and many constraints of existing research, but two main things are considered first. When designing the layout, we should first check the overlap with many pillars that form the framework of FAB. A more realistic layout can be obtained by avoiding many pillars that are designed at regular intervals to support the FAB. The second consideration is to connect the process facilities with the AMHS. This is a system that transports materials between facilities, and the larger the FAB, the more significant the impact becomes on manufacturing operations and productivity [10]. In particular, since display materials are mainly loaded on AMHSs such as stockers and vehicles and then transported to process facilities, connected PD points for receiving materials between facilities and AMHSs should be considered. We design a layout that optimizes AMHS performance indicators, such as the total transport time (TTT) and the distance, as well as the traffic volumes, thereby satisfying the above two priorities and other constraints.

In our model, we will consider minimum material handling cost and solve the problem through mathematical programming. Also, to make the model more realistic, we use an un-directional rectilinear metric when computing distance between facilities. Table 1 is a comparative summary of previous studies most relevant to our study.

Table 1: Comparison with Previous Paper on Facility Layout Problems.

Paper	Objective function	Material handling system	Distance metric	Equipment clearance	Methodology
Kim et al. (2019)	Minimize) Size of the loop	Single loop line	Loop	X	Meta-heuristic algorithm
Chae et al. (2019)	Minimize) Material handling cost	Double-row line	Rectilinear	O	Mixed integer programming
Pourvaziri et al. (2020)	Minimize) Material handling cost	Double-row line	Rectilinear	O	Mixed integer linear programming
This project	Minimize) Material handling cost	Single loop line Double-row line	Rectilinear (Un-directional)	O	Mathematical programming

1.3 Purpose of Research

FLP is a well-known non-deterministic polynomial time hard (NP-hard) problem that finds the optimal facility location in a given space to maximize or minimize the objective function while satisfying the constraints [11]. A non-deterministic polynomial time (NP) problem is a problem that can be solved in polynomial time by a non-deterministic Turing machine. That is, the NP problem can check the existence of an answer within polynomial time. An NP-hard problem is a problem that cannot be solved within the polynomial time, and all cases must be checked; and a traveling salesman problem (TSP) is a representative problem. It is well known that a problem's complexity, such as in the case of an FLP or a TSP problem, exponentially increases with the number of entities [12]. The display layout study is also an NP-hard problem, and moreover, the time complexity increases rapidly because all object coordinates are real numbers. On the other hand, the actual industry layout planning project period is very short for engineers to analyze the layout of all cases, so they determine the optimal layout based on past experience and engineer rules. In this study, we developed the mathematical programming (MP) model that minimizes the TTT between PD points of facilities considering the overlap between pillars, facilities, and AMHSs, and we proposed an optimal display facility location for test instances in file and layout form. To do that, we compared the engineer rule-based layout and the optimal layout of the MP model when maximizing the number of facilities. The performance indicators for determining the optimal layout are TTT, the total distance between facilities, the traffic volume of vehicle rail, and the number of stockers. This research model can maximize productivity by improving the display FAB area and AMHS performance, and engineers can focus more on making decisions based on the optimal results proposed through software, thereby minimizing iterative layout design procedures such as layout drawing, analysis, and modification.

Chapter 2

Characteristics of Display FAB

2.1 Layout Planning

Facility layout planning in a manufacturing system is a key activity in achieving greater production efficiency and manufacturing operation, such as in a new factory set-up, in operating FAB capacity expansion, and in changing old FAB structure [13]. As mentioned earlier, facility arrangement results have a significant impact on productivity and area efficiency of the entire plant. In particular, since large-sized display facilities and AMHSs are densely placed within the FAB, once arranged, objects are very difficult to reconfigure, and the scope of change is extremely limited. Therefore, it is good to efficiently arrange facilities, but the priority is to understand the purpose and utilization of the FAB design, such as its planning stage, investment scale, and the product types. Layout is classified into two categories: green field and re-layout, according to the problem type, and block layout and detailed layout, according to the planning phase [7]. The layout characteristics, according to the criteria, are summarized in Table 2, and the descriptions of them are as follows:

- Green field design: This involves arranging new facilities in a new space if you need to increase production capacity by adding factories due to lack of supply compared to demand, or if you need to produce new types of products that cannot be produced in operating FAB.

- Re-layout design: This involves changing the structure of the existing FAB, such as adding or switching the facilities and expanding the storage to manage the increase in demand.

The following is a description of two layouts classified according to the planning phase:

- Block layout (zoning): This proceeds in the early stages of planning and divides the designated space through the block, as shown in Figure 1. The area classification criteria may be process sequence, facility size, and cycle time of process facilities, and are also referred to as "zoning," according to the layout planning concept.

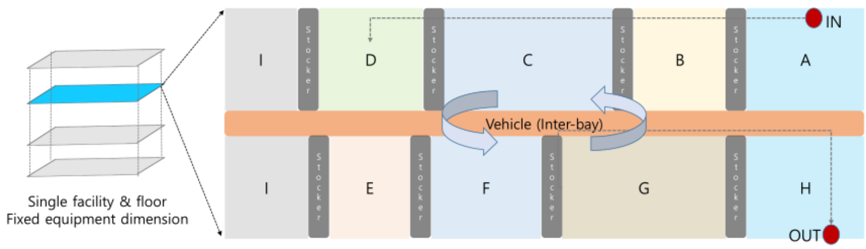


Figure 1: Block Layout of the Display FAB.

- Detailed layout: This is a step to design all necessary matters for the production system, such as process facilities, AMHSs, auxiliary equipment, safety distance between objects, engineer movement lines, and maintenance areas inside the block.

Table 2: Classification of Layout.

Category	Layout	Contents
Problem type	Green field layout	New plant or facility arrangement
		Increase the production capacity
		Production of a new type of product
	Re-layout	Change or extend existing FAB structure
		Add or change processes
		Increase factory AMHS or storage
Planning phase	Block layout	Separate the specified space through a block
		Concept design stage in the early stages of planning
	Detailed layout	Design all the requirements for FAB operations within the block
		Facilities, AMHS, moving lines of engineers, and maintenance areas

2.2 Basic Layout Types

Layout type varies according to industry characteristics and scales, as well as production systems. As mentioned, purpose of layout design is to maximize productivity, so the optimal layout type for the industry should be determined by considering the product type, target production system, process complexity, and appropriate AMHS at the beginning of planning. Layout is classified into four types, such as fixed-position layout, product layout, process layout, and hybrid layout, as shown in Table 3 [14].

Fixed-position layout is a type in which the material is fixed to a specific place, and an engineer or machine moves to it and works. It is advantageous in industries with large-sized products and very small quantities [15], such as aircraft and ships, and productivity is proportional to the scheduling and ability of engineers or machines.

Product layout is a type in which facilities are placed according to the process flow until the material is completed as a final product in the FAB, and is also called an in-line type or flow shop system [16]. It is applied when

Table 3: Basic Layout Types.

Layout	Contents
Fixed-position layout	Product is located in a fixed location
	Manual production (man and machine)
	High technology, big size, and small quantity
	Aircraft, ships
Product layout	Flow shop, in-line type
	Product flow batch
	Fast transportation speed and high area efficiency
	Risk of full line down → Need a high reliability of facility
Process layout	Job shop, batch type
	Process group batch
	High flexibility and facility utilization
	Congested AMHS, low area efficiency
Hybrid layout	Process+ product layout
	Job+ flow shop
	Multiple -products mass production
	Combining advantages of two layout types

a small variety of products are produced in mass quantities with similar process flows. Most facilities are connected in-line, so transportation time between facilities is fast, but if a specific facility fails or if performance is compromised, it affects the overall operation rate, so high facility reliability is required. In addition, there are limitations to changing the process flow or to adding a new process.

Process layout is a batch type in which facilities in the same or similar environment are arranged in groups, also known as job shop systems [17]. It is a flexible production system that is advantageous when the process flow is different and varied for each product, and even if the product process flow is changed or other processes are added, it does not significantly affect production.

Hybrid layout is a type in which two or more of the three layout types are mixed and arranged. It can obtain advantages and remedy disadvantages of each type. This layout satisfies many requirements of customers by producing a lot of various products.

2.3 Display Manufacturing System

Display products are largely composed of four major steps, such as back plane, evaporation, encapsulation, and cell and module (CMD), and usually involve 10 to 25 processes, inspections, and measurements, all repeated at least four times. Therefore, the display FAB applies a hybrid layout type that combines a product layout that is advantageous for continuous flow and a process layout for repeating process groups.

Figure 2 shows the display management system according to the layout type. Figure 2(a) is a product layout in which facilities are connected to the conveyor belt in an in-line setup, according to the process flow. As mentioned earlier, product layout has a fast transportation time and very good area efficiency, but it is limited to changes in the order of the processes or to adding new processes. For example, a system that proceeds with 1, 2, 3, 4, 5, 6, and 7 process flows is shown in Figure 2(a). If the new product proceeds to process 5 and then processes 2 and 4 additionally, the process flow is 1, 2, 3, 4, 5, 2, 4, 6, and 7. Due to the unidirectional characteristic of the conveyor belt, the material cannot go directly from facility 5 to facility 2, but is transported through facilities 6, 7, and 1, resulting in a longer distance and a longer transportation time.

Figure 2(b) is a process layout in which facilities are arranged according to the process group, and a vehicle transports materials to facilities. The batch type as shown in Figure 2(b) can respond flexibly, even if a specific facility fails or a process flow changes, and even if the facility has a high operating rate but the transportation distance between process groups is long and the AMHS is very complicated compared to product layout. In addition, the area efficiency is relatively low due to the addition of systems such as vehicle rail and vehicle buffer. Most semiconductor industries apply process layout.

In the semiconductor and display industries, manufacturing systems and FAB environments are very similar, so facilities and AMHS types are almost the same. However, the layout of the two industries is very different, and one of the biggest reasons is the material size. Since the semiconductor wafer material diameter is up to 450 mm but the display glass material exceeds 2,000 mm in length, process layout is sometimes applied in post-processes such as CMD, but it is often disadvantageous in terms of transportation time, area efficiency, and productivity in most display industries. Therefore, the display FAB is a hybrid layout type that combines product layout and process layout, as shown in Figure 2(c), and transportation in bays proceeds through stockers, and movement between bays proceeds through vehicles. This system remedies the disadvantage of product layout by flexibly responding through stockers even if the process flow changes, and it solves the weakness of process layout by distributing traffic to the stocker and vehicle. The display industry is efficiently responding to increasingly complex manufacturing systems through the hybrid layout setup, which remedies disadvantages of each layout type.

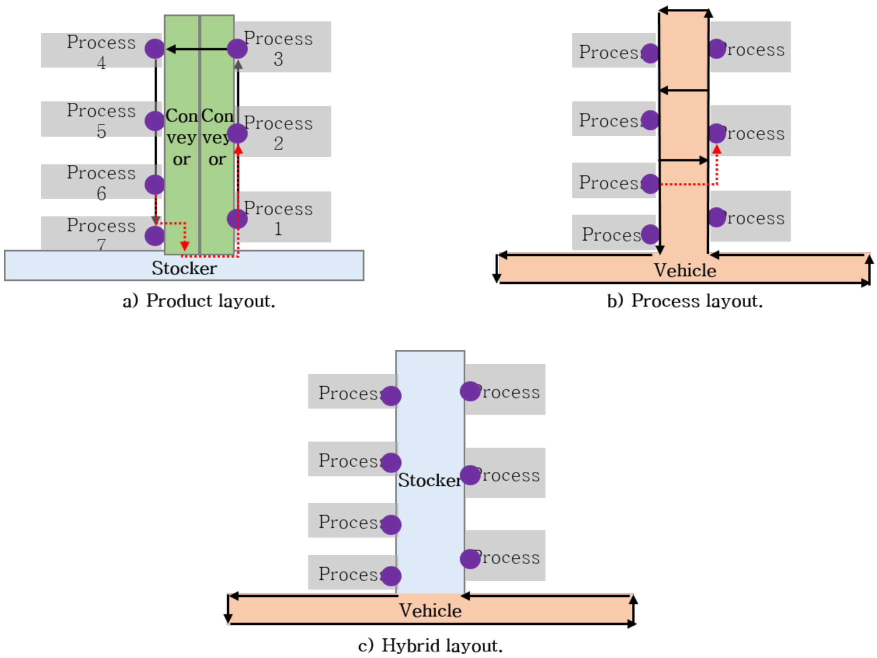


Figure 2: Display Manufacturing System according to Layout Type.

Chapter 3

Model Formulation

In this section, we study a model to find the optimal solution a of complex display FLP more efficiently and accurately by clearly defining the problem and designing the necessary elements.

To do this, we selected the input table required for the model and defined each column and data. In addition, factors such as setting coordinates within the FAB area, overlap between pillars and facilities, and connection between facilities and AMHSs are defined as constraints, and the top priority indicators determining the optimal solution are determined as objective functions. Reflecting all the factors associated with the display FLP makes the model very complicated, so to simplify the model, only the high-priority items are reflected, and the remaining uncertain situations or complex items are assumed.

We designed the MP model by reflecting the aforementioned categories, and we proposed a solution through optimization software.

3.1 Problem Definition

Figure 3 shows a schematic diagram of the display FLP model. As shown in Figure 3, the objective function minimizes TTT, and input data and constraints are as follows. Input data includes specifications of objects constituting FAB, such as FAB area, pillar size, and facility size, and production information such as material volume and process flow. The first and last process location of the material and the AMHS area in the FAB are also essential. In the initialization step, the model reads the input table file and saves the columns and values as parameters.

The model then checks the constraints which are as follows. Constraints of overlap between pillars, facilities, and AMHS are one of the key points, so they must be checked first when arranging objects. Since the facility size includes a safety range, satisfying the above constraints is the same as securing an area for engineers and parts movement, as well as facility maintenance. The second key constraint is to connect the facilities to the AMHS. Basically, the stocker is connected to the facilities and the vehicle rail and is in charge of transporting between facilities.

The MP model allocates decision values that satisfy the constraints and finds a case with the optimal objective function among many scenarios. In addition, coordinates and PD points of objects are displayed in layout form on the screen through a visualization library as well as text. TTT is a top priority indicator for determining the optimal solution of our model, and the traffic conditions can be identified through indicators such as the distance between facilities and the traffic volumes. The traffic of the AMHS is the quantity of materials transported during a period of time. It is an important indicator that can predict the congestion of materials movement in advance. For example, if the traffic of a particular stocker exceeds its transport capacity, queues and congestion occur in the stocker, which increases the transportation time of the materials.

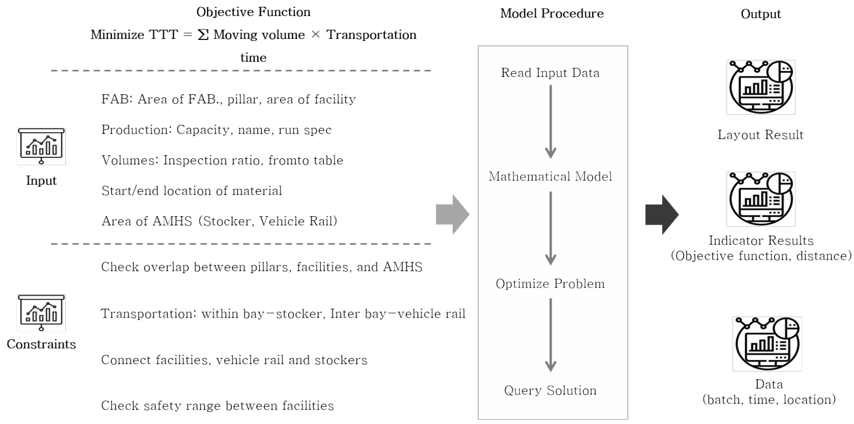


Figure 3: Display FLP Schematic Diagram.

As mentioned earlier, we improved the performance and accuracy of the MP model by simply assuming uncertain or complicated elements. Table 4 summarizes the assumptions applied to the MP model into three categories: infrastructure, production, and AMHS. First, the infrastructure is excluded from our study and is considered as FAB basics such as electricity, wiring areas, stairs, emergency exits, buildings, air -ducts, and offices. In addition, all pillars supporting the FAB are squares of the same size, and their positions and relative intervals are regular.

Production is a category related to manufacturing operations and processes such as material quantity, product type, and facility allocation. In this study, FAB produces only one product, and it is assumed that facilities of the same process group are equal in size. Materials shall be evenly allocated to the number of facilities in the pre- and post-process as shown in Figure 4. As illustrated in Figure 4, suppose that 80 different materials are put into the FAB to proceed with the processes, and since the number of facilities in process 1 is two, 40 materials are allocated to each facility. After the process is finished, materials are transported to the facilities of process 2 via the AMHS. Because there are four facilities in process 2 and a total of eight facilities that perform processes 1 and 2, 10 materials are allocated between facilities before and after.

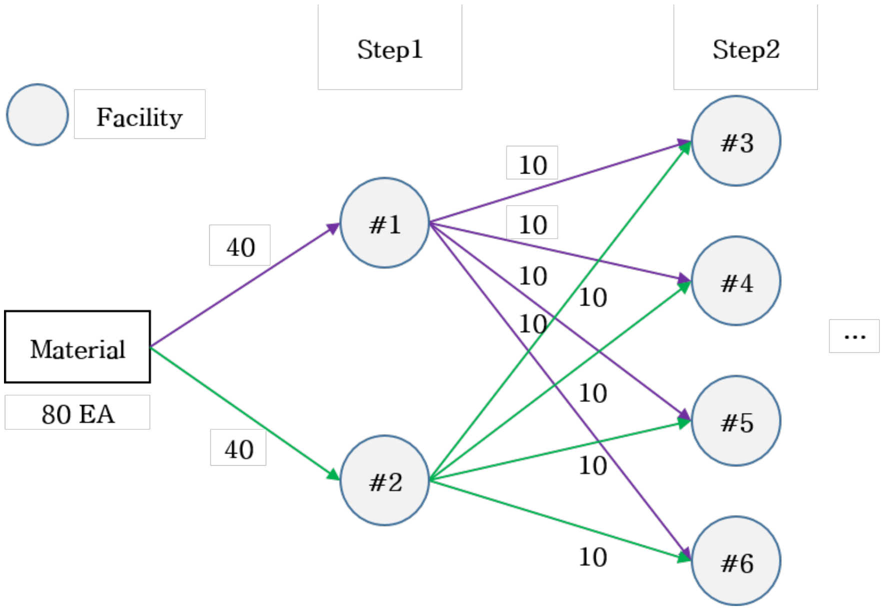


Figure 4: Rules for Allocation of Materials between Facilities.

Finally, there is no manual transportation to the facility by the manufacturing engineer, and the inspection rate is the same.

AMHS is a system that becomes more important as the display manufacturing industry scale extends, and it plays the key role in finding optimal solutions of our model. In the manufacturing site, various phenomena occur frequently in real time, such as waiting for materials in the buffer due to facility issues during transportation, and then having materials delivered again

Table 4: Assumptions Applied in the MP Model.

Category	Contents
Infrastructure	Utility costs, FAB environment, air-ducts, and office area are excluded.
	Position and interval of the pillars are fixed.
Production	Produce only one display product.
	For the same process facility, the area is the same.
	Materials shall be evenly allocated to the number of facilities in the pre- and post-processes.
	No manual loading and un-loading of materials.
	Sampling ratio of the inspection process is the same.
AMHS	No transferring failure due to manufacturing issues such as rework and facility failure.
	The width and length of the vehicle rail are fixed.
	All materials are moved only through stocker and vehicle rail. (Bridge, and lifter are excluded.)
	Distance between facilities through AMHS: rectilinear metric (un-directional)

in a few minutes, or failures due to AMHS errors. However, these events are very complex and uncertain, so we assume a simpler delivery process.

The first assumption is that all materials are transferred unconditionally to facilities without failure. In addition, they are transported only through a vehicle rail or stocker, and the moving distance via vehicle rail is computed by an un-directional rectilinear metric.

3.2 Notations and Formulation

Sets, indices, parameters, and decision variables used in this study are as follows.

Sets and Indices

P	Set of pillars, denoted by index p
M	Set of facilities, denoted by indices i, j
V	Set of vehicle rail, denoted by index v
S	Set of stockers, denoted by indices m, n

Parameters

W	Width of the FAB along the *x–axis*
H	Height of the FAB along the *y–axis*
(x_p^P, y_p^P)	Centroid of pillar p
(lx_p^P, ly_p^P)	Length of pillar p in the x and *y–axis*
(lx_i^M, ly_i^M)	Length of facility i in the x and *y–axis*
w^V	Width of vehicle rail
h^V	Height of vehicle rail
w_m^S	Width of stocker m
$minh_m^S$	Minimum height of stocker m
sp_m^S	Speed of stocker m
sp^V	Speed of vehicle rail
(x_{start}, y_{start})	Start point
(x_{end}, y_{end})	End point
x^V	Centroid of vehicle rail in the *x–axis*
$f_{i,j}$	Total material flow between facilities i and j
$limit^S$	Limit of moving volume of stocker m
$limit^V$	Limit of moving volume of vehicle rail
M	Large number

Decision variables

(x_i^C, y_i^C)	Centroid of facility i
(x_m^S, y_m^S)	Centroid of stocker m
y^V	Centroid of vehicle rail in the $y-axis$
h_m^S	Height of stocker m
(x_i^{PD}, y_i^{PD})	PD point of facility i
(x_m^{PD}, y_m^{PD})	PD point of stocker m
$traffic_m^S$	Volume of traffic in the stocker m
$traffic^V$	Volume of traffic in the vehicle rail
$tt_{i,j}$	Total transportation time between facilities i and j
$d_{i,j}$	Distance between facilities i and j
$dist_{i,j}^{MM}$	Distance between the PD point of facilities i and j through AMHS
$dist_{i,m}^{MS}$	Distance between PD point of facility i and stocker m
$dist_{m,n}^{SS}$	Distance between PD Point of stockers m and n
$dist_{n,j}^{SM}$	Distance between PD Point of stocker n and facility j
$(dix_{i,j}^{MM}, diy_{i,j}^{MM})$	Distance between PD point of facilities i and j in the x and y–*axis*
$(dix_{i,m}^{MS}, diy_{i,m}^{MS})$	Distance between PD point of facility i and stocker m in the x and y–*axis*
$(dix_{m,n}^{SS}, diy_{m,n}^{SS})$	Distance between PD point of stockers m and n in the x and y–*axis*
$(dix_{n,j}^{SM}, diy_{n,j}^{SM})$	Distance between PD point of stocker n and facility j in the x and y–*axis*

$left^{MP}_{i,p}$	$\begin{cases} 1 & \text{if facility } i \text{ is on the left side of pillar } p \\ 0 & \text{otherwise} \end{cases}$
$right^{MP}_{i,p}$	$\begin{cases} 1, & \text{if facility } i \text{ is on the right side of pillar } p \\ 0, & \text{otherwise} \end{cases}$
$below^{MP}_{i,p}$	$\begin{cases} 1, & \text{if facility } i \text{ is below the pillar } p \\ 0, & \text{otherwise} \end{cases}$
$above^{MP}_{i,p}$	$\begin{cases} 1, & \text{if facility } i \text{ is above the pillar } p \\ 0, & \text{otherwise} \end{cases}$
$below^{MV}_{i}$	$\begin{cases} 1, & \text{if facility } i \text{ is below the vehicle rail} \\ 0, & \text{otherwise} \end{cases}$
$above^{MV}_{i}$	$\begin{cases} 1, & \text{if facility } i \text{ is above the vehicle rail} \\ 0, & \text{otherwise} \end{cases}$
$left^{MS}_{i,m}$	$\begin{cases} 1 & \text{if facility } i \text{ is on the left side of stocker } m \\ 0 & \text{otherwise} \end{cases}$
$right^{MS}_{i,m}$	$\begin{cases} 1 & \text{if facility } i \text{ is on the right side of stocker } m \\ 0 & \text{otherwise} \end{cases}$
$ladjoin^{MS}_{i,m}$	$\begin{cases} 1 & \text{if facility } i \text{ adjoin the left of stocker } m \\ 0 & \text{otherwise} \end{cases}$
$radjoin^{MS}_{i,m}$	$\begin{cases} 1 & \text{if facility } i \text{ adjoin the right of stocker } m \\ 0 & \text{otherwise} \end{cases}$
$wlower^{MS}_{i,m}$	$\begin{cases} 1 & \text{if facility } i \text{ is above the lower edge of stocker } m \\ 0 & \text{otherwise} \end{cases}$
$wupper^{MS}_{i,m}$	$\begin{cases} 1 & \text{if facility } i \text{ is below the upper edge of stocker } m \\ 0 & \text{otherwise} \end{cases}$

$left^{MM}_{i,j}$	$\begin{cases} 1 & \text{if facility } i \text{ is on the left side of facility } j \\ 0 & \text{otherwise} \end{cases}$
$right^{MM}_{i,j}$	$\begin{cases} 1 & \text{if facility } i \text{ is on the right side of facility } j \\ 0 & \text{otherwise} \end{cases}$
$below^{MM}_{i,j}$	$\begin{cases} 1 & \text{if facility } i \text{ is below the facility } j \\ 0 & \text{otherwise} \end{cases}$
$above^{MM}_{i,j}$	$\begin{cases} 1 & \text{if facility } i \text{ is above the facility } j \\ 0 & \text{otherwise} \end{cases}$
$left^{SP}_{m,p}$	$\begin{cases} 1 & \text{if stocker } m \text{ is on the left side of pillar } p \\ 0 & \text{otherwise} \end{cases}$
$right^{SP}_{m,p}$	$\begin{cases} 1 & \text{if stocker } m \text{ is on the right side of pillar } p \\ 0 & \text{otherwise} \end{cases}$
$left^{SS}_{m,n}$	$\begin{cases} 1 & \text{if stocker } m \text{ is on the left side of stocker } n \\ 0 & \text{otherwise} \end{cases}$
$right^{SS}_{m,n}$	$\begin{cases} 1 & \text{if stocker } m \text{ is on the right side of stocker } n \\ 0 & \text{otherwise} \end{cases}$
$below^{VP}_{p}$	$\begin{cases} 1 & \text{if vehicle rail is below the pillar } p \\ 0 & \text{otherwise} \end{cases}$
$above^{VP}_{p}$	$\begin{cases} 1 & \text{if vehicle rail is above the pillar } p \\ 0 & \text{otherwise} \end{cases}$
$below^{VS}_{m}$	$\begin{cases} 1 & \text{if vehicle rail is below the stocker } m \\ 0 & \text{otherwise} \end{cases}$
$above^{VS}_{m}$	$\begin{cases} 1 & \text{if vehicle rail is above the stocker } m \\ 0 & \text{otherwise} \end{cases}$

$z_{i,m}^{MS}$	$\begin{cases} 1 & \text{if facility } i \text{ is connected to stocker } m \\ 0 & \text{otherwise} \end{cases}$
$zl_{i,m}^{MS}$	$\begin{cases} 1 & \text{if facility } i \text{ is connected to the left of stocker } m \\ 0 & \text{otherwise} \end{cases}$
$zr_{i,m}^{MS}$	$\begin{cases} 1 & \text{if facility } i \text{ is connected to the right of stocker } m \\ 0 & \text{otherwise} \end{cases}$
z_{m}^{SV}	$\begin{cases} 1 & \text{if stocker } m \text{ is connected to vehicle rail} \\ 0 & \text{otherwise} \end{cases}$
za_{m}^{SV}	$\begin{cases} 1 & \text{if stocker } m \text{ is connected above the vehicle rail} \\ 0 & \text{otherwise} \end{cases}$
zb_{m}^{SV}	$\begin{cases} 1 & \text{if stocker } m \text{ is connected below the vehicle rail} \\ 0 & \text{otherwise} \end{cases}$
$C_{i,j,m,n}^{V}$	$\begin{cases} 1 & \text{if vehicle rail is in the path of materials transpor-} \\ & \text{ted between facilities } i \text{ and } j \text{ in stockers } m \text{ and } n \\ 0 & \text{otherwise} \end{cases}$
$C_{i,m}^{S}$	$\begin{cases} 1 & \text{if stocker } m \text{ is in the path of facility } i \\ 0 & \text{otherwise} \end{cases}$
$Ci_{i,j,m}^{S}$	$\begin{cases} 1 & \text{if stocker } m \text{ is in the path of materials transported} \\ & \text{between facilities } i \text{ and } j \\ 0 & \text{otherwise} \end{cases}$

Objective function, constraints, performance indicators used in this study are as follows.

Objective function

$$\text{Minimize} \quad \sum_{i \in M}^{n} \sum_{j \neq i, j \in M}^{n} f_{ij} tt_{ij} \tag{1}$$

Subject to

1) Transportation time and distance constraints when two facilities are supplied by the same stocker.

$$tt_{i,j}^{MM} \geq \frac{dist_{i,j}^{MM}}{sp_m^S} - M(2 - z_{i,m}^{MS} - z_{j,n}^{MS}) \qquad \forall i \neq j, \forall m = n \tag{2}$$

$$dist_{i,j}^{MM} \geq dix_{i,j}^{MM} + diy_{i,j}^{MM} - M(2 - z_{i,m}^{MS} - z_{j,n}^{MS}) \qquad \forall i \neq j, \forall m = n \tag{3}$$

$$dix_{i,j}^{MM} \geq x_i^{PD} - x_j^{PD} \qquad \forall i, j \in M \tag{4}$$

$$dix_{i,j}^{MM} \geq x_j^{PD} - x_i^{PD} \qquad \forall i, j \in M \tag{5}$$

$$diy_{i,j}^{MM} \geq y_i^{PD} - y_j^{PD} \qquad \forall i, j \in M \tag{6}$$

$$diy_{i,j}^{MM} \geq y_j^{PD} - y_i^{PD} \qquad \forall i, j \in M \tag{7}$$

2) Transportation time and distance constraints when two facilities are supplied by different stockers.

$$tt_{i,j}^{MM} \geq \frac{(dix_{i,m}^{MS}+diy_{i,m}^{MS}+dix_{j,n}^{MS}+diy_{j,n}^{MS})}{sp_m^S} + \frac{(dix_{m,n}^{SS}+diy_{m,n}^{SS}+dia_{m,n}^{SS}+dib_{m,n}^{SS})}{sp^V} - M(2-z_{i,m}^{MS}-z_{j,n}^{MS}) \quad \forall i \neq j, \forall m \neq n \quad (8)$$

$$dist_{i,j}^{MM} \geq dix_{i,m}^{MS}+diy_{i,m}^{MS}+dix_{m,n}^{SS}+diy_{m,n}^{SS} + dia_{m,n}^{SS}+dib_{m,n}^{SS}+dix_{j,n}^{MS}+diy_{j,n}^{MS} - M(2-z_{i,m}^{MS}-z_{j,n}^{MS}) \quad \forall i \neq j, \forall m \neq n \quad (9)$$

$$dix_{i,m}^{MS} \geq x_i^{PD} - x_m^{PD} \quad \forall i \in M, \forall m \in S \quad (10)$$

$$dix_{i,m}^{MS} \geq x_m^{PD} - x_i^{PD} \quad \forall i \in M, \forall m \in S \quad (11)$$

$$diy_{i,m}^{MS} \geq y_i^{PD} - y_m^{PD} \quad \forall i \in M, \forall m \in S \quad (12)$$

$$diy_{i,m}^{MS} \geq y_m^{PD} - y_i^{PD} \quad \forall i \in M, \forall m \in S \quad (13)$$

$$dix_{m,n}^{SS} \geq x_m^{PD} - x_n^{PD} \quad \forall m, n \in S \quad (14)$$

$$dix_{m,n}^{SS} \geq x_n^{PD} - x_m^{PD} \quad \forall m, n \in S \quad (15)$$

$$diy_{m,n}^{SS} \geq y_m^{PD} - y_n^{PD} \quad \forall m, n \in S \quad (16)$$

$$diy_{m,n}^{SS} \geq y_n^{PD} - y_m^{PD} \quad \forall m, n \in S \quad (17)$$

$$dix_{j,n}^{MS} \geq x_j^{PD} - x_n^{PD} \quad \forall j \in M, \forall n \in S \quad (18)$$

$$dix_{j,n}^{MS} \geq x_n^{PD} - x_j^{PD} \quad \forall j \in M, \forall n \in S \quad (19)$$

$$diy_{j,n}^{MS} \geq y_j^{PD} - y_n^{PD} \quad \forall j \in M, \forall n \in S \quad (20)$$

$$diy_{j,n}^{MS} \geq y_n^{PD} - y_j^{PD} \quad \forall j \in M, \forall n \in S \quad (21)$$

$$dia_{m,n}^{SS} \geq 2 \times h^V - M(3 - za_m^{SV} - za_n^{SV} - left_{m,n}^{SS}) \quad \forall m \neq n \quad (22)$$

$$dia_{m,n}^{SS} \leq 2 \times h^V + M(3 - za_m^{SV} - za_n^{SV} - left_{m,n}^{SS}) \quad \forall m \neq n \quad (23)$$

$$dib_{m,n}^{SS} \geq 2 \times h^V - M(3 - zb_m^{SV} - zb_n^{SV} - right_{m,n}^{SS}) \quad \forall m \neq n \quad (24)$$

$$dib_{m,n}^{SS} \leq 2 \times h^V + M(3 - zb_m^{SV} - zb_n^{SV} - right_{m,n}^{SS}) \quad \forall m \neq n \quad (25)$$

3) Coordinates allocation constraints within the FAB. Facilities and AMHS are placed within the area of the FAB.

$x_i^C + 0.5x_i^M \leq W$	$\forall i \in M$	(26)
$x_i^C - 0.5x_i^M \geq 0$	$\forall i \in M$	(27)
$y_i^C + 0.5y_i^M \leq H$	$\forall i \in M$	(28)
$y_i^C - 0.5y_i^M \geq 0$	$\forall i \in M$	(29)
$y^V + 0.5y^V \leq 0.75H$		(30)
$y^V - 0.5y^V \geq 0.25H$		(31)
$x_m^S + 0.5w_m^S \leq W$	$\forall m \in S$	(32)
$x_m^S - 0.5w_m^S \geq 0$	$\forall m \in S$	(33)
$y_m^S + 0.5h_m^S \leq H$	$\forall m \in S$	(34)
$y_m^S - 0.5h_m^S \geq 0$	$\forall m \in S$	(35)

4) Non-overlapping constraints.

[Between facilities and pillars.]

$left_{i,p}^{MP} + right_{i,p}^{MP} + below_{i,p}^{MP} + above_{i,p}^{MP}$	$\forall i \in M, \forall p \in P$	(36)
$x_p^P - 0.5w_p^P \geq x_i^C + 0.5lx_i^M - M(1 - left_{i,p}^{MP})$	$\forall i \in M, \forall p \in P$	(37)
$x_p^P + 0.5w_p^P \leq x_i^C - 0.5lx_i^M + M(1 - right_{i,p}^{MP})$	$\forall i \in M, \forall p \in P$	(38)
$y_p^P - 0.5h_p^P \geq y_i^C + 0.5ly_i^M - M(1 - below_{i,p}^{MP})$	$\forall i \in M, \forall p \in P$	(39)
$y_p^P + 0.5h_p^P \leq y_i^C - 0.5ly_i^M + M(1 - above_{i,p}^{MP})$	$\forall i \in M, \forall p \in P$	(40)

[Between facilities.]

$$left_{i,j}^{MM} + right_{i,j}^{MM} + below_{i,j}^{MM} + above_{i,j}^{MM} \qquad \forall i \neq j \qquad (41)$$

$$x_j^C - 0.5lx_j^M \geq x_i^C + 0.5lx_i^M - M(1 - left_{i,j}^{MM}) \qquad \forall i \neq j \qquad (42)$$

$$x_j^C + 0.5lx_j^M \leq x_i^C - 0.5lx_i^M + M(1 - right_{i,j}^{MM}) \qquad \forall i \neq j \qquad (43)$$

$$y_j^C - 0.5ly_j^M \geq y_i^C + 0.5ly_i^M - M(1 - below_{i,j}^{MM}) \qquad \forall i \neq j \qquad (44)$$

$$y_j^C + 0.5ly_j^M \leq y_i^C - 0.5ly_i^M + M(1 - above_{i,j}^{MM}) \qquad \forall i \neq j \qquad (45)$$

$$below_{i,j}^{MM} + above_{i,j}^{MM} \geq zl_{i,m}^{MS} + zl_{j,m}^{MS} - 1 \qquad \forall i \neq j \qquad (46)$$

$$below_{i,j}^{MM} + above_{i,j}^{MM} \geq zr_{i,m}^{MS} + zr_{j,m}^{MS} - 1 \qquad \forall i \neq j \qquad (47)$$

[Between facilities and stockers.]

$$left_{i,m}^{MS} + right_{i,m}^{MS} \geq above_i^{MV} + za_m^{SV} - 1 \qquad \forall i \in M, \forall m \in S \qquad (48)$$

$$left_{i,m}^{MS} + right_{i,m}^{MS} \geq below_i^{MV} + zb_m^{SV} - 1 \qquad \forall i \in M, \forall m \in S \qquad (49)$$

$$left_{i,m}^{MS} + right_{i,m}^{MS} \geq z_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (50)$$

$$left_{i,m}^{MS} \geq zl_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (51)$$

$$right_{i,m}^{MS} \geq zr_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (52)$$

$$ladjoin_{i,m}^{MS} \geq zl_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (53)$$

$$radjoin_{i,m}^{MS} \geq zr_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (54)$$

$$x_m^S - 0.5w_m^S \geq x_i^C + 0.5lx_i^M - M(1 - left_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (55)$$

$$x_m^S - 0.5w_m^S \leq x_i^C + 0.5lx_i^M + M(1 - ladjoin_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (56)$$

$$x_m^S + 0.5w_m^S \leq x_i^C - 0.5lx_i^M + M(1 - right_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (57)$$

$$x_m^S + 0.5w_m^S \geq x_i^C - 0.5lx_i^M - M(1 - right_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (58)$$

$$wlower_{i,m}^{MS} \geq z_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (59)$$

$$wupper_{i,m}^{MS} \geq z_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (60)$$

$$y_m^S - 0.5h_m^S \leq y_i^C - 0.5ly_i^C + M(1 - wlower_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (61)$$

$$y_m^S + 0.5h_m^S \geq y_i^C + 0.5ly_i^C - M(1 - wupper_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (62)$$

[Between stockers and pillars.]

$$left^{SP}_{m,p} + right^{SP}_{m,p} = 1 \qquad \forall m \in S, \forall p \in P \qquad (63)$$

$$x^P_p - 0.5w^P_p \geq x^S_m + 0.5w^S_m - M(1 - left^{SP}_{m,p}) \qquad \forall m \in S, \forall p \in P \qquad (64)$$

$$x^P_p + 0.5w^P_p \leq x^S_m - 0.5w^S_m + M(1 - right^{SP}_{m,p}) \qquad \forall m \in S, \forall p \in P \qquad (65)$$

[Between facilities and vehicle rail.]

$$above^{MV}_i \geq z^{MS}_{i,m} + za^{SV}_m - 1 \qquad \forall i \in M, \forall m \in S \qquad (66)$$

$$below^{MV}_i \geq z^{MS}_{i,m} + zb^{SV}_m - 1 \qquad \forall i \in M, \forall m \in S \qquad (67)$$

$$y^V - 0.5h^V \geq y^C_i + 0.5ly^C_i - M(1 - below^{MV}_i) \qquad \forall i \in M \qquad (68)$$

$$y^V + 0.5h^V \leq y^C_i - 0.5ly^C_i + M(1 - above^{MV}_i) \qquad \forall i \in M \qquad (69)$$

[Between stockers.]

$$left^{SS}_{m,n} + right^{SS}_{m,n} \geq za^{SV}_m + za^{SV}_n - 1 \qquad \forall m \neq n \qquad (70)$$

$$left^{SS}_{m,n} + right^{SS}_{m,n} \geq zb^{SV}_m + zb^{SV}_n - 1 \qquad \forall m \neq n \qquad (71)$$

$$x^S_n - 0.5w^S_n \geq x^S_m + 0.5w^S_m - M(1 - left^{SS}_{m,n}) \qquad \forall m \neq n \qquad (72)$$

$$x^S_n + 0.5w^S_n \leq x^S_m - 0.5w^S_m + M(1 - right^{SS}_{m,n}) \qquad \forall m \neq n \qquad (73)$$

[Between stockers and vehicle rail.]

$below_m^{SV} \geq zb_m^{SV}$	$\forall m \in S$	(74)
$above_m^{SV} \geq za_m^{SV}$	$\forall m \in S$	(75)
$y_m^S + 0.5h_m^S \leq y^V - 0.5h^V + M(1 - below_m^{SV})$	$\forall m \in S$	(76)
$y_m^S + 0.5h_m^S \geq y^V - 0.5h^V - M(1 - below_m^{SV})$	$\forall m \in S$	(77)
$y_m^S - 0.5h_m^S \geq y^V + 0.5h^V - M(1 - above_m^{SV})$	$\forall m \in S$	(78)
$y_m^S - 0.5h_m^S \leq y^V + 0.5h^V + M(1 - above_m^{SV})$	$\forall m \in S$	(79)

[Between pillars and vehicle rail.]

$below_p^{VP} + above_p^{VP} = 1$	$\forall p \in P$	(80)
$y_p^P - 0.5h_p^P \geq y^V + 0.5h^V - M(1 - below_p^{VP})$	$\forall p \in P$	(81)
$y_p^P + 0.5h_p^P \leq y^V - 0.5h^V + M(1 - above_p^{VP})$	$\forall p \in P$	(82)

5) PD points accessibility constraints.

[PD point of stocker when it is supplied by the vehicle rail.]

$$z_m^{SV} = 1 \qquad \forall m \in S \qquad (83)$$

$$z_m^{SV} = za_m^{SV} + zb_m^{SV} \qquad \forall m \in S \qquad (84)$$

$$x_m^{PD} \leq x_m^S + M(1 - z_m^{SV}) \qquad \forall m \in S \qquad (85)$$

$$x_m^{PD} \geq x_m^S - M(1 - z_m^{SV}) \qquad \forall m \in S \qquad (86)$$

$$y_m^{PD} \leq y_m^S + 0.5h_m^S + M(1 - zb_m^{SV}) \qquad \forall m \in S \qquad (87)$$

$$y_m^{PD} \geq y_m^S + 0.5h_m^S - M(1 - zb_m^{SV}) \qquad \forall m \in S \qquad (88)$$

$$y_m^{PD} \leq y_m^S - 0.5h_m^S + M(1 - za_m^{SV}) \qquad \forall m \in S \qquad (89)$$

$$y_m^{PD} \geq y_m^S - 0.5h_m^S - M(1 - za_m^{SV}) \qquad \forall m \in S \qquad (90)$$

$$y_m^{PD} \leq y^V - 0.5h^V + M(1 - zb_m^{SV}) \qquad \forall m \in S \qquad (91)$$

$$y_m^{PD} \geq y^V - 0.5h^V - M(1 - zb_m^{SV}) \qquad \forall m \in S \qquad (92)$$

$$y_m^{PD} \leq y^V + 0.5h^V + M(1 - za_m^{SV}) \qquad \forall m \in S \qquad (93)$$

$$y_m^{PD} \geq y^V + 0.5h^V - M(1 - za_m^{SV}) \qquad \forall m \in S \qquad (94)$$

[PD point of facility when it is supplied by the stocker.]

$$\sum_m z_{i,m}^{MS} = 1 \qquad \forall i \in M \qquad (95)$$

$$z_{i,m}^{MS} = zl_{i,m}^{MS} + zr_{i,m}^{MS} \qquad \forall i \in M, \forall m \in S \qquad (96)$$

$$y_i^{PD} \leq y_i^C \qquad \forall i \in M \qquad (97)$$

$$y_i^{PD} \geq y_i^C \qquad \forall i \in M \qquad (98)$$

$$x_i^{PD} \le x_i^C + 0.5lx_i^M + M(1 - zl_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (99)$$

$$x_i^{PD} \ge x_i^C + 0.5lx_i^M - M(1 - zl_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (100)$$

$$x_i^{PD} \le x_i^C - 0.5lx_i^M + M(1 - zr_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (101)$$

$$x_i^{PD} \ge x_i^C - 0.5lx_i^M - M(1 - zr_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (102)$$

$$x_i^{PD} \le x_m^S - 0.5w_m^S + M(1 - zl_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (103)$$

$$x_i^{PD} \ge x_m^S - 0.5w_m^S - M(1 - zl_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (104)$$

$$x_i^{PD} \le x_m^S + 0.5w_m^S + M(1 - zr_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (105)$$

$$x_i^{PD} \ge x_m^S + 0.5w_m^S - M(1 - zr_{i,m}^{MS}) \qquad \forall i \in M, \forall m \in S \qquad (106)$$

6) Workload constraints of AMHS.

[Workload of vehicle rail.]

$$limit^V \ge traffic^V \qquad \forall i \in M \qquad (107)$$

$$traffic^V = \sum_i \sum_j f_{i,j} c_{i,j,m,n}^V \qquad \forall i \ne j, \forall m \ne n \qquad (108)$$

$$c_{i,j,m,n}^V \ge z_{i,m}^{MS} + z_{j,n}^{MS} - 1 \qquad \forall i \ne j, \forall m \ne n \qquad (109)$$

$$c_{i,j,m,n}^V \le z_{i,m}^{MS} \qquad \forall i \ne j, \forall m \ne n \qquad (110)$$

$$c_{i,j,m,n}^V \le z_{j,n}^{MS} \qquad \forall i \ne j, \forall m \ne n \qquad (111)$$

[Workload of stockers.]

$$limit^S \geq traffic^S_m \qquad \forall m \in S \qquad (112)$$

$$traffic^S_m = \sum_i \sum_j f_{i,j}(c^S_{i,m} + c^S_{j,m} - ci^S_{i,j,m}) \qquad \forall i \neq j, \forall m \in S \qquad (113)$$

$$c^S_{i,m} \leq z^{MS}_{i,m} \qquad \forall i \in M, \forall m \in S \qquad (114)$$

$$c^S_{i,m} \geq z^{MS}_{i,m} \qquad \forall i \in M, \forall m \in S \qquad (115)$$

$$c^S_{j,m} \leq z^{MS}_{j,m} \qquad \forall i \in M, \forall m \in S \qquad (116)$$

$$c^S_{j,m} \geq z^{MS}_{j,m} \qquad \forall i \in M, \forall m \in S \qquad (117)$$

$$ci^S_{i,j,m} \geq z^{MS}_{i,m} + z^{MS}_{j,m} - 1 \qquad \forall i \neq j, \forall m \in S \qquad (118)$$

$$ci^S_{i,j,m} \leq z^{MS}_{i,m} \qquad \forall i \neq j, \forall m \in S \qquad (119)$$

$$ci^S_{i,j,m} \leq z^{MS}_{j,m} \qquad \forall i \neq j, \forall m \in S \qquad (120)$$

The objective function (1) minimizes the total transportation time (TTT) between each pair of facilities. Constraints (2) and (3) compute the TTT and distance between facilities when two facilities are supplied by the same stocker. This means that the two facilities are connected to the same stocker, so the material is transported through that stocker. By applying Constraints (4)-(7) we can obtain the distance between facilities using a rectilinear distance metric. Constraints (8) and (9) compute the TTT and distance between facilities when two facilities are supplied by different stockers. When two facilities are connected to different stockers, the material is transported through two stockers and vehicle rail connected to them. Constraints (10)-(21) compute the distance from the two facilities to the respective connected stockers and the distance between the two stockers using an un-directional rectilinear metric. Vehicles moving through rail only move in one direction due to restrictions on inline robot motion, and vehicles in this study are transported counterclockwise. Figure 5 shows the transportation route according to the location of the two stockers. As shown in Figure 5(a), the transportation path between the two stockers is the same as the direction of the vehicle rail, so only the rectilinear distance between the two objects is computed. However, when the transportation path between the two stockers is opposite to the vehicle rail direction as depicted in Figure 5(b), the junction distance is added to the rectilinear distance. By applying Constraints (22)-(25) we obtain the junction distance between two stockers.

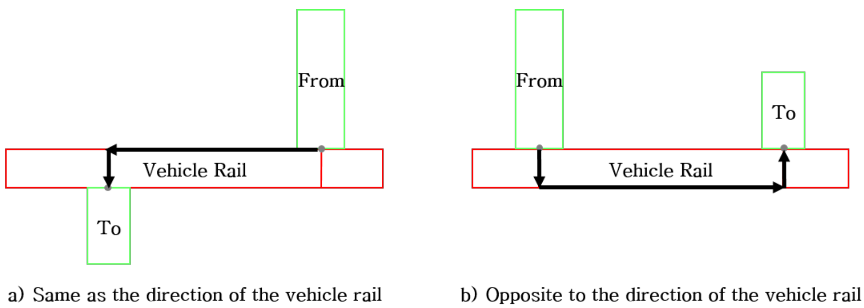


Figure 5: Transportation Routes according to the Location of the Two Stockers.

Constraints (26) - (35) ensure that facilities and AMHSs are placed inside the boundaries of the FAB and Constraints (36) - (82) indicate that all objects do not overlap with each other. Constraints (36)-(40) ensure that facilities and pillars cannot overlap each other. Constraints (41)-(47), which check overlap between facilities, are similar to Constraints (36)-(40), but conditions are added, as in Equations (46)-(47). Figure 6 shows the relative overlap range according to the connection position between facilities and stockers. As depicted in Figure 6 (a), the two facilities generally do not overlap with each other from above, below, left, or right, but as shown in Figure 6 (b), if the two facilities are placed on the same side of one stocker, they should be in one of the above, or below positions. In other words, in this case, left and right overlap checks are excluded through Equations (46)-(47).

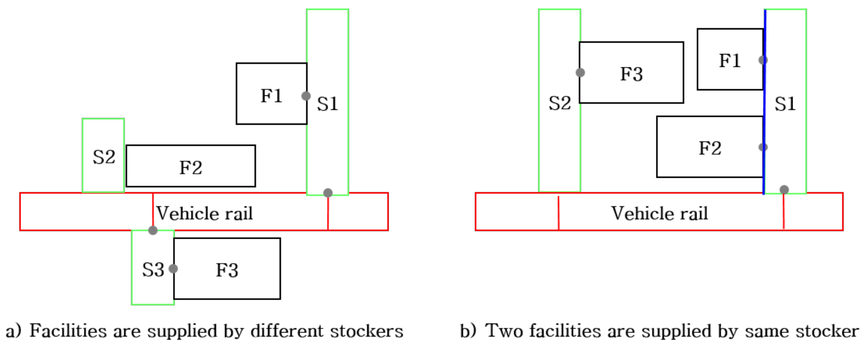


Figure 6: Comparison of Relative Overlap Ranges according to the Connection Positions of Facilities and Stockers.

Constraints (48)-(62) ensure that facilities and stockers cannot overlap each other. Constraints (63), (64), and (65) indicate that stockers should avoid pillars. Using Constraints (66)-(69), the coordinates of the facilities are designed to avoid vehicle rail. Constraints (70)-(73) guarantee that all stockers do not overlap each other. By applying Constraints (74)-(79), vehicle rail and stockers are designed without overlapping each other. Constraints (80)-(72) ensure that pillars and vehicle rail cannot overlap each other.

When materials are transported and delivered to the facility, the contact point with the AMHS is called the PD point [7][18]. As shown in Figure 6, since facilities are connected to the left and right sides of a stocker, the material is loaded into the facility or unloaded from the facility through the facility's PD point. In addition, since the stockers are connected to the upper and lower sides of the vehicle rail, the material enters and exits the vehicle rail through the PD point of the stocker. Constraints (83)-(94) indicate the PD point of the stocker when it is supplied by the vehicle rail and Constraints (95)-(106) ensure the PD point of the facility when it is supplied by the stocker. Through the last Constraints (107)-(120), we calculate the traffic volume of the AMHS and determine if it exceeds the maximum traffic limit. When traffic becomes very congested during rush hour, it adversely affects the connecting road, and all surroundings are jammed, and when any AMHS exceeds the limit traffic, material transportation is congested and cannot be delivered to the facility on time, which eventually adversely affects FAB productivity. Therefore, it is very important to design the layout so as not to exceed the limit traffic.

3.3 Solution Approach

Our display FLP is a mixed integer linear programming (MILP) model. The decision variable of the MILP is a mixture of integer and real numbers in the linear programming setup [19]. For example, decision variables such as $left_{i,p}^{MP}$, $right_{i,p}^{MP}$, $below_{i,p}^{MP}$, and $above_{i,p}^{MP}$ in Constraint (36), which computes the relative positions of the facilities and the pillars, are integers 0 or 1, but decision variables such as x_i^C, and x_i^M in Equation (26), one of the coordinate allocation constraints within the FAB, are real numbers. In the case of the MILP with a small number of entities or constraints, many researchers create their own MP model to obtain optimal solutions or solve them using optimization software [20]. In this work, we used the mathematical optimization software, CPLEX (from the optimization studio of the International Business Machines (IBM) Corporation) to find an exact solution. However, due to the NP-hard characteristics of the developed problem, it is difficult to find an exact solution for large-sized instances through the MP model. Therefore, meta-heuristic algorithms such as partial swarm optimization (PSO), simulated annealing (SA), and genetic algorithm (GA) should be developed to obtain a practical solution in a reasonable computation time [7] [21].

Chapter 4

Computational Experiments

In this section, we make a CPLEX MP model and obtain the optimal layout through many experiments. CPLEX is an optimization software that has very powerful strengths in terms of speed and performance [22]. First of all, we built a software development environment and designed the data structure and logic of the model. In addition, we described modeling and experimental procedures, and we interpreted the meaning of the optimal solution. During the model implementation, code was modified and updated repeatedly to verify data integrity and functionality, but in order to further improve model completeness before the experiment, we performed extreme tests, such as setting the size of pillars or some very large facilities, or connecting many facilities to one stocker.

The experiment was conducted in two main steps. The first experiment was to analyze the optimal layout and performance indicators according to the number of facilities, while identifying the maximum number of facilities that the CPLEX model could perform within laptop computer performance. The second step was to compare the engineer rule-based layout and the optimal layout of the CPLEX model for the maximum number of facilities, and to then analyze the proposed optimal layout, objective function, and important performance indicator for each case.

4.1 CPLEX Optimizer Model

As described in Table 5, the CPLEX optimization model is completed through steps such as building a development environment, reading and setting up input data, modeling, and testing a model.

- Building a development environment: This is the step of installing and interconnecting libraries with the program and development environment to make a software model more easily and efficiently. In this study, a JAVA-based eclipse integrated development environment (IDE) is used, and CPLEX software is connected inside the eclipse. In addition, the STDDRAW library is additionally installed and linked. STDDRAW is one of the representative powerful JAVA application programming interfaces (API) that helps to visualize object coordinates very easily and that can be displayed in layout form on the screen [23].

- Reading and setting up input data: To find the optimal solution, a CPLEX model is simulated using parameters, variables, and constraints. Among them, the parameter is input data, which is used as a constant that does not change during simulation, and the CPLEX reads input data and saves them in the database. Since the data determines the model components such as the FAB area, the number of facilities, the pillar size, and the moving volume, the data must be accurately defined and allocated.

- Modeling: To convert the mathematical model to CPLEX, we redesigned some structures to fit the software language and style. This model explores the results that meet the problem by implementing objective features, decision variables, constraints, and performance indicators to fit the CPLEX environments, and proposes the best solution among them. In addition, through the visualization module implemented using the STDDRAW class, the coordinates of the decision variables are displayed on the screen as a layout as well as a text file to visually check the connection, overlap, and placement results.

- Testing a model: Even if the development environment and previous steps are well finished, it is very difficult for the model to be completed at once without errors in code or results. The code is repeatedly edited and updated whenever a simple code error is encountered, or whenever a variable range or implementation error occurs, or even whenever a model behavior error occurs, until one model is completed. Therefore, the model is efficiently tested by capturing abnormal data and identifying batch errors through performance indicators and layout. As a result, we can prepare a high-quality model for efficient and accurate experiments.

The flow of action until the model finds a solution that meets the problem and proposes the optimal solution is as follows.

First of all, the FAB area and pillars are arranged through input data, and AMHS specifications and material moving volume are set. The model then allocates facilities and AMHS coordinates and then checks the constraints of the MP model, which first checks the overlap between all objects.

Table 5: Completion Step of CPLEX Optimization Model.

Category	Contents
Development environment	Install JAVA language and eclipse IDE. Install libraries (CPLEX and STDDRAW). Build and connect eclipse and two libraries.
Read and set input data	FAB area (width, height). Pillar size and distance between pillars. Minimum width of stockers. Size of facilites and AMHS (width, height). Fromto table (moving volume between facilities).
Modeling	Variables (include decision variables). Single objective function Constraints. Performance indicator. Visualization.
Test a model	Make some scenarios and test model. Check errors and edit the model repeatedly. Complete the model for the experiments.

After checking the overlap constraints, the model checks the connection between stocker and vehicle rail. If connected, place the stocker above or below the vehicle rail and assign the PD point of the stocker. Then check the connection between the facility and the stocker. If connected, arrange the facility on the left or right side of the stocker, and set the PD point of the facility. If all facilities and AMHS meet conditions that do not overlap with each other, the model calculates the total transportation time (TTT) and distance between facilities, and computes the traffic volume of AMHS. The calculated objective function TTT and indicators are stored in the database, and the above procedure is repeated as much as in all cases, and the decision variable values and results at the minimum TTT are proposed in the form of both a file and a layout.

The optimal layout of the MP model for the five-facility problem using CPLEX and STDDRAW API was displayed on the screen, as shown in Figure 7. Also as shown in Figure 7, all facilities are connected to the left or right side of a stocker, and stockers are connected above or below the vehicle rail. Through the PD point of connected facilities and stockers, materials move between facilities.

By completing a high completeness model, we are ready to perform many computational experiments and conduct two main tests in the next section.

4.2 Test Instances

Before comparing engineer rule-based layouts with MP models, we obtain the maximum number of facilities available based on laptop computer specifications and the completed CPLEX MP model. The simulation is performed by increasing the facilities by 1 from 6 units until the CPLEX "out of memory" error occurs and the optimal solution and performance indicators

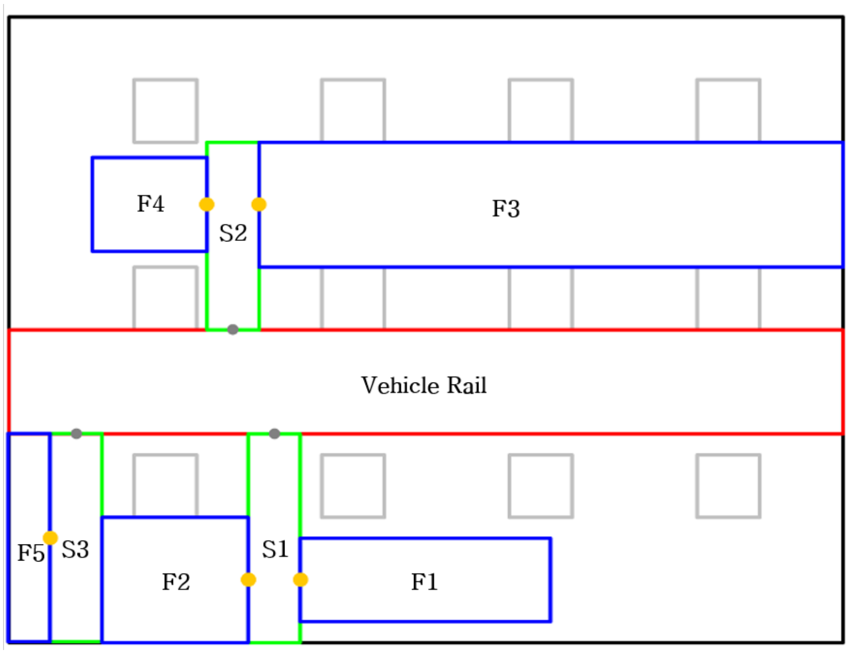


Figure 7: Optimal Layout of the MP Model for Five-Facility Problem.

are recorded. Table 6 summarizes the main parameter items and values. The width of the FAB is 94 meters (m), and the height is 80 m, and the width and length of the pillars are 6 m each, and the interval between pillars is 12 m. The width of the stocker is 5 m, and length varies depending on the number of connected facilities. The width of the vehicle rail is set to 94 m, which is the same as the width of the FAB, and the length is set to 10 m.

The FAB and pillar layout based on the input data of the table is displayed as shown in Figure 8.

Table 7 indicates the size of the process facilities. As shown in Table 7, facility sizes vary for each process, and facilities in the same process group are the same size. There are 17 facilities in 7 process groups, and when

Table 6: Input Data of CPLEX Model.

Category	Width (m)	Height (m)	Interval (m)
FAB	94	80	-
Pillar	6	6	12
Stocker	5	variable	-
Vehicle rail	94	10	-

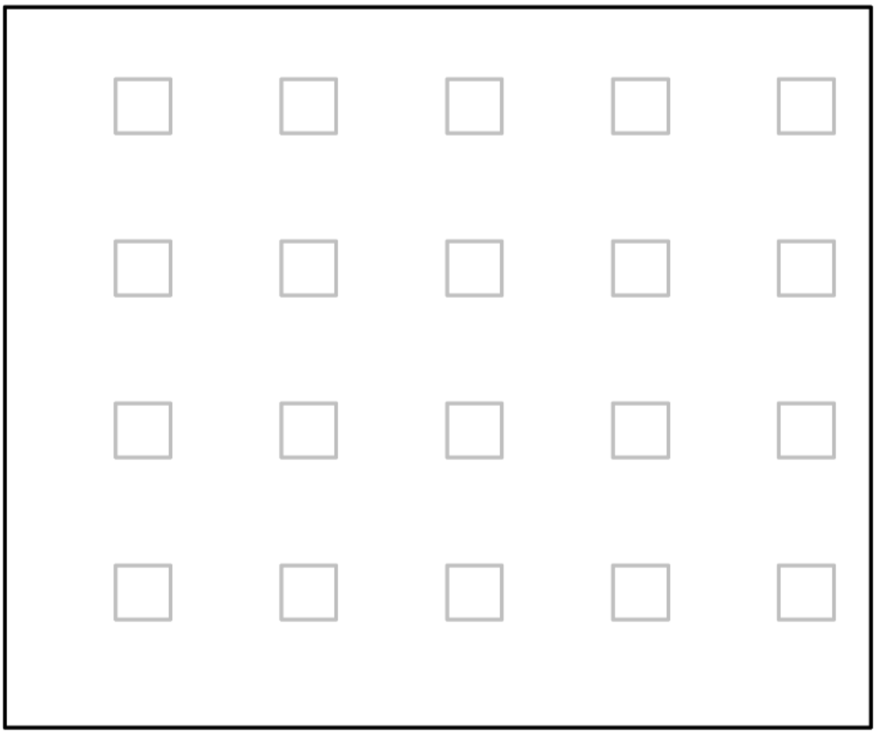


Figure 8: The FAB and Pillar Layout of This Study.

simulation proceeds according to the number of facilities, it is allocated in the order of tables.

Table 8 shows the moving volume per day (MPD) between facilities. From and to numbers in Table 8 are matched with facility numbers in Ta-

Table 7: Dimension of Process Facilities.

No	Process facility	Facility area (m × m)
1	Cleaner 01	24×8
2	Laser 01	14×12
3	Laser 02	14×12
4	Depo 01	11×9
5	Depo 02	11×9
6	Depo 03	11×9
7	Depo 04	11×9
8	Photo 01	55×9
9	Photo 02	55×9
10	Etch 01	11×12
11	Etch 02	11×12
12	Stripper 01	33×5
13	Photo 03	55×9
14	Photo 04	55×9
15	Etch 03	11×12
16	Etch 04	11×12
17	Middle cleaner 01	18×7

ble 7. Since TTT, a time unit, is calculated through distance indicator and AMHS speed, the vehicle rail speed is set to 180 m/min., and the stocker is set to 120 m/min. The simulation performance indicators according to the number of facilities are TTT, the traffic of the AMHS, and the total run time of simulation.

After determining the maximum number of facilities through the first experiment, the second experiment is to compare the analysis results based on the engineer rule with the proposed optimal solution through the CPLEX

MP model. There are many engineer rules, but in this study, we decided on a large facility size priority arrangement rule, and we compared TTT, the total distance, the traffic volume of vehicle rail, and the number of stockers indicators.

Table 8: Moving Volume per Day between Facilities.

From facility	To facility	From no.	To no.	MPD
Cleaner 01	Laser 01	1	2	54
Cleaner 01	Laser 02	1	3	54
Laser 01	Depo 01	2	4	14
Laser 01	Depo 02	2	5	14
Laser 01	Depo 03	2	6	14
Laser 01	Depo 04	2	7	14
Laser 02	Depo 01	3	4	14
Laser 02	Depo 02	3	5	14
Laser 02	Depo 03	3	6	14
Laser 02	Depo 04	3	7	14
Depo 01	Photo 01	4	8	14
Depo 01	Photo 02	4	9	14
Depo 02	Photo 01	5	8	14
Depo 02	Photo 02	5	9	14
Depo 03	Photo 01	6	8	14
Depo 03	Photo 02	6	9	14
Depo 04	Photo 01	7	8	14

Depo 04	Photo 02	7	9	14
Photo 01	Etch 01	8	10	27
Photo 01	Etch 02	8	11	27
Photo 02	Etch 01	9	10	27
Photo 02	Etch 02	9	11	27
Etch 01	Stripper 01	10	12	54
Etch 02	Stripper 01	11	12	54
Stripper 01	Middle 01	12	17	108
Middle 01	Photo 03	17	13	54
Middle 01	Photo 04	17	14	54
Photo 03	Etch 03	13	15	27
Photo 03	Etch 04	13	16	27
Photo 04	Etch 03	14	15	27
Photo 04	Etch 04	14	16	27
Etch 03	Depo 01	15	4	14
Etch 03	Depo 02	15	5	14
Etch 03	Depo 03	15	6	14
Etch 03	Depo 04	15	7	14
Etch 04	Depo 01	16	4	14
Etch 04	Depo 02	16	5	14
Etch 04	Depo 03	16	6	14
Etch 04	Depo 04	16	7	14

4.3 Experiment Results

As mentioned above, the first experiment was to find the maximum number of facilities that can be simulated, and the experiment was conducted by increasing by 1 starting from 6 units. The maximum number of facilities that could be simulated was 10, and the "CPLEX "out of memory" error" occurred during the simulation of 11 facilities and was then stopped. Figure 9 shows the simulation results according to the number of facilities. As shown in Figure 9, the CPLEX model places an increasing number of facilities within the same FAB area, satisfies the constraints, and proposes an optimal layout with minimum TTT results. This is because there is room in the FAB area until the ninth -facility is reached, so material transportation using stockers was possible by connecting adjacent process facilities to the stocker as much as possible, but when the tenth facility was reached, some process facilities were placed in other stockers, resulting in transportation between stockers through vehicle rail. Simulation running time is an important indicator that determines the maximum number of facilities, and as the number of facilities increases, it takes three to six times more running time. When simulating 11 facilities, the running time was stopped with the "out of memory" notification after 712 minutes. Since our work is an NP-hard problem, it indicates that the rate of increase in execution time according to the number of objects is much steeper.

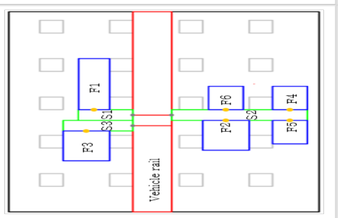
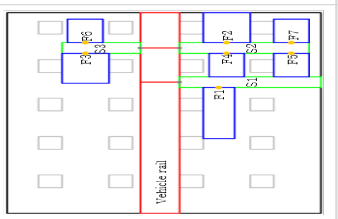
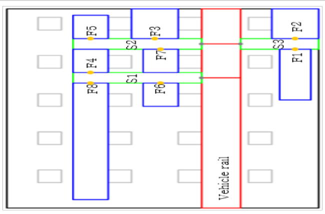
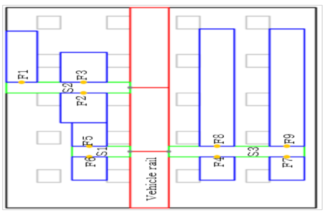
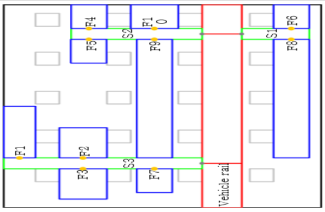
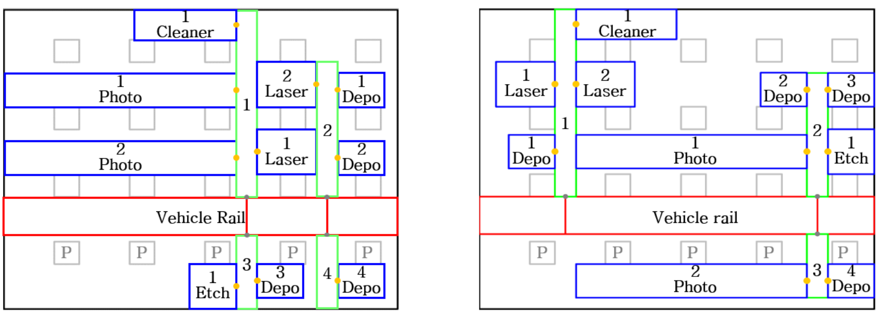
Category	Number of facilities 6	7	8	9	10
					
Total transportation time (min)	41.42	55.75	59.21	82.46	144.37
Distance (km)	6.74	8.63	9.47	12.68	21.38
Traffic of vehicle rail (mpd)	149	162	163	163	204
Run time (min)	1.08	4.00	19.04	89.26	531.37

Figure 9: Optimal Layout Results according to the Number of Facilities.

Second, we compared the engineer rule-based layout and the optimal layout of the MP model for the ten-facility problem. Figure 10 illustrates two proposed optimal layouts for each case. The first layout, as shown in Figure 10(a), is a rule-based layout that places the largest area of the facility first, with photo facilities and cleaner facilities are placed first on the upper left side of the vehicle rail, and the remaining laser, etch, and depo facilities are arranged counter-clockwise. On the other hand, the second layout is the optimal layout arranged through CPLEX, as shown in Figure 10(b), and the layout is proposed by finding the coordinates of the AMHS with facilities where the objective function TTT is minimized. As can be seen, the optimal layout connected continuous process facilities to the same stocker as much as possible, and only three stockers, one less than that obtained from the rule-based layout, were placed.



(a) Rule of engineer (b) Optimal layout

Figure 10: Comparison between Layout Results for Ten-Facility Problem.

Table 9 summarizes the main performance indicators for each case. Comparing the TTTs of the two cases, the optimal layout case is 144.4 minutes, 28.8 minutes (20.2%) shorter than that obtained from the rule-based layout (173.2 minutes). The total distance of the optimal layout case is 21.4 kilometers (km), 6.1 km (28.6%) shorter than that obtained from the rule-based layout case (27.5 km). The AMHS traffic indicators also show that the optimal layout is much less. The traffic volume of the vehicle rail of the optimal layout case is 204 MPD, and the stockers are 637 MPD, which decreased by 149 MPD (42.3%) and 148 MPD (18.9%), respectively, compared to the traffic volume 353 MPD and 786 MPD of the rule-based layout. This means that the vehicle rail traffic volume can be further reduced by connecting continuous process facilities to the stocker as much as possible to decrease moving volume between the stockers. As mentioned earlier, the number of stocker arrangements in the optimal layout case is three, one less than the four in the rule-based layout case. In other words, the optimal layout not only saves the investment cost by reducing one stocker, but it ultimately improves productivity by reducing transportation times and distance between facilities.

Table 9: Comparison between Indicator Results for Ten-Facility Problem.

Indicator	Rule of engineer	Optimal layout
TTT	173.2 min	144.4 min (▼28.8, 20.2%)
Total distance	27.5 km	21.4 km (▼6.1, 28.6%)
Traffic (Stockers)	785 MPD	637 MPD (▼148, 18.9%)
Traffic (Vehicle rail)	353 MPD	204 MPD (▼149, 42.3%)

Chapter 5

Conclusions

Prior works have documented the results of an optimal facility layout that satisfies a minimum objective, such as material-handling costs, while avoiding overlap between facilities in the certain FAB. However, these studies do not consider pillars, which are the basic structures of the FAB, the results of which thus significantly differ from the industrial site.

In this study, we developed the optimal layout of process facilities and AMHSs that satisfy the TTT, distance, and the traffic of AMHSs while avoiding overlap with pillars designed at regular intervals, as well as with facilities and AMHSs. Furthermore, we also added stocker and vehicle rail systems specialized in display FAB to make a more reliable model. We proposed a layout that allows for moving between process facilities in the minimum transportation time through an AMHS such as a stocker and a vehicle while avoiding pillars. In addition to the objective function TTT, layout was analyzed from a more diverse perspective through material-handling cost indicators such as the distance between facilities and the traffic volume of an AMHS.

These results obtained the reliable objective function value by reflecting the constraints of the display industry, such as the constant arrangement of pillars and the connection of stocker and process facilities, compared to the previous study, which considers overlap between facilities and aisles [4].

In addition, the improvements noted in our study can advance many previous mathematical programming formulations. This study, therefore, contributes to allowing facility layout problem researchers to study by, including pillars and AMHSs, which are essential elements of display industry sites. The optimal layout reduces investment costs for vehicles and stockers by distributing material transportation routes to smooth traffic and by efficiently positioning facilities within limited areas. Above all, it ultimately enhances productivity by reducing TTT and distance between facilities within the FAB.

Our results provide scenarios in all cases that satisfy the constraints of the new planning site and propose the optimal reliable layout within a reasonable time. However, some limitations are worth noting. Since our study is an NP-hard problem of searching for real number coordinates, we were able to arrange up to 10 facilities through the CPLEX model. However, since the number of process facilities in the display industry is larger than 10, there is a limit to solving that problem with the CPLEX model. Therefore, we are further working on solving large-scale FLPs using metaheuristic algorithms such as the genetic algorithm and particle swarm optimization [24].

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Abstract

Modeling of Optimal Facility Layout considering Stocker and Pillar Structure in the Display Industry

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디스플레이 제조 시스템에서 최적의 설비 배치는 한정된 공장내 영역을 효율적으로 활용하여 최소의 투자 비용으로 제조 생산성을 극대화 시킬 수 있다. 산업 엔지니어들은 초기 기획단계에서 목적에 부합하는 레이아웃을 설계하기 위해 노력하지만, 모든 시나리오를 분석하여 최적안을 결정하기에는 프로젝트 기간이 매우 부족하기 때문에 그 대신, 과거 경험과 엔지니어의 규칙에 기반하여 최적 설비 배치안을 제안하고 있다. 이를 해결하기 위해 우리는 설비 레이아웃 문제를 수학적으로 접근하여, 최적 위치에 설비를 배치하는 모형을 제안한다. 모델은 공장을 지탱하는 기둥과의 간섭을 회피하면서 한정된 공간내 공정 설비들과 물류시스템을 효율적으로 배치하며, 특히, 디스플레이 물류의 큰 비중을 차지하는 스토커와 비클 시스템을 함께 고려한다. 우리는 CPLEX 최적화 소프트웨어를 사용하여 테스트 인스턴스 대해 물류 운송 비용을 최소화하는 최적의 레

이아웃을 설계하였다. 최적 설비 배치 결과는 운송 시간 및 거리, 물류시스템의 교통량, 그리고 물류 투자비용 측면에서 큰 효과를 보였다. 이 모델은 주어진 프로젝트 기간 내에 공장의 기둥과 고도화된 물류 시스템을 고려한 설비 배치 문제를 제안할 수 있으며, 엔지니어는 자동으로 출력되는 결과를 통해 보다 객관적이고 신뢰할 수 있는 의사 결정을 할 수 있음을 시사한다.

Keywords : Facility layout problem (FLP), Display manufacturing system, Hybrid layout, Mixed integer linear programming (MILP), Automated material handling system

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