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Non-traditional Aisle Design for a Manufacturing Facility Layout

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Abstract

Methods for designing a facility layout typically assume that the aisles for interdepartmental travel will be parallel to the exterior walls of the facility. However, by putting aisles at an angle to the exterior walls, more direct routes between departments can be created, reducing travel distance. This paper describes a method to create a facility layout that does not have orthogonal aisles and testing of the resulting layouts shows that travel distance is reduced.

1 Introduction

There has been much research done to develop methods for determining the layout of a facility. Typically, the objective of the Facility Layout Problem (FLP) is to position the departments to minimize the total travel distance between departments, so that departments with the highest rate of interdepartmental travel are located closest to each other in the facility.

A variety of methods have been developed for solving the FLP. Drira, et al. [1] reviewed different many approaches. Davoudpour, et al. [2] also reviewed approaches to the FLP, considering specifically layouts utilizing a bay structure, in which the departments are organized into lateral bays that run the width of the facility.

Across all formulations of the FLP that have been used in previous research, one common assumption is that boundaries of the departments are parallel to the exterior walls of the facility. Travel between departments is typically constrained to departmental boundaries (rather than passing through departments), so as a consequence of the boundaries being parallel to the facility walls, travel occurs along a rectilinear path rather than a more direct Euclidean path.

However, there are no physical reasons that this assumption is necessary. In general, as long as a travel path doesn't pass through one of the support columns in a facility, it is a feasible path. The reason that this assumption is typically made is that it makes solving the FLP more manageable.

One common approach to the solving the FLP is to represent the facility as a grid, assigning each department to the appropriate number of squares in the grid. This allows non-rectangular departments (e.g., L-shaped) to be formed, but the department boundaries follow the gridlines, which are parallel to the walls of the facility.

Another approach to the FLP is to define the location of each department based on the location of one corner of the department (e.g., lower left) and its length (or height); by knowing the area of the department, the height (or length), and therefore the opposite corner of the department (e.g., upper right) can be calculated. This frees the boundaries from needing to align exactly with the gridlines, but it results in rectangular departments that are parallel to facility walls.

Looking beyond manufacturing facilities, Gue and Meller [3] demonstrated that using non-rectilinear aisles in a warehouse could reduce travel distances, since workers can use a path between the origin and destination of their travel that is closer to being a straight line. Non-rectilinear aisles can also provide benefits to a manufacturing facility, but integrating them into the layout is more difficult than applying them in a warehouse for two reasons.

First, a warehouse layout consists mainly of racks and a manufacturing layout consists of departments. The racks can essentially be represented by lines and the departments are represented by areas. As lines, the position of the racks can be manipulated more easily, to adapt to the location of the angled aisles. Department shapes cannot be adjusted as easily, since they must fit into the space left between aisles and cannot be divided by an aisle. In most FLP methods, the areas are placed first and the aisles are assumed to run along the department boundaries. This approach is difficult when department boundaries are not parallel to the facility walls, since allowing boundaries to be at any angle increases the complexity of the problem.

Second, most trips in a warehouse start and/or end from a small number of locations, typically receiving and shipping docks. This means that aisles can be set with one endpoint at or near these locations. For a manufacturing facility, trips can begin and end in any department, so the design of aisles should take into account the relative frequency of trips between all possible origins and destinations.

The methodology described in this paper provides a method to create a layout that does not require all aisles be rectilinear. The method avoids the complications described above by separating the process of determining the layout and the process of determining the aisles. Once the layout and travel paths have been defined, the aisles can be rotated from a rectilinear position to determine the angle for each aisle that minimizes overall travel distance. Aisles that are not rectilinear are referred to as angled or rotated aisles.

2 Methodology

As described in the previous section, most approaches to solving the FLP deal with the complexity of the problem by limiting the departmental boundaries to be parallel to the exterior walls of the facility. If a department's location, wall length, and corner angles were all allowed to be manipulated, the complexity of the problem would become even more difficult to solve.

To facilitate the development of a layout with angled aisles, the process of arranging the departments is separated from the process of rotating the aisles. In the Creation Phase of the methodology, the layout is generated. Then in the Improvement Phase, the aisles are rotated to determine the angle for each aisle to minimize the overall travel distance.

In addition, the methodology assumes that the layout developed in the Creation Phase utilizes a flexible bay approach. In a flexible bay layout, the bays run the entire width of the facility and the length of each bay is adjusted to provide the area needed for the departments located in that bay. An example is shown in Figure 1.

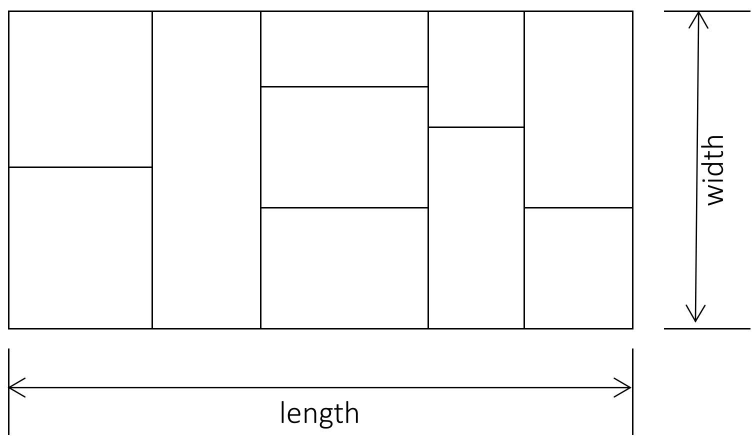


Figure 1: Example of a Flexible Bay Layout

Flexible bays have been used by many previous researchers, including Tate and Smith [4], Konak, et al. [5], and Kulturel-Konak and Konak [6]. All of these researchers demonstrated methods for generating a layout that utilized the flexible bay structure and their results have been used to evaluate the performance of a layout with angled aisles.

The flexible bay layout is well-suited to allowing angled aisles because it has a limited number of aisles. In the Improvement Phase, only vertical aisles (i.e., the bay boundaries) or horizontal aisles (i.e., boundaries between departments in a bay) are rotated, which limits the complexity of finding the optimal angle for each aisle.

Masel and Hedges [7] demonstrated the potential for reducing travel distance by rotating the boundaries of the bay. This paper formalizes the procedure for determining the angle of the aisles and also explores the potential for benefits if the horizontal aisles are rotated instead of the vertical aisles.

2.1 Overview of Situation

The primary assumption made in this methodology is that the facility utilizes a flexible bay structure, with bays running the width of the facility (top to bottom in Figure 1) and the length of each department in a given bay is the entire length of the bay. The “flexible” part of the layout structure refers to the fact that the length of a bay can be adjusted; depending on what departments are assigned to a bay, its length is set to provide sufficient area for all of the assigned departments. As shown in Figure 1, this results in each bay being a different length.

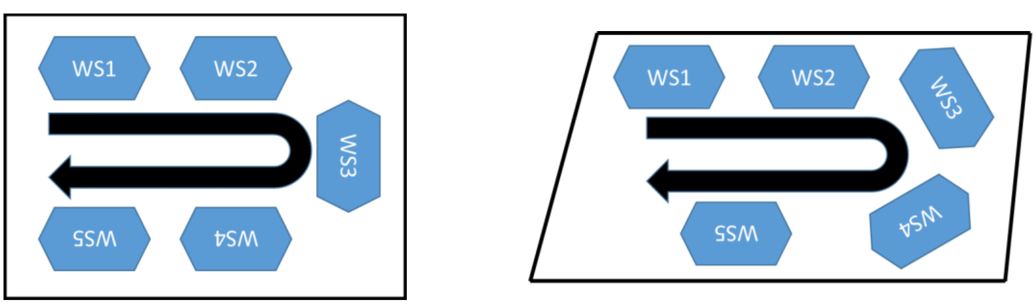
It is assumed that all interdepartmental travel will take place in aisles that are concurrent with the borders of the departments in the facility. For calculating travel distance between a pair of departments, it is assumed that the contour distance metric will be used to calculate the length of the route between the input/output (I/O) stations of the two departments.

The contour metric is used in order to reflect the location of the department boundaries that will be used for interdepartmental travel. The contour metric measures the length of each segment of the departmental borders that are used for a trip. In contrast, both the rectilinear and Euclidean metrics ignore departmental boundaries when calculating the distance between two points. When measuring with the contour metric, the length of the path between two departments will change as the shapes of the departments change, but the rectilinear and Euclidean paths would not change in a way that reflects the new aisles.

Using I/O stations as the endpoints of the travel paths is also necessary to reflect the impact of changes in departmental shapes. Because the contour metric measures distance by following departmental boundaries, the endpoint representing a department should fall on the boundary of that department. Additionally, although the location of the centroid for a department will change as the shape of the department changes, the magnitude of the change in location doesn't necessary reflect the impact of the effect on travel, since interdepartmental travel doesn't go from or to the centroid.

In defining the I/O stations, it will be assumed that there is a single point in each department from which all outgoing trips depart and to which all incoming trips arrive. This is for simplification in the travel calculations, but if there were multiple points for a given department (e.g., separate locations for input and output) the methodology could be adapted to accommodate this.

Within a given department, it is assumed that there is a limited effect on operations as the department's shape changes so that the location of equipment in a department can be shifted to reflect the new boundaries without affecting the flow between machines, as shown in Figure 2.



(a) (b)

Figure 2: Example of Departmental Layouts (a) Before Changing Aisles; (b) After Changing Aisles

There may be a small amount of unusable space at the corners that have acute angles, but the extent to which a department can be deformed will be limited by using a minimum side length or a minimum aspect ratio (i.e., ratio of the shorter side to the longer side). Note that both departments in Figure 2 have the same area, so the machines in the department are shifted to adapt the layout to the new shape.

2.2 Creation Phase

The first phase of the procedure involves creating the layout that will be modified in the next phase. There are three main aspects of the layout that must be defined in this phase:

1. Location of departments
2. Location of I/O stations
3. Travel paths between I/O stations

For the first step, there are many approaches in the literature that have been developed to determine the layout of the departments in a facility, as noted in Section 1. When creating the layout, the only restriction for the remainder of the methodology is that the layout follow the flexible bay structure.

After the layout has been created, the location of the I/O station for each department must be determined. As with the layout, there are alternate approaches for positioning the I/O stations. If the equipment for each department is known, the layout within each department can be defined and the I/O station can be placed appropriately for the flow between machines.

If the layout within departments cannot be determined, the I/O stations can be placed based on the interdepartmental flows. Kim and Kim [8] proved that to minimize the travel distance, the I/O stations should be located at intersections of departmental boundaries. For a given department, this includes corners where the department's own walls meet and intersections where another department's boundary connects. Figure 3 shows the candidate locations for I/O stations for Department A. There are four candidates at corners (#1, 2, 5, and 6) and three candidates from horizontal boundaries in adjacent bays (#3, 4, and 7).

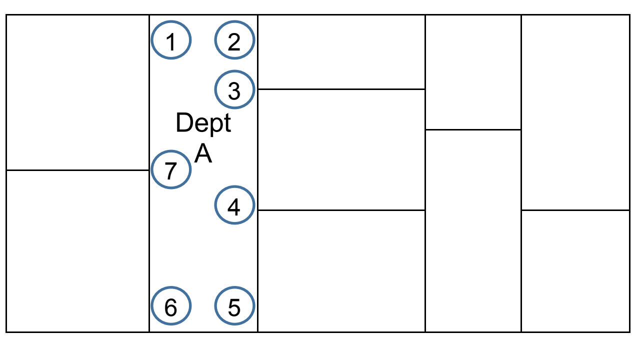


Figure 3: Examples of Options for Placing I/O Stations

Once locations of all I/O station candidates have been identified, the shortest path between all pairs of points can be determined. Using these distances, the combination of locations that minimizes the total travel distance can be determined, selecting exactly one I/O station per department. The calculation of total travel distance, *D*, is shown in Equation (1):

$$D = \sum_{i=1}^{n} \sum_{j=i}^{n} f_{ij} \cdot d_{ij} \tag{1}$$

where f_{ij} is total flow (i.e., number of trips) between departments i and j and d_{ij} is the travel distance between departments i and j.

Finally, the path between each department must be defined. The path between departments i and j corresponds to the aisle segments that are traveled to obtain the shortest distance between the I/O stations of i and j.

2.3 Improvement Phase

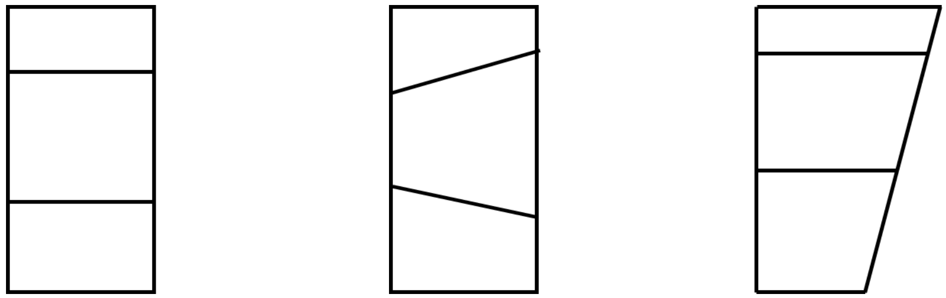
Once the location of the departments and I/O stations has been defined, the layout can be improved by rotating the aisles. In doing the rotation, it is important to note what does **not** change as the aisles are rotated:

- Area of a department
- Area of a bay
- Aisle intersection a department's I/O station is located at
- Path traveled between a given pair of departments

The area of the departments and the bays should remain constant as the aisles are rotated. This allows the coordinates of the corners of each department to be recalculated after the aisles are rotated. The corners must be defined to determine the length of each segment of the travel paths.

In the flexible bay layout, the shapes of the departments change from rectangular to trapezoidal as the aisles rotate, but the width of the bay remains constant, allowing the dimensions to be easily calculated. One restriction on rotation is that either horizontal or vertical boundaries can be rotated, but not both. Figure 4a shows a layout of a single bay before rotation, and Figures 4b and 4c show examples of horizontal and vertical rotation, respectively.

When rotating aisles, it is important to note that departmental boundaries that are created by the exterior walls of the facility are never rotated so that the shape of the facility is not affected. Also, each horizontal aisle is rotated independently, since there typically isn't a connection between the horizontal boundaries. However, when vertical aisles are rotated, it is the bay boundaries that are rotated, so all departments in that bay have the same angle. The reason for this is that each vertical aisle is a boundary for two bays and the horizontal aisles in each of the two bays aren't aligned. Allowing each segment of a vertical aisle to rotate independently would produce departments with non-trapezoidal shapes, which would make calculation of areas much more difficult and could also provide unusable department geometries.



(a) (b) (c)

Figure 4: Layout of a Single Bay (a) Before Aisles are Rotated; (b) With Horizontal Aisles Rotated; (c) With a Vertical Aisle Rotated.

For determining the optimal angle for each horizontal (or vertical) aisle, equation 1 provides the objective function. As noted in section 2.2, d_{ij} can be calculated by summing the length of each segment along the travel path from i to j. The path (in terms of which segments are traveled between i and j) will not be altered from what was determined in the construction phase. The length of each segment will be recalculated as aisles are rotated, so that the travel distance from i to j can still be calculated as the sum of the assigned segments.

Because the endpoints of each segment of the travel path are located at the corner of one or more departments, knowing the dimensions of each department provides information on the coordinates of the endpoints. All segments of the travel path are straight lines, even as the aisles rotate, so the distance of a segment can be calculated as the Euclidean distance between its endpoints.

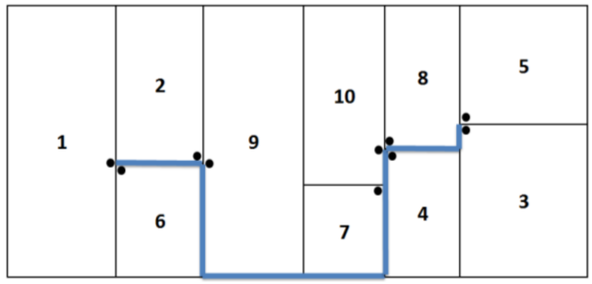
Once the optimal angle has been determined for each aisle, the paths should be rechecked. The rotated aisles may provide the opportunity for a shorter path (i.e., changing some of the segments that are traveled), which could further reduce the travel distance.

3 Testing and Results

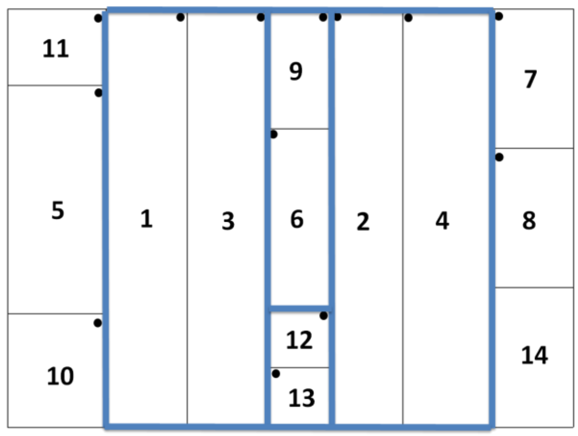
Testing of the methodology was performed on three layout problems from the literature. The problems were chosen because the flexible bay structure had been used to determine a layout for each problem, though the best flexible bay layout was determined by later authors. The layouts are shown in Figure 5.

For all of the layouts from the literature that are shown in Figure 5, the authors used centroid-to-centroid distances in determining the layouts. Therefore, the location of I/O stations needed to be determined for each layout. This was done by considering the shortest path from each candidate location for each department to every candidate in every other department, then determining which location in each department minimized the total travel distance.

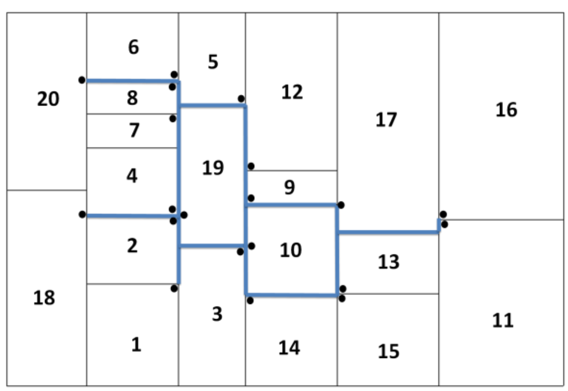
In Figure 5, the location chosen for the I/O station in each department is shown as a dot. The dark lines indicate the travel paths that are used in moving between those stations.



(a)



(b)

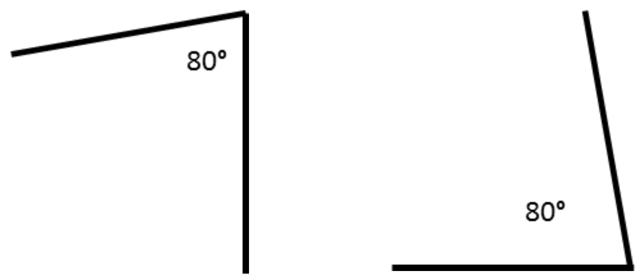


(c)

Figure 5: Original Layouts Used to Test the Methodology (a) van Camp 10-Department Problem [9] (Layout Shown from [4]); (b) Bazaraa 14-Department Problem [10] (Layout Shown from [5]; (c) Armour and Buffa 20-Department Problem [11] (Layout Shown from [6])

Note that Department 14 in Figure 5b does not have an I/O station defined because it is a dummy department (included to represent space in the facility that is not needed for any department) and therefore there are no flows to or from this department.

Once the I/O stations and travel paths were determined, the optimal angle was determined for each horizontal or vertical aisle. For reference, examples of aisle measurements are shown in Figure 6.



(a) (b)

Figure 6: Examples of Aisle Measurements for (a) Horizontal Aisles; (b) Vertical Aisles

Table 1 shows the results of the testing when rotating horizontal aisles and Table 2 shows the results of rotating vertical aisles. In Table 1, when there are multiple angles listed for a bay, they are for the aisles going from top to bottom in the bay.

Table 1: Optimal Angles for Horizontal Aisles

	Bay 1	**Bay 2**	**Bay 3**	**Bay 4**	**Bay 5**	**Bay 6**	**Bay 7**
VC10	No Aisles	108.1°	No Aisles	58.1°	65.4°	83.6°	N/A
B14	70.9° 40.8°	No Aisles	No Aisles	153.4° 90.0° 90.0°	No Aisles	No Aisles	154.3° 90.0°
AB20	83.0°	110.7° 109.6° 108.2° 92.4° 57.5°	99.8° 113.0°	77.2° 80.0° 120.3°	94.1° 67.3°	76.2°	N/A

Table 2: Optimal Angles for Vertical Aisles

	Aisle 1	**Aisle 2**	**Aisle 3**	**Aisle 4**	**Aisle 5**	**Aisle 6**
VC10	81.1°	65.4°	82.5°	103.5°	105.0°	N/A
B14	98.1°	93.5°	90.0°	90.0°	87.6°	85.3°
AB20	91.7°	88.4°	92.7°	87.6°	90.9°	N/A

The cost of each layout is given in Table 3. The values are based on the flows provided in the original problem. However, because previous testing on these problems used a centroid-to-centroid distance, the values in the table for Original Cost were calculated assuming the locations for the I/O stations shown in Figure 5. For each of the new designs, Table 3 also provides the percent decrease in cost from the original layout.

Table 3: Layout Costs

	Original Cost	**Horizontal Rotation**	**Percent Decrease**	**Vertical Rotation**	**Percent Decrease**
VC10	$7,166	$5,992	16.4%	$5,672	20.9%
B14	$4,718	$4,262	9.7%	$4,256	9.8%
AB20	$3,484	$3,286	5.7%	$3,289	5.6%

Each layout shows a reduction in travel distance as either horizontal and vertical aisles are rotated. The percent reduction decreases when there are more departments, but it is unclear if this is due to generally having more complex interdepartmental flows in the larger problems, or if it is due to the specific flows in these problems. To evaluate the relationship between the number of departments and percent improvement, multiple problems with the same number of departments would be needed.

4 Conclusions

Rotating the aisles in a flexible bay layout provides opportunities for reducing the travel distance in a facility. The two-phase process of creation and then improvement provides a feasible model for optimization because in the improvement phase, the only decision variables are the aisle angles.

There are opportunities for further improvement in travel distance by creating departmental shapes that are more complex than trapezoids by allowing all four walls of a department to not be parallel to the facility walls. Further improvement may also be possible if the locations of departments and/or I/O stations were re-evaluated after the aisle angles are set.

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