Effects of Distance Metrics on Unequal-Area Facility Layouts under Predefined Aisle Constraints: An Experimental Study

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Abstract

Objectives: Unequal-area facility layout problems under predefined aisle constraints are common in real manufacturing systems; however, most existing studies assume equal-area departments or unconstrained travel paths. This creates a research gap regarding how distance metrics affect layout quality when department sizes vary, and travel must follow actual aisles. Therefore, this study aimed (1) to examine the effects of search distance metrics (Rectilinear, Pathway, and Euclidean) and levels of department area heterogeneity (Space) on layout quality when performance is evaluated by total travel distance along actual aisles (Pathway distance), and (2) to compare the best layouts obtained from each metric and Space level through cross-evaluation to derive practical guidelines for selecting distance metrics in facility layout problems with predefined aisle constraints.

Methods: Four benchmark quadratic assignment problems (Nug12, Nug16a, Nug20, and Nug24) were modified to represent unequal-area layouts using three Space levels (20–40, 20–60, and 20–80 m^2). For each problem–Space combination, facility layouts were generated using a Genetic Algorithm under three search distance metrics, with 30 independent runs per setting. Layout performance was evaluated using the total material-handling distance calculated by the Pathway distance metric. The results were analyzed using a two-way analysis of variance with factors Search metric and Space, followed by post-hoc comparisons. The best layout from each search metric was further examined through cross-evaluation using all three distance metrics.

Results: Space had the largest effect on Pathway distance, with very large effect sizes ($\eta^2 \approx 0.85–0.93$), whereas the Search metric showed medium-sized effects, and the interaction was relatively small. When evaluated by Pathway distance, layouts obtained from Pathway search had the lowest mean total distances across all problem–space combinations, although statistically significant advantages over Rectilinear and Euclidean search were observed only in some instances. In many cases, the geometric search metrics yielded layouts whose Pathway performance was statistically indistinguishable from or only slightly worse than that of Pathway search. Overall, the results suggest using Pathway distance as the final evaluation metric, while employing Rectilinear or Euclidean distance in the search phase for simplicity and computational efficiency, with candidate layouts re-evaluated using Pathway distance before implementation.

Keywords: facility layout, distance measurement, unequal-area.

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1. Background

Facility layout design serves as a crucial instrument for improving the operational efficacy of organizations. The main objective of layout planning is to arrange departments or facilities within a given area in such a way that the movement of materials, personnel, or equipment is minimized, thereby reducing total cost and ensuring smooth workflow (Adeleke & Olukanni, 2020). Because the number of feasible layouts grows rapidly when the number of departments and constraints increases, efficient solution procedures and clear performance measures are needed to identify good layouts within limited computational effort. A widely used approach is to evaluate candidate layouts based on distances between departments and select the layout with the minimum total distance (Balasundram et al., 2025).

At present, at least three types of distance metrics are commonly used: (1) displacement distance, defined as the straight-line distance between representative points of departments, typically their centroids; (2) rectilinear distance, measured along the horizontal and vertical axes of the layout; and

(3) pathway distance, which measures travel distance along actual aisles while accounting for corridors, walls, obstacles, and safety requirements (Raman et al., 2007). The choice of distance metric can significantly affect both the evaluation of layout quality and the resulting solution, as illustrated in Figure 1. In real-world situations, layout design must specify clear transport routes in order to control movements within the building. However, many previous studies have still relied on displacement and rectilinear distances as the primary performance measures for selecting layouts, even though these metrics do not reflect the actual walking behavior inside buildings where flows must follow predefined aisles (Besbes et al., 2020). Existing comparative studies of layout design under different distance metrics typically consider only two types of distance, such as comparisons between rectilinear and displacement distance (Öfele et al., 2024), and rarely address unequal-area layouts with explicit aisle structures and obstacles.

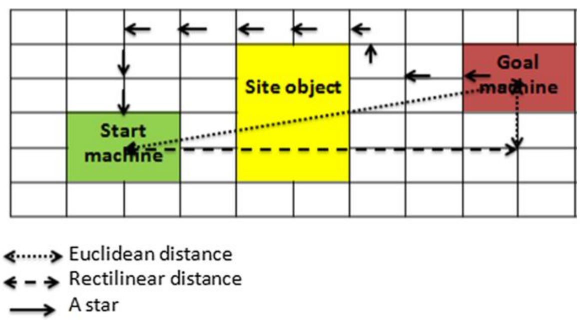

Fig 1. Distance measurement methods (Besbes et al., 2020)

The authors' previous work compared distance metrics under the case where all departments had equal areas (Wattanaweerapong et al., 2025). The results indicated that different metrics led to different best-layout solutions; however, when total distance was evaluated, the differences were rather small and not statistically significant. That study did not cover the more realistic condition in which departments have unequal areas and varying aspect ratios, for which a single representative point may not capture true travel distances, especially when aisles and physical obstacles are present. Therefore, the present study extends the previous equal-area case to unequal-area layouts with predefined aisle structures in order to systematically investigate the impact of the three distance metrics on layout quality. The experimental design incorporates different levels of area heterogeneity and employs statistical tests and cross-evaluation to identify the conditions under which each distance metric is more appropriate. The results are expected to provide empirical evidence for selecting distance metrics that are consistent with the layout context, reduce bias in cost estimation, and support more effective decision-making in facility layout design (Aslan et al., 2025; Rusek et al., 2020).

2. Research Objectives

2.1. To analyze the effects of distance metrics used in the search process (Search metrics), namely Rectilinear, Pathway, and Euclidean, together with the levels of department area heterogeneity (Space), on the quality of the resulting layouts when performance is evaluated by the total travel distance along actual aisles (Pathway distance).

2.2. To perform an in-depth comparison of the best layouts obtained from each Search metric under each Space level by cross-evaluation using all three distance metrics, especially Pathway distance, in order to develop practical guidelines for selecting appropriate distance metrics for solving unequal-area facility layout problems under predefined aisle constraints.

3. Research Methodology

3.1. Scope and conceptual framework

This study focuses on unequal-area facility layout problems on a single floor under predefined aisle constraints. It analyzes the effects of three search distance metrics—Rectilinear, Pathway, and Euclidean—together with three levels of department area heterogeneity (Space: 20–40, 20–60, and 20–80 m²), on layout quality when performance is evaluated by total travel distance along actual aisles (Pathway distance). The objective function is defined as the minimization of the "sum of the material flow between department pairs multiplied by the distance between them," subject to non-overlapping constraints, minimum aisle-width requirements, and physical constraints of the building. The study uses four benchmark quadratic assignment instances (Nug12, Nug16a, Nug20, and Nug24) as test problems. The overall conceptual framework is shown in Figure 2. In this framework, Space levels (area heterogeneity) determine the unequal-area layout geometry in terms of department shapes and adjacencies, while the chosen search distance metric (Rectilinear, Pathway, or Euclidean) guides the Genetic Algorithm in generating and iteratively improving candidate layouts. The candidate layouts are then evaluated in terms of Pathway performance, defined as the total travel distance along aisles, which serves as the final criterion for comparing search metrics and Space levels.

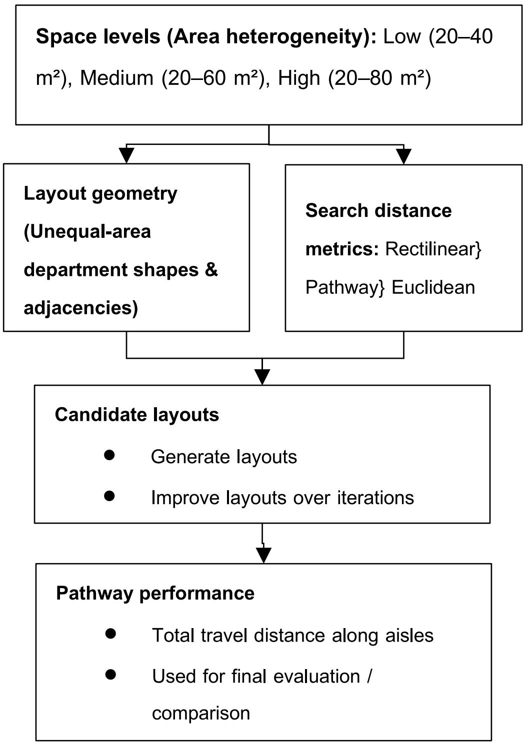

Figure 2. Conceptual framework

3.2. Data and experimental settings

3.2.1. Number of departments and interdepartmental flows

The number of departments and the material flow between department pairs are based on benchmark quadratic assignment problems (QAPs), namely Nug12, Nug16a, Nug20, and Nug24, which correspond to problem sizes of 12, 16, 20, and 24 departments, respectively as shown in Figure 3.

3.2.2. Department areas

Department areas are unequal and are generated under a fixed total target area. Individual department areas are randomly assigned within acceptable aspect ratios of width and length. The degree of area heterogeneity (Space) is divided into three levels: (1) Low: 20–40 m², (2) Medium: 20–60 m², and (3) High: 20–80 m². The specific department areas used in the experiments are shown in Table 1.

3.2.3. Flow data: The material flow between department pairs is taken from the reference QAP data sets, and the density of non-zero flows is adjusted to cover multiple levels of flow intensity.

3.3. Distance metrics

3.3.1. Displacement (Euclidean) distance: measured as the straight-line distance between departments using their centroids as representative points.

3.3.2. Rectilinear distance: measured along the vertical and orizontal axes of the layout.

3.3.3. Pathway distance (walking-path distance): measured along a predefined corridor network that represents the aisles inside the facility. The aisles are modeled as

Table 1. Department areas

Department	Department area by level of heterogeneity (m^2)		
	Low	Medium	High
1	30	20	40
2	25	40	80
3	20	35	50
4	30	60	80
5	35	55	55
6	35	55	65
7	40	55	50
8	30	45	45
9	30	30	60
10	35	25	60
11	40	25	70
12	25	35	55
13	30	40	60
14	40	60	70
15	20	40	80
16	35	40	45
17	25	30	55
18	35	25	25
19	20	40	80
20	40	40	35
21	30	25	65
22	30	20	60
23	40	50	45
24	25	55	25

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	5	2	4	1	0	0	6	2	1	1	1
2	5	0	3	0	2	2	2	0	4	5	0	0
3	2	3	0	0	0	0	0	5	5	2	2	2
4	4	0	0	0	5	2	2	10	0	0	5	5
5	1	2	0	5	0	10	0	0	0	5	1	1
6	0	2	0	2	10	0	5	1	1	5	4	0
7	0	2	0	2	0	5	0	10	5	2	3	3
8	6	0	5	10	0	1	10	0	0	0	5	0
9	2	4	5	0	0	1	5	0	0	0	10	10
10	1	5	2	0	5	5	2	0	0	0	5	0
11	1	0	2	5	1	4	3	5	10	5	0	2
12	1	0	2	5	1	0	3	0	10	0	2	0

Nug12

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	3	2	0	0	2	10	5	0	5	2	5	0	0	2	0	5	6	3	0	1	10	0	10
2	3	0	4	0	10	4	0	0	2	2	1	0	5	0	0	0	0	2	0	1	6	1	0	1
3	2	4	0	3	4	0	5	5	5	1	4	1	0	4	0	4	0	6	3	2	5	5	2	1
4	0	0	3	0	0	0	0	2	2	0	6	0	2	5	2	5	1	1	1	1	2	2	4	0
5	0	10	4	0	0	5	2	0	0	0	0	2	0	0	0	0	2	1	0	0	2	0	5	1
6	2	4	0	0	5	0	1	2	2	1	4	10	10	2	5	5	0	5	0	0	0	10	0	0
7	10	0	5	0	2	1	0	10	10	5	10	10	6	0	0	10	2	1	10	1	5	5	2	3
8	5	0	5	2	0	2	10	0	1	3	5	0	0	0	2	4	5	2	10	6	0	5	5	2
9	0	2	5	2	0	2	10	1	0	10	2	1	5	2	0	3	0	2	0	0	4	0	5	2
10	5	2	1	0	0	1	5	3	10	0	5	5	6	0	1	5	5	0	5	2	3	5	0	5
11	2	1	4	6	0	4	10	5	2	5	0	0	0	1	2	1	0	2	0	0	0	6	6	0
12	5	0	1	0	2	10	10	0	1	5	0	0	5	5	2	0	0	0	0	2	0	4	5	10
13	0	5	0	2	0	10	6	0	5	6	0	5	0	2	0	4	2	2	1	0	6	2	1	5
14	0	0	4	5	0	2	0	0	2	0	1	5	2	0	2	1	0	5	3	10	0	0	4	2
15	2	0	0	2	0	5	0	2	0	1	2	2	0	2	0	4	5	1	0	1	0	5	0	2
16	0	0	4	5	0	5	10	4	3	5	1	0	4	1	4	0	0	3	0	2	2	0	2	0
17	5	0	0	1	2	0	2	5	0	5	0	0	2	0	5	0	0	2	2	0	0	0	6	5
18	6	2	6	1	1	5	1	2	2	0	2	0	2	5	1	3	2	0	5	1	2	10	10	4
19	3	0	3	1	0	0	10	10	0	5	0	0	1	3	0	0	2	5	0	0	5	5	1	0
20	0	1	2	1	0	0	1	6	0	2	0	2	0	10	1	2	0	1	0	0	5	2	1	3
21	1	6	5	2	2	0	5	0	4	3	0	0	6	0	0	2	0	2	5	5	0	4	0	1
22	#	1	5	2	0	10	5	5	0	5	6	4	2	0	5	0	0	10	5	2	4	0	5	0
23	0	0	2	4	5	0	2	5	5	0	6	5	1	4	0	2	6	10	1	1	0	5	0	0
24	#	1	1	0	1	0	3	2	2	5	0	10	5	2	2	0	5	4	0	3	1	0	0	0

Nug24

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	5	0	5	2	10	3	1	5	5	5	0	0	5	4
2	0	0	3	10	5	1	5	1	2	4	2	5	0	10	10	3
3	5	3	0	2	0	5	2	4	4	5	0	0	0	5	1	0
4	0	10	2	0	1	0	5	2	1	0	10	2	2	0	2	1
5	5	5	0	1	0	5	6	5	2	5	2	0	5	1	1	1
6	2	1	5	0	5	0	5	2	1	6	0	0	10	0	2	0
7	10	5	2	5	6	5	0	0	0	0	5	10	2	2	5	1
8	3	1	4	2	5	2	0	0	1	1	10	10	2	0	10	2
9	1	2	4	1	2	1	0	1	0	2	0	3	5	5	0	5
10	5	4	5	0	5	6	0	1	2	0	5	5	0	5	1	0
11	5	2	0	10	2	0	5	10	0	5	0	5	2	5	1	10
12	5	5	0	2	0	0	10	10	3	5	5	0	2	10	5	0
13	0	0	0	2	5	10	2	2	5	0	2	2	0	2	2	1
14	0	10	5	0	1	0	2	0	5	5	5	10	2	0	5	5
15	5	10	1	2	1	2	5	10	0	1	1	5	2	5	0	3
16	4	3	0	1	1	0	1	2	5	0	10	0	1	5	3	0

Nug16a

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	5	0	5	2	10	3	1	5	5	5	0	0	5	4	4	0	0	1
2	0	0	3	10	5	1	5	1	2	4	2	5	0	10	10	3	0	5	10	5
3	5	3	0	2	0	5	2	4	4	5	0	0	0	5	1	0	0	5	0	0
4	0	10	2	0	1	0	5	2	1	0	10	2	2	0	2	1	5	2	5	5
5	5	5	0	1	0	5	6	5	2	5	2	0	5	1	1	1	5	2	5	1
6	2	1	5	0	5	0	5	2	1	6	0	0	10	0	2	0	1	0	1	5
7	10	5	2	5	6	5	0	0	0	0	5	10	2	2	5	1	2	1	0	10
8	3	1	4	2	5	2	0	0	1	1	10	10	2	0	10	2	5	2	2	10
9	1	2	4	1	2	1	0	1	0	2	0	3	5	5	0	5	0	0	0	2
10	5	4	5	0	5	6	0	1	2	0	5	5	0	5	1	0	0	5	5	2
11	5	2	0	10	2	0	5	10	0	5	0	5	2	5	1	10	0	2	2	5
12	5	5	0	2	0	0	10	10	3	5	5	0	2	10	5	0	1	1	2	5
13	0	0	0	2	5	10	2	2	5	0	2	2	0	2	2	1	0	0	0	5
14	0	10	5	0	1	0	2	0	5	5	5	10	2	0	5	5	1	5	5	0
15	5	10	1	2	1	2	5	10	0	1	1	5	2	5	0	3	0	5	10	10
16	4	3	0	1	1	0	1	2	5	0	10	0	1	5	3	0	0	0	2	0
17	4	0	0	5	5	1	2	5	0	0	0	1	0	1	0	0	0	5	2	0
18	0	5	5	2	2	0	1	2	0	5	2	1	0	5	5	0	5	0	1	1
15	0	10	0	5	5	1	0	2	0	5	2	2	0	5	10	2	2	1	0	6
16	1	5	0	5	1	5	10	10	2	2	5	5	5	0	10	0	0	1	6	0

Nug20

Figure 3. Problem instances used in this study

a node–edge graph, and the Pathway distance between two departments is defined as the length of the shortest path between their access nodes on this graph, so that all walking distances respect corridor locations, walls, obstacles, and minimum aisle-width requirements.

3.4. Objective function and constraints

$$Z = \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} d_{ij} \quad (1)$$

where Z is the total material-handling distance (meters), f_{ij} is the material flow or relationship value from department i to department j, and d_{ij} is the shortest distance between departments i and j.

The layout is subject to the following constraints: (1) Departments must not overlap; (2) each department is rectangular with an aspect ratio within a specified range; (3) departments must avoid forbidden areas and obstacles; and (4) when partition walls divide the floor into zones, each department must lie entirely within its assigned zone.

3.5. Solution method

For this study, a Genetic Algorithm (GA) was employed as the optimization tool to search for good facility layouts. Each chromosome encodes a permutation of departments, which is translated into a feasible layout by the construction procedure described earlier. In each generation, new layouts are created by crossover and mutation, infeasible layouts are repaired or discarded, and all constraints are checked before evaluation. The objective function is then computed under the specified distance metric, and the best layout found so far is retained. The search is terminated when the population diversity falls below 0.10 for a specified number of consecutive generations or when a maximum number of generations is reached.

From a computational perspective, using Pathway distance in the evaluation step is more demanding than

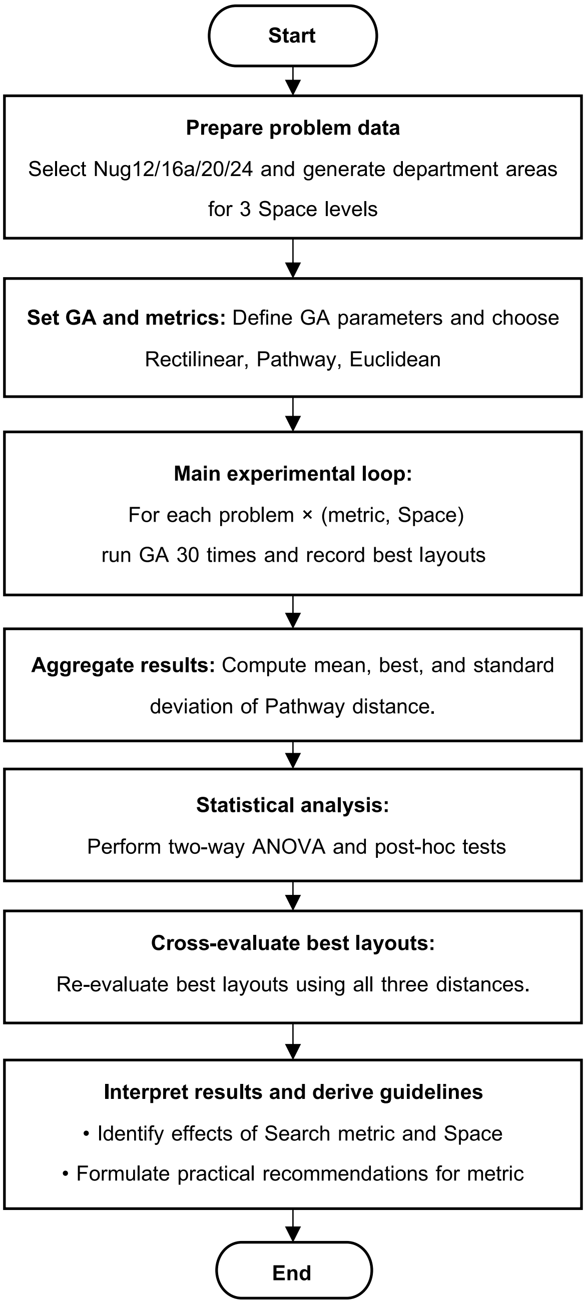

Figure 4. Experimental workflow

using geometric metrics, because each layout requires repeated shortest-path calculations on the aisle network. Together with the stochastic nature of the GA, this implies that Pathway-based search may explore fewer layouts within a given time budget than search based on Rectilinear or Euclidean distance. This limitation is taken into account when interpreting the comparative performance of the distance metrics.

3.6. Experimental design and analysis

This study adopts a two-factor factorial design within each problem instance, with Search metric and Space as fixed factors. The Search metric factor has three levels: Rectilinear, Pathway, and Euclidean. The Space factor represents three levels of department area heterogeneity: 20–40, 20–60, and 20–80 m². For each combination of problem instance (Nug12, Nug16a, Nug20, and Nug24), Search metric, and Space level, the GA is run 30 times with different random seeds, resulting in a total of 4 × 3 × 3 × 30 = 1,080 runs across all problem instances.

For each treatment combination, the mean, best, and standard deviation of the total material-handling distance are recorded, with performance always evaluated by the Pathway distance metric. The effects of Search metric and Space, as well as their interaction, are analyzed using two-way analysis of variance (ANOVA), followed by Tukey's post-hoc tests when significant differences are detected. The algorithm was implemented in VBA for Microsoft Excel and executed on standard desktop PCs. Because the experiments were distributed across multiple machines with different hardware configurations, exact computation times are not reported; instead, all methods are compared under identical GA parameter settings and numbers of runs to ensure a fair basis for practical comparison. Workflow of this study is shown in Figure 4.

4. Results and Discussion

4.1. Experimental results

Table 2 summarizes the mean total distances evaluated by the Pathway metric for all combinations of problem instance, Search metric, and Space level, while Figure 6 presents the same information graphically. Across all problems and Space levels, layouts obtained from Pathway search achieve the lowest mean Pathway distance, but the gaps to Rectilinear and Euclidean search are generally small, often within a few percent. This indicates that, in terms of average performance under Pathway evaluation, the simpler geometric metrics can produce layouts that are close to those obtained by Pathway-based search.

The influence of Space is much stronger. As the allowable range of department areas widens from 20–40 to 20–80 m², the mean Pathway distance increases almost linearly for all three search metrics and all problem instances, as shown by the steep and nearly parallel slopes in Figure 6. This pattern reflects the fact that higher area heterogeneity reduces the available flexibility for arranging departments compactly and forces longer travel along aisles, regardless of the search metric used.

Figure 5 illustrates typical best layouts for the Nug12 problem with low area heterogeneity (Space 20–40) obtained from Rectilinear, Pathway, and Euclidean search. Although the overall block structure is similar across metrics, the shapes and adjacencies of some departments differ, leading to variations in the lengths and directions of the main transport routes. Pathway search tends to place high-flow departments in positions that align more closely with the main aisles, whereas geometric metrics sometimes produce slightly more compact layouts that are advantageous when evaluated by Rectilinear or Euclidean distance but may imply longer walking paths along actual aisles. These visual differences are consistent with the numerical results reported in Table 2 and Figure 6.

4.2. Statistical test results

The descriptive results in Table 2 and Figure 6 suggest that both distance metrics and area heterogeneity affect the total Pathway distance, but statistical tests are required to quantify these effects. For each problem instance, a two-way ANOVA with factors Search metric (Rectilinear, Pathway, Euclidean) and Space (20–40, 20–60, 20–80 m²) was performed using the total Pathway distance from the 30 GA runs per treatment combination as the response variable. The resulting F-statistics, p-values, and partial eta squared (η^2) values are summarized in Table 3.

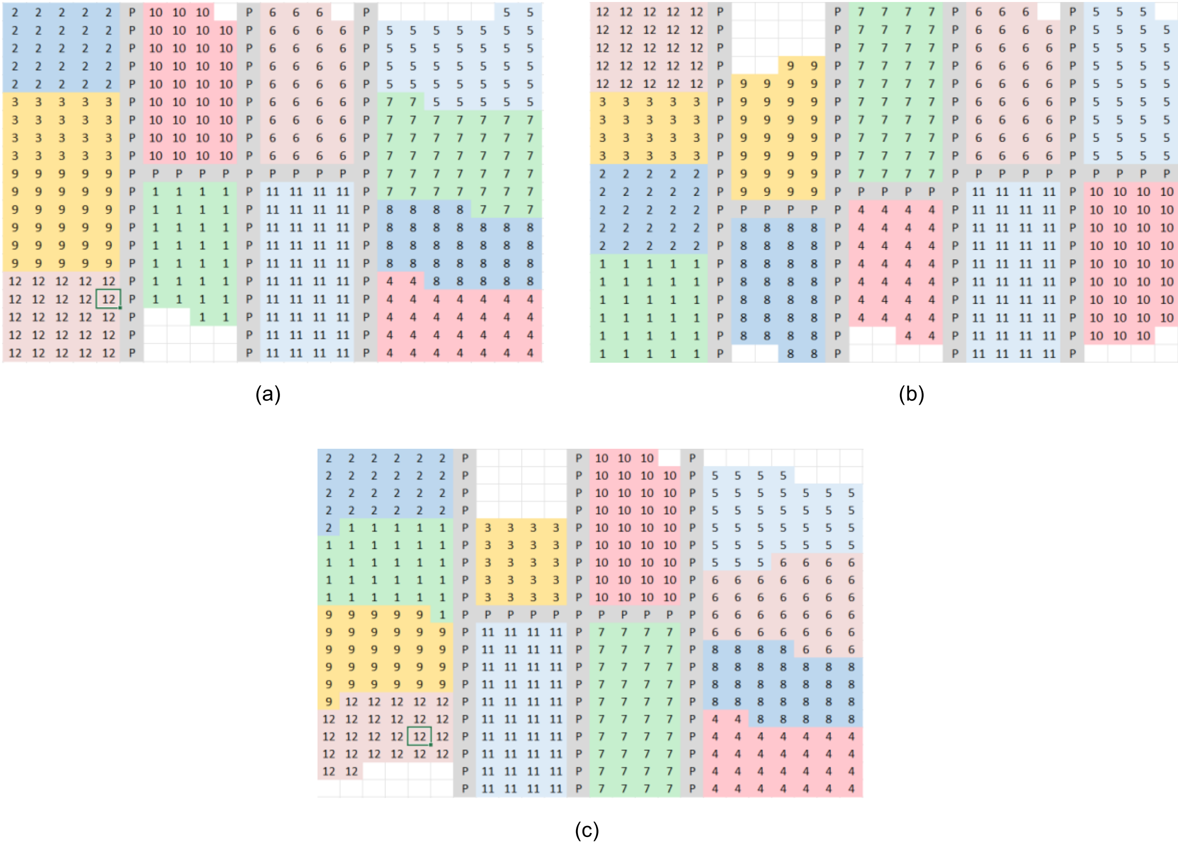

Figure 5. Best layouts for the Nug12 problem with low area heterogeneity: (a) Rectilinear search metric, (b) Pathway search metric, and (c) Euclidean search metric

Table 2. Summary of mean Pathway distance by search metric for each problem and Space level (values in parentheses indicate % difference from the best metric in each row).

Problem	Space level (m²)	Mean Pathway distance evaluated by search metric			Best metric
		Rectilinear	Pathway	Euclidean	
Nug12	20-40	5,424.94 ± 184.27 (5.98%)	5,118.96 ± 138.22 (0%)	5,375.13 ± 129.31 (5%)	Pathway
	20-60	6,086.51 ± 304.1 (4.98%)	5,797.77 ± 268.81 (0%)	6,011.1 ± 203 (3.68%)	Pathway
	20-80	7,359.82 ± 202.73 (8.84%)	6,762 ± 224.77 (0%)	7,237.99 ± 151.05 (7.04%)	Pathway
Nug16a	20-40	14,593.33 ± 466.83 (1.92%)	14,318.71 ± 526.67 (0%)	14,506.33 ± 399.1 (1.31%)	Pathway
	20-60	17,127.75 ± 551.06 (5.04%)	16,305.86 ± 567.94 (0%)	17,138.92 ± 473.75 (5.11%)	Pathway
	20-80	20,503.25 ± 487.21 (6.15%)	19,316.24 ± 556.42 (0%)	20,847.71 ± 461.7 (7.93%)	Pathway

Table 2. Summary of mean Pathway distance by search metric for each problem and Space level (values in parentheses indicate % difference from the best metric in each row). (continue)

Problem	Space level (m²)	Mean Pathway distance evaluated by search metric			Best metric
		Rectilinear	Pathway	Euclidean	
Nug20	20-40	25,751.41 ± 609.43 (3.71%)	24,829.01 ± 609.78 (0%)	25,472.41 ± 484.14 (2.59%)	Pathway
	20-60	29,987.67 ± 1041.16 (4.51%)	28,694.76 ± 945.35 (0%)	29,480.37 ± 827.49 (2.74%)	Pathway
	20-80	36,335.41 ± 1169.21 (6.54%)	34,103.75 ± 1131.66 (0%)	36,329.78 ± 1081.55 (6.53%)	Pathway
Nug24	20-40	37,885.51 ± 1177.76 (5.68%)	35,850.59 ± 1005.47 (0%)	36,834.57 ± 1014.8 (2.74%)	Pathway
	20-60	44,446.59 ± 1122.39 (8%)	41,152.37 ± 1134.5 (0%)	44,168.26 ± 1069.28 (7.33%)	Pathway
	20-80	52,292.25 ± 1304.45 (7.63%)	48,584.7 ± 1597.16 (0%)	51,047.17 ± 1269.81 (5.07%)	Pathway

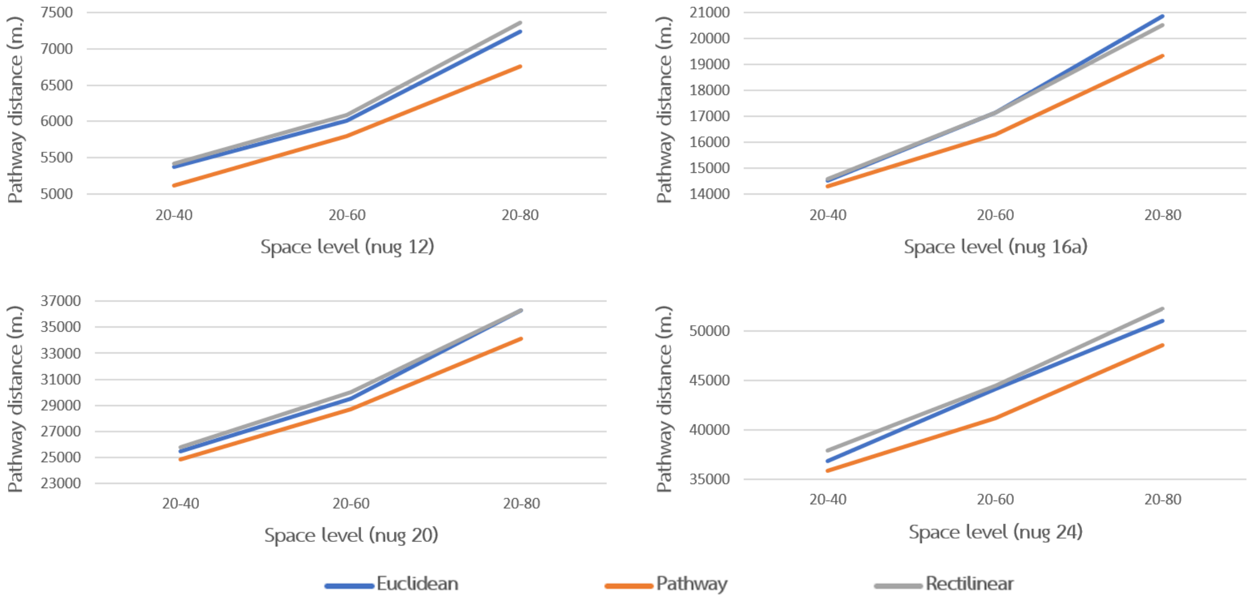

Figure 6. Mean Pathway distance for layouts obtained from each search metric across Space levels for problems Nug12, Nug16a, Nug20, and Nug24.

Table 3. Two-way ANOVA results for total distance evaluated by the Pathway metric

Problem	Effect	df	F	p-value	Partial η²
Nug12	Search metric	2	38.9198	1.61E-15	0.230
	Space	2	745.1267	1.30E-108	0.851
	Search metric × Space	4	2.5225	4.15E-02	0.037
Nug16a	Search metric	2	42.6150	9.6493E-17	0.246
	Space	2	1627.3230	4.1487E-148	0.926
	Search metric × Space	4	7.7329	6.66028E-06	0.106
Nug20	Search metric	2	31.9534	3.86426E-13	0.197
	Space	2	1716.5418	6.4858E-151	0.929
	Search metric × Space	4	2.3709	0.05290665	0.035
Nug24	Search metric	2	61.3429	1.45462E-22	0.320
	Space	2	1212.0133	7.8306E-133	0.903
	Search metric × Space	4	3.0057	0.01891112	0.044

Table 4. Tukey HSD pairwise comparisons for Search metric (evaluated by Pathway distance)

Problem	Comparison pair	Mean diff	p-adj	Interpretation
Nug12	Euclidean vs Pathway	-315.1622	0.028	Pathway mean > Euclidean (significant)
	Pathway vs Rectilinear	397.5112	0.004	Pathway mean > Rectilinear (significant)
	Rectilinear vs Euclidean	82.349	0.779	No significant difference
Nug16a	Euclidean vs Pathway	-850.7169	0.057	No significant difference (trend: Pathway mean > Euclidean)
Nug16a	Pathway vs Rectilinear	761.1732	0.1	No significant difference
Nug16a	Rectilinear vs Euclidean	-89.5436	0.968	No significant difference
Nug20	Euclidean vs Pathway	-1082.523	0.236	No significant difference (trend: Pathway mean > Euclidean)
Nug20	Pathway vs Rectilinear	1346.5006	0.108	No significant difference
Nug20	Rectilinear vs Euclidean	263.9779	0.917	No significant difference
Nug24	Euclidean vs Pathway	-2154.115	0.043	Pathway mean > Euclidean (significant)
Nug24	Pathway vs Rectilinear	3012.2277	0.002	Pathway mean > Rectilinear (significant)
Nug24	Rectilinear vs Euclidean	858.1127	0.601	No significant difference

Across all four problems, both Search metric and Space exhibit statistically significant main effects ($p < 0.001$). Space shows very large effect sizes, with partial η^2 values in the range of approximately 0.85–0.93, confirming that area heterogeneity is the dominant factor influencing total Pathway distance. Search metric has partial η^2 values of about 0.20–0.32, corresponding to medium effect sizes and indicating that the choice of distance metric in the search phase also affects layout quality, but to a lesser extent than Space. The interaction between Search metric and Space is statistically significant for Nug12, Nug16a, and Nug24 (and close to significant for Nug20), yet its partial η^2 values remain small (about 0.04–0.11), implying only modest variation in the Search-metric effect across Space levels.

When the Search metric factor is significant, Tukey's HSD pairwise comparisons (Table 4) show that Pathway search often, but not always, yields higher mean total Pathway distances than Rectilinear or Euclidean search. For Nug12 and Nug24, the differences between Pathway and the geometric metrics are statistically significant, whereas Rectilinear and Euclidean do not differ significantly from each other. For Nug16a and Nug20, no pairwise differences among the three metrics reach statistical significance, even though the mean values still tend to be slightly higher for layouts generated by Pathway search. These results support the descriptive finding that geometric metrics can deliver layouts whose Pathway performance is comparable to that of Pathway-based search.

Table 5. Ranking of mean Pathway distance by Space level

Problem	Ranking of mean distance (best ⟶ worst)
Nug12	20–80 < 20–60 < 20–40
Nug16a	20–80 < 20–60 < 20–40
Nug20	20–80 < 20–60 < 20–40
Nug24	20–80 < 20–60 < 20–40

For the Space factor, Tukey's tests consistently yield the ordering 20–80 < 20–60 < 20–40 for all four problems, with all pairwise differences being statistically significant (Table 5). As the allowable area range widens, the mean total Pathway distance increases monotonically, confirming that higher area heterogeneity systematically leads to longer travel along aisles. Overall, the statistical evidence reinforces the conclusion that Space is the primary driver of Pathway distance, while the choice of Search metric has a secondary but non-negligible influence.

4.3. Discussion

The results confirm that both the distance metric used in the search phase and the degree of area heterogeneity influence layout quality when performance is measured by Pathway distance. However, their relative importance is clearly different: the ANOVA shows that Space has very large effect sizes, whereas the Search metric has only medium-sized effects and the interaction is small. This indicates that the available flexibility in department areas is the primary driver of total travel distance along aisles, and that the choice of Search metric plays a secondary but non-negligible role.

From the perspective of Search metrics, Pathway search generally yields the lowest mean Pathway distances, but its advantage over the geometric metrics is modest and statistically significant only for some instances (notably Nug12 and Nug24). For Nug16a and Nug20, no significant differences among the three metrics are found, and Rectilinear and Euclidean never differ significantly from each other. Together with the computational burden of Pathway evaluation, these findings suggest that the simpler geometric metrics can often explore the search space more extensively within the same GA budget and thereby produce layouts whose Pathway performance is statistically indistinguishable from, or only slightly inferior to, that of layouts obtained from Pathway search.

When the best solutions from each Search metric and Space level are compared, Pathway search still tends to produce layouts with the lowest Pathway distances, but the observed differences remain small relative to the variation induced by Space. This pattern reflects the heuristic and stochastic nature of the GA: with a fixed number of runs and common parameter settings, the search cannot guarantee global optima for any metric, and the comparison should therefore be interpreted as one of practical search performance under equal computational budgets rather than intrinsic superiority of a particular distance metric.

In practical terms, the results highlight two main points. First, when aisles and obstacles are explicitly modeled, Pathway distance should be used as the final evaluation metric to avoid choosing layouts that look good under geometric distances but imply unnecessarily long walking routes in practice. Second, during the search phase, Rectilinear or Euclidean distance remain viable and often preferable options, because they are easier to implement, computationally less demanding, and still yield layouts whose Pathway performance is not clearly inferior, and in many cases statistically indistinguishable, to that of layouts obtained from Pathway search. A reasonable guideline is to use Rectilinear or Euclidean distance for GA search and then re-evaluate the candidate layouts with the Pathway metric before implementation.

5. Conclusions

This study examined how three search distance metrics (Rectilinear, Pathway, Euclidean) and three levels of department area heterogeneity jointly influence unequal-area facility layouts when travel must follow predefined aisles. Four Nugent-based problems with unequal areas were solved using a GA, and the resulting layouts were evaluated by total Pathway distance and analyzed using two-way ANOVA and post-hoc tests.

The results consistently show that Space is the dominant factor, with very large effect sizes (partial $\eta^2 \approx 0.85–0.93$), while Search metric has only medium effects (partial $\eta^2 \approx 0.20–0.32$). Pathway search yields the lowest mean Pathway distance in all problem–Space combinations, but statistically significant advantages over geometric metrics occur only in some instances (Nug12 and Nug24), and the observed differences are small compared with the impact of Space. In many cases, Rectilinear and Euclidean searches produce layouts whose Pathway performance is statistically indistinguishable from that of Pathway search. These findings extend the authors' previous equal-area study and complement earlier works that relied mainly on geometric distances, by showing that—even under unequal areas and explicit aisles—the choice of search metric is less critical than the level of area heterogeneity and the use of an evaluation metric consistent with actual walking paths.

The occasional cases where geometric metrics outperform Pathway search can be explained by the heuristic and stochastic nature of the GA under a fixed computational budget, rather than by any fundamental superiority of geometric metrics. Thus, the conclusions should be interpreted as a comparison of practical search performance under equal computational effort, not as claims about global optimality for each metric.

From a practical standpoint, the results support a two-stage guideline. First, Pathway distance should be used as the final evaluation metric whenever aisles and obstacles are modeled explicitly, to avoid layouts that look good under geometric measures but perform poorly in reality. Second, simpler metrics such as Rectilinear or Euclidean remain viable in the search phase, because they are easier to compute and usually yield layouts whose Pathway distances are not clearly inferior to those from Pathway search. A pragmatic strategy is therefore to conduct GA search with a geometric metric and then re-evaluate promising layouts using the Pathway metric, optionally refining the best candidates with a limited number of Pathway-based search runs.

Future work could investigate other aisle topologies, alternative metaheuristics or adaptive parameter control, and multi-objective formulations that incorporate safety, flexibility, and space-utilization efficiency, as well as validate the proposed guidelines on real industrial case studies.

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