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Integrated facilities design using a contour distance metric

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Integrated facilities design using a contour distance metric

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The unequal area facility design problem has been studied in the literature generally by considering block layout separate from detailed design. This paper shows a tractable method for concurrently optimizing department shape and location within the facility, and selection of the appropriate number of Input/Output (I/O) stations per department and then optimally locating them. The distance metric used is the contour distance that measures transport between I/O stations along the perimeters of departmental boundaries. This distance metric better reflects allowable material flow for many industrial applications and it directly implies the optimal aisle structure for the facility.

1. Introduction

The block layout problem in facilities design provides the basic area partition of a given rectangular area into departments with an interest of minimizing projected material handling costs. This problem has been well studied in the literature – for a recent review of the literature see Meller and Gau (1996). Subsequent to the block partition a detailed facility design is developed by formulating material handling aisles (that are traditionally along departmental boundaries) and assigning Input/Output (I/O) points through which departments communicate material. The problem has been studied primarily in the literature by separating block layout from detailed design to allow for computationally tractable formulations. This paper presents a more realistic scoring method for block layouts that simultaneously integrates aspects of the detailed layout problem by considering material flow from departmental I/O points. We propose using this scoring method within an existing Genetic Algorithm (GA) block layout generation procedure.

Armour and Buffa (1963) originally formalized the block layout problem as follows. There is a rectangular region, R, with fixed dimensions H and W, and a collection of n required departments, each of specified area a_j and dimensions (if rectangular) of h_j and w_j, whose total area, $\sum_j a_j = \mathrm{A} = \mathrm{H} \times \mathrm{W}$. There is a material flow $F(j,k)$ associated with each pair of departments (j,k) which generally includes a traffic volume in addition to a unit cost to transport that volume. There may also be fixed costs between departments j and k. The objective is to partition R into n subregions representing each of the n departments, of appropriate area, in order to:

$$\min Z = \sum_{j=1}^{n} \sum_{\substack{k=1 \\ j \neq k}}^{n} F(j,k) d(j,k,\Pi), \tag{1}$$

where $d(j,k,\Pi)$ is the distance (using a pre-specified metric) between the centroid of department j and the centroid of department k in the partition Π. The centroidal distance is easy to calculate for rectangular departments and it is intuitive in that the mass of material is considered to move from center to center of departments along the shortest rectilinear (Manhattan) or Euclidean distance. However, the centroid distance measure is not realistic for many applications, as it allows for material transport through departments and does not imply a reasonable aisle structure.

Chhajed *et al.* (1992) present a comprehensive discussion on flow networks and distinguish between free flow (shortest distance paths) and flow which follows departmental contours. The authors then present both exact and heuristic algorithms to optimize a free flow path for a given block layout with pre-determined I/O points. The idea of contour flow has been used in the literature related to discrete material handling systems such as Automated Guided Vehicles (AGVs), as found in the Segmented Flow Topology (SFT) work of Sinriech and Tanchoco (1995, 1997). In this work, I/Os and the resulting flow paths are chosen based on both distance-based transport costs and on fixed costs for building an I/O. In Sinriech and Tanchoco (1997), it is further allowed that material flow between two departments may be heuristically split among different paths if it is cost effective. A complete review of approaches to discrete flow systems can be found in Sinriech (1995).

A number of papers have dealt with optimally choosing the I/O locations and/or aisles for a given block layout (see for example, Montreuil and Ratliff (1988) who use free flow and Sinriech and Edouard (1996) who use the SFT flow along contours). Palliyil and Goetschalckx (1994) present exact and heuristic methods for optimally locating I/O stations and their flowpaths that can be applied to unidirectional or bidirectional flowpaths.

Integrating block layout with I/O placement has rarely been considered in the literature, probably because of the computational difficulties. Montreuil (Montreuil, 1987; Montreuil and Ratliff, 1988) optimally complete the block layout and place a pre-specified number of I/Os per department given a design skeleton. Luxhoj (1991) presents a two-part approach where a constructive heuristic creates a block layout that is then improved upon by pairwise interchange and material flows along a spine. Benson and Foote (1997) consider the placement of aisles and I/O points after the relative location of the departments and the general aisle structure have been selected. In the work of Nagi and others (Harhalakis *et al.*, 1996; Kane and Nagi, 1997), pre-defined departmental shapes are set on a grid covering the facility space, which is larger than the sum of the department areas. In Harhalakis *et al.* (1996) Dijkstra's shortest path algorithm is used to calculate the rectilinear distance to and from pre-specified I/O points. In Kane and Nagi (1997) I/O points are placed during the optimization and a corner constraint is imposed to encourage paths that are straight. Both papers use a simulated annealing heuristic to alter departmental placement. Banerjee *et al.* (1997) uses a genetic algorithm to search over design skeletons[1] that are then optimized using a subordinate mathematical programming routine. The number of I/Os per department is prespecified (either one or two per department) and then optimally located with the departmental placement. The shortest rectilinear distance between I/O points (free flow paths) is used in the objective function.

This paper seeks to integrate block layout (including both placement and shaping of the departments) with the choice of I/O stations (both number and location) and identification of aisle structure assuming uncapacitated, bidirectional aisles of negligible area. The contour distance metric enables this integrated design to translate well into physical reality while allowing computational feasibility. This still does not achieve the ideal situation where a true aisle structure will also be optimally designed concurrently. This simplification, instead, assumes that all departmental perimeters are potentially legitimate aisles.

2. Problem formulation and solution methodology

The basic assumption is that the facility is comprised of rectangular departments of specified area within a rectangular bounding facility that is equal to, or larger than, the sum of the departmental areas. The formulation used is "flexbay"[2], or flexible bay, by Tong (1991) and Tate and Smith (1993, 1995) (Fig. 1a and b). Flexbay makes cuts in a single direction to establish a set of bays that can vary in area. The bays are then subdivided into departments. The flexbay encoding can strictly enforce both

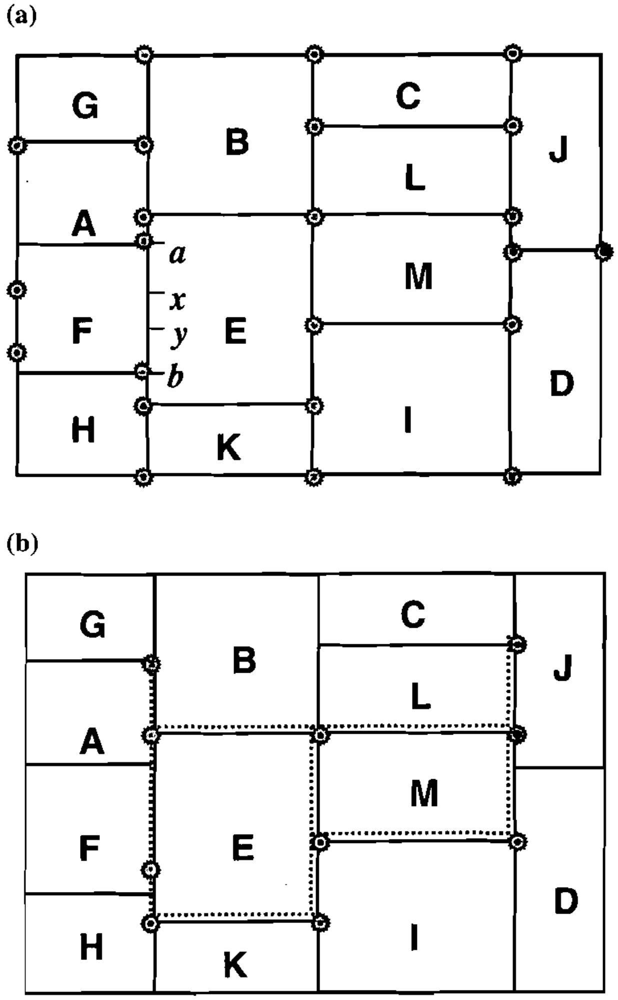

Fig. 1. Possible I/O points on a: (a) flexbay layout; and (b) material travel after I/O placement.

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[1] A design skeleton was originally defined by Montreuil and Ratliff (1989) and consists of the relative location of the departments within the facility.

[2] The term "flexbay" was first given in the review paper by Meller and Gau (1996).

departmental areas and departmental shapes, through use of a maximum aspect ratio constraint[3] or a minimum departmental side length constraint for a stated departmental area.

2.1. *Optimization methodology*

To find the optimal or near-optimal block layout, a Genetic Algorithm (GA) is used with the flexbay formulation. The genetic algorithm works with a variable length encoding of the layout where there is a one-to-one correspondence between each encoding and each layout. The encoding is a permutation of departments that specifies their order within the layout, with a concatenated string indicating where the bay breaks within the permutation occur. For example, the flexbay layout of Fig. 1 would be represented with the following encoding:

G A F H B E K C L M I J D H K I

where the last three characters indicate bay breaks after departments H, K and I.

Crossover is accomplished through a variant of uniform crossover (Goldberg, 1989), where two parents create one offspring. The department sequence is subject to uniform crossover with repair to ensure feasible permutations. The bay structure is taken directly from one parent or another with equal probability. Mutation consists of permutation altering (50%), or adding (25%) or deleting (25%) a bay. The permutation mutation is inversion between two randomly selected departments. Crossover and mutation are performed independently of each other, with all solutions (parents and offspring) currently available equally likely to be mutated. Solutions are selected for crossover using a rank-based quadratic method and the worst solutions are deleted during each generation to maintain a constant population size. Tate and Smith (1995) includes the details of these.

2.2. *I/O location and distance measure in the objective function*

The version of I/O location that is considered in this paper is where the allowable number of I/Os per department is not constrained. This might seem ungainly, but due to the contour measure the set of candidate I/O points for a department can be limited to the locations where that department intersects the corner of any of its adjacent departments, as will be proven below. Using the example of Fig. 1(a and b), the candidate I/O points include all of the shaded circles in the top portion of the figure. To clarify the contour distance measure, if the I/Os used were as shown on the bottom, the material will traverse over the perimeters shown in the dashed line.

The set of departmental intersection points represents a dominant set of locations to consider for the departmental I/O points. Consider Fig. 1 where x represents the location for the I/O point for department F which is currently not at an intersection point and a and b represent the locations where department F intersects with department E. It will be shown that x can be moved to one of the two intersection points a or b without increasing the overall travel distance. A related result for automated guided vehicle paths was proven in Tanchoco and Sinriech (1992) and De Guzman *et al.* (1997). The discussion is broken into two cases.

Case 1: Assume that department F has no flow relationship with department E. Because the flow paths go around the contour of departments all of the flow through x must pass through either a or b prior to reaching x. If more than 50% of the total flow through x passes through a then invoking the median condition (Francis and White, 1974) from location theory it is clear that moving x to a would reduce the overall travel distance. Similarly, x should be placed at b if more than 50% of the total flow through department F comes through b. If exactly 50% of the total flow through department F comes through both a and b then x can be placed at either a or b.

Case 2: Assume department F has a flow relationship with department E. If department E's I/O location is not on the line segment connecting a and b then the result from case 1 holds. Otherwise, let y represent the location of department E's I/O point. The median condition (Francis and White, 1974) can be applied to the location problem for x on the line segment joining a and b considering the flows through a, b and y. If the result is to move x to either a or b, these are intersection points. Or, if the result is to move x to y then it must be shown that the location for x and y together will be at an intersection point. Let ϕ represent the magnitude of the total flow through departments E and F that comes from relationships with departments other than E and F. Similar to case 1, all of the flows through x and y must flow through either location a or b. Utilizing the median condition, if the flow through a is $> 0.5\phi$ then place x and y together at a, if the flow through $a < 0.5\phi$ place x and y together at b, otherwise place x and y together at either a or b.

Thus the set of intersection points represent a dominant set for locating the I/O points of each department. The results for cases 1 and 2 readily extend to the case of multiple I/O points or the case where a department has several departments along one edge, for example, department B, J or D in Fig. 1.

Furthermore, the set of intersection points can be upper bounded at $2n - 2$ using the following argument.

1. Consider a flexible bay facility with n departments and b bays. Each department can cause at most four intersection points, located at each of its four

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[3] Aspect ratio is defined as the quotient of the longer side divided by the shorter side.

corners, giving a total possible number of intersection points of $4n$.

2. However, many of the intersection points will be located concurrently. Wherever an interior bay division intersects the facility perimeter, two intersection points will be concurrent. This eliminates $2(b-1)$ intersection points.
3. For bays that contain more than one department, at each interior departmental boundary, two more intersection points will be concurrent. This eliminates $2(n-b)$ intersection points.
4. The four corners of the entire facility are dominated considering the objective function.
5. Combining the quantities yields $4n-2(b-1)-2(n-b)-4$ which reduces to $2n-2$.

Therefore, the number of potential intersection sites depends only on n, and is $O(n)$.

When each department can have an unconstrained number of I/O stations the interdepartmental aisle travel distances can be found by formulating the problem as one of finding the shortest path on a network. All of the arc lengths in the resulting shortest path problem will be positive since they represent physical distances. The shortest path problem with positive arc lengths has been well studied in the network optimization literature and efficient algorithms exist for solving this problem (Ahuja *et al.*, 1993). This makes it possible to quickly evaluate the actual aisle travel distance for each layout that is generated during the search process. The objective function of the integrated optimization is:

$$Z(\Pi) = \sum_{j=1}^{n} \sum_{\substack{k=1 \\ j \neq k}}^{n} F_{j,k} d_{j,k} + m^3 (Z_{\text{feas}} - Z_{\text{all}}), \qquad (2)$$

where m is the number of departments in layout Π which violate the aspect ratio constraint, Z_{feas} is the objective function value for the best feasible solution found so far, and Z_{all} is the unpenalized objective function value for the best solution found so far. The penalty function is a variation of the adaptive one by Smith and others (Smith and Tate, 1993; Coit *et al.*, 1996; Smith and Coit, 1997). In this case $d_{j,k}$ is defined as the shortest rectilinear distance along departmental contours between the I/O stations of departments j and k as given by:

$$d_{j,k} = \text{Min}\ \{d_{j,l,k,m} : l \in \text{Loc}_j,\ m \in \text{Loc}_k\}, \qquad (3)$$

where Loc_j and Loc_k are the set of candidate I/O locations for departments j and k, respectively, and $d_{j,l,k,m}$ is the shortest distance, following the department contours, from candidate I/O location l of department j to candidate I/O location m of department k.

The algorithm begins with a randomly generated initial population of chromosomes. In each generation, crossover and mutation are applied to create new solutions. For the crossover step, two parents are selected based on ranked fitness and crossover is performed to produce one child. The child is evaluated and the worst solution from the current population is deleted and the child solution is added to the population. Mutation is performed by randomly selecting members of the population with each having an equal probability of selection. The mutated solutions are evaluated and replace the worst solutions in the current population. Each new solution that is generated using crossover or mutation is evaluated using the following evaluation procedure:

Step 1. Determine the current facility design from the chromosome.
Step 2. Calculate the number of infeasible departments.
Step 3. Construct a network of nodes corresponding to each department in the design and its candidate I/O locations.
Step 4. Find the shortest path between each pair of nodes in the network.
Step 5. Sum the flow costs along the shortest path according to Equation (2).

3. Test problems and results

Several unequal area problems from the literature were solved in the manner described in Section 2. While the material flows, departmental areas and constraints are identical to those previously studied, results cannot be compared directly as the distance measure used previously was the centroid to centroid. The problems are from Bazaraa (1975) and Hassan *et al.* (1986) (14 departments) and Armour and Buffa (1963) (20 departments). The 10 department problem of van Camp *et al.* (1991) was also studied, however there is a solution (optimal) where Equation (2) is equal to zero. In this design, all departments are located adjacent to the departments with which they have material flow, and since there is no limitation on the number of I/Os, the distance traveled over the entire facility is zero. The GA settings were the same as in Tate and Smith (1995): population size of 10, mutation rate of 50% (five mutants per generation) and number of generations generated = 100 000.

Objective function values from the contour measure are in Table 1, where the best, median, worst and standard deviation over 10 runs using different random number seeds are shown. The 20 department Armour and Buffa (A&B) was studied with maximum aspect ratios of ten, seven, five, four, three and two. At a maximum aspect ratio of ten, the problem is nearly unconstrained, while a maximum aspect ratio of two is extremely constrained. The Bazaraa problem used a minimum side length of one as the shape constraint, as done by previous authors. This minimum side length requirement loosely constrains the Bazaraa 14 problem.

Table 1. Comparisons of results over 10 seeds

Problem (# dept/aspect ratio)	*Best*	*Median*	*Worst*	*Standard deviation*
Bazaraa 14	1343.2	1459.2	1607.9	92.8
A&B 20/10	757.1	862.9	1221.0	147.2
A&B 20/7	785.8	1079.9	1267.4	155.2
A&B 20/5	949.4	1319.6	2176.4	343.0
A&B 20/4	1025.7	1189.2	1758.1	236.3
A&B 20/3	942.6	1478.1	2298.5	354.0
A&B 20/2*	1244.1	1873.6	3359.8	787.2

* Over the six of the 10 runs that found feasible layouts.

For comparison, Fig. 2 (a and b) shows the best layout using the contour measure compared to the best layout from Tate and Smith (1995) using the rectilinear centroid to centroid distance measure for the Bazaraa 14 problem. Also shown are the assumed I/O points and the assumed material flow paths inherent in each formulation. Note that department 14 is a "dummy" department with no flows, hence the lack of an I/O. In comparing the two layouts it is important to recall that centroid to centroid distance is not intended to indicate material flow paths; rather, it is a convenient way to approximate material handling effort between dispersed machines/resources within departmental areas. However, it is true that if this metric is used in the objective function then there is an implicit assumption that material can move along the shortest path between departmental centroids. This often necessitates material moving through, rather than around, the other departments in the layout. For the layouts in Fig. 2 (a and b), it appears that the contour measure with I/O location on the boundaries of the departments is a better reflection of the physical movement of material for most manufacturing and service scenarios. The centroid method not only traverses through the interior of intervening departments. Layouts where the centroids were not located along the same line, as in departments 1 through 4 of Fig. 2 (a and b), would create even more paths, as shown in Fig. 3 (a and b). The best Tate and Smith (1995) layout for the Amour and Buffa problem using an aspect ratio constraint of three is compared to the best of this paper. The implicit centroid to centroid aisles result in parallel paths that traverse departments, and traffic through departments would normally be unacceptable in actual facilities. The Appendix includes the best feasible designs identified for the other test problems.

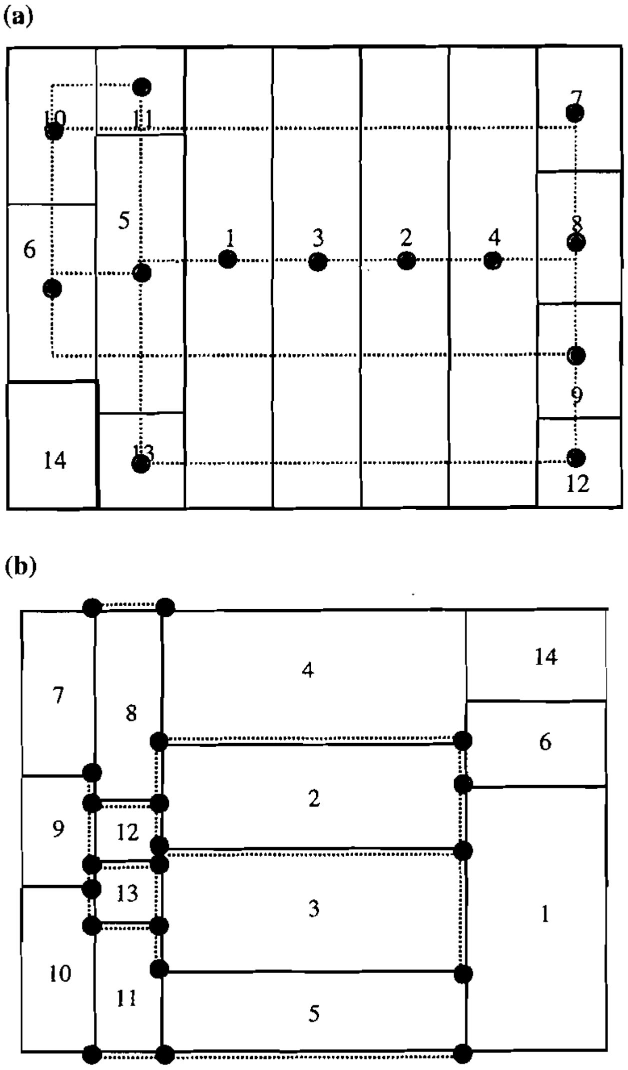

Fig. 2. I/O points and implied flow paths (dashed) for: (a) the centroid distance measure; and (b) the contour distance measure for the Bazaraa 14 problem.

Further study of the layouts in Figs. 2 (a and b) and 3 (a and b) and the other test problems indicates that the layouts developed using the centroid metric often perform poorly for the contour metric. The differences range from 4.6 to 112% more total travel distance. Similarly, the layouts developed using the contour metric did not perform as well for the centroid based objective. These results highlight the benefit of explicitly considering flowpath structure in the objective function.

4. Conclusions

This paper puts forth a tractable and effective methodology for integrated optimization of facilities designs that will translate well into physical reality. The solution methodology, based on a network algorithm that exploits the flexible bay structure within a genetic algorithm metaheuristic framework, makes it possible to concurrently optimize five facets of the facility design problem: departmental location within the facility, departmental shape within certain constraints, selection of the proper number of I/Os, their placement, and flow paths along the departmental contours. This last item may be regarded as a precursor to development of a true aisle structure,

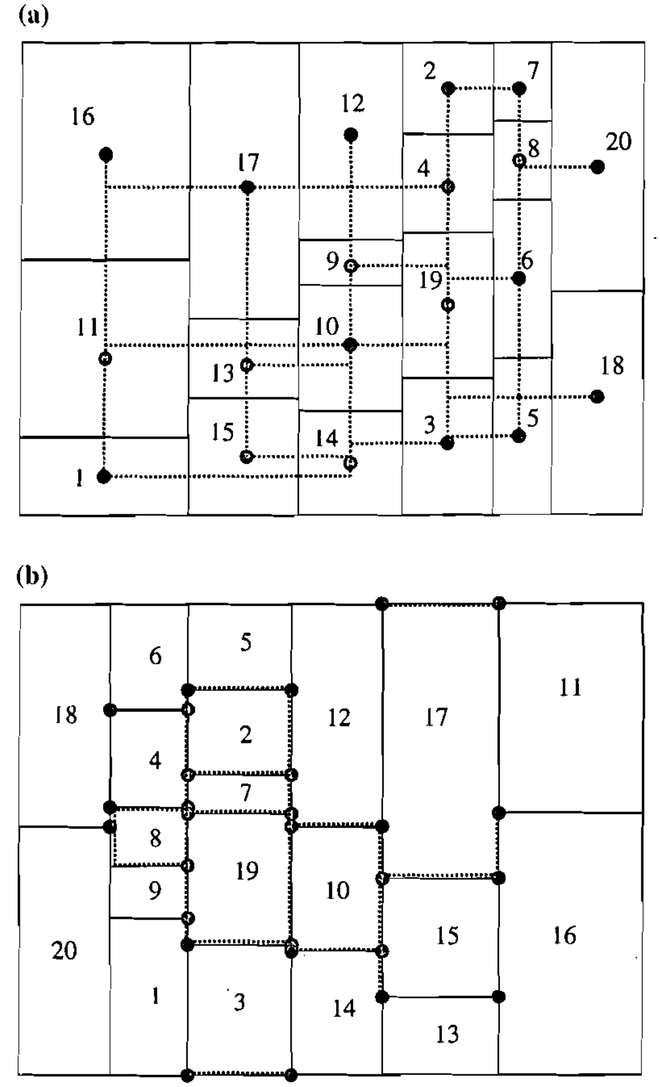

Fig. 3. I/O points and implied flow paths (dashed) for: (a) the centroid distance measure; and (b) the contour distance measure for the Armour and Buffa problem with a maximum aspect ratio constraint of three.

where contour travel is further constrained. It is shown that although the number of I/Os per department is not constrained, the candidate I/O locations must be at departmental intersection points, and this number is bounded above by $2n - 2$. Further work should consider incorporation of a fixed cost per I/O in the objective function so that the initial costs of building an I/O can be weighed with the subsequent reduction in material flow distance. It should also consider explicitly constraining the number and location of the input and output locations. The addition of these constraints makes the problem considerably more difficult because the evaluation routine must solve network problems that have greater complexity than the shortest path problem. It would also be interesting to consider aisle capacities and directional flow in future work.

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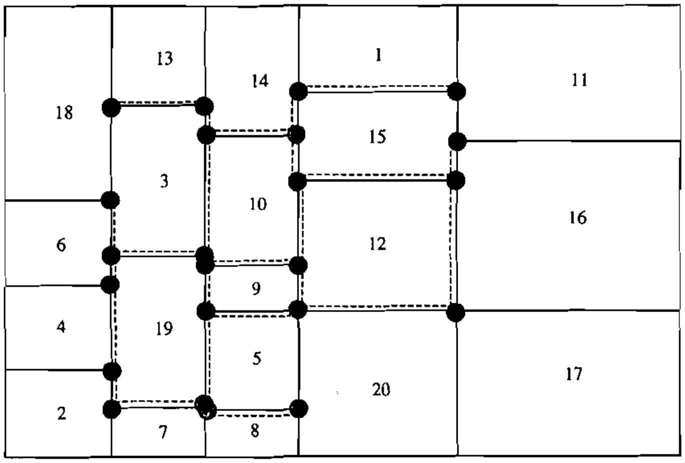
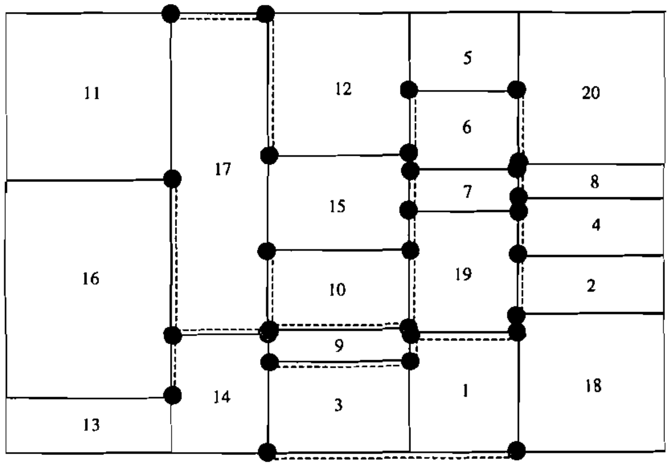
Appendix

The design of the best feasible solution for each maximum aspect ratio constraint.



Maximum Aspect Ratio = 2



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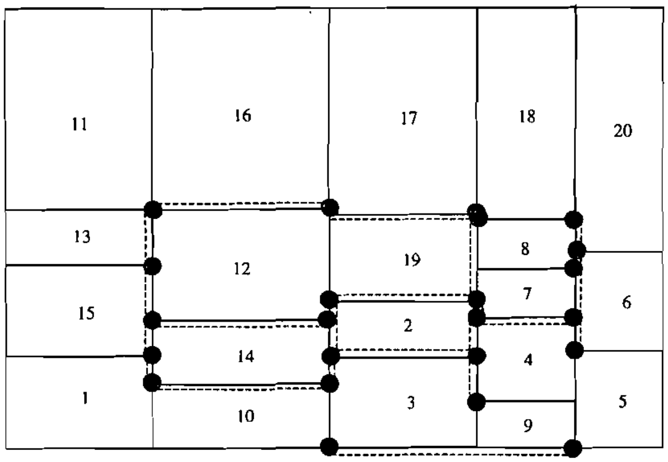
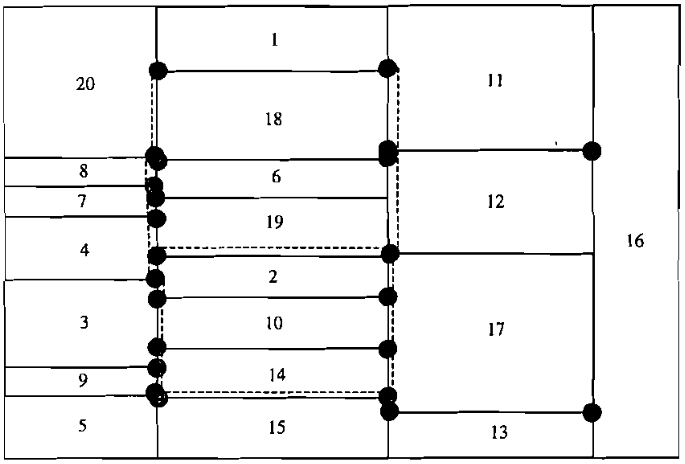
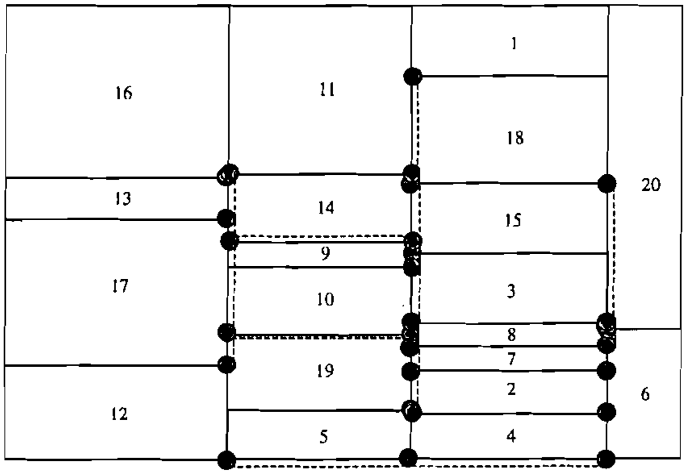


Maximum Aspect Ratio = 4



Maximum Aspect Ratio = 7



Maximum Aspect Ratio = 10

Biographies

Bryan A. Norman is an Assistant Professor of Industrial Engineering at the University of Pittsburgh. He received the Ph.D. degree in Industrial and Operations Engineering from the University of Michigan in 1995, where he was a National Science Foundation Fellowship holder, and has B.S.I.E. and M.S.I.E. degrees from the University of Oklahoma. His research interests primarily focus on the modeling of complex problems in manufacturing systems. His areas of application include scheduling, sequencing, job rotation, assembly line balancing and facility layout and material handling system design. His research has been funded by the National Science Foundation, the Ben Franklin Technology Center of Western Pennsylvania, the Society of Manufacturing Engineers and by local industry. He has published his research in *IIE Transactions*, *Naval Research Logistics*, *Engineering Design and Automation*, and *Computers and Industrial Engineering*. He is a member of IIE and INFORMS.

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Alice E. Smith is Professor and Chair of Industrial and Systems at Auburn University. Previous to this position, she was on the faculty of the Department of Industrial Engineering at the University of Pittsburgh, which she joined in 1991 after 10 years of industrial experience with Southwestern Bell Corporation. Dr. Smith has degrees in engineering and business from Rice University, Saint Louis University and University of Missouri – Rolla. Her research in analysis, modeling and optimization of manufacturing processes and engineering design has been funded by the National Institute of Standards (NIST), Lockheed Martin, DaimlerChrysler Rail System NA (Adtranz NA), the Ben Franklin Technology Center of Western Pennsylvania and the National Science Foundation (NSF), from which she was awarded a CAREER grant in 1995. Her industrial partners on sponsored research projects have included Eljer Plumbingware, Extrude Hone, Ford Motor, PPG Industries and Crucible Compaction Metals. Dr. Smith has served as a principal investigator on about $1.8 million of sponsored research. She received the University of Pittsburgh School of Engineering Board of Visitors annual Faculty Award in 1996 for outstanding achievements in research and scholarly activity. Dr. Smith has authored over 100 publications in books, refereed proceedings and journals including articles in *IIE Transactions*, *IEEE Transactions on Reliability*, *INFORMS Journal on Computing*, *International Journal of Production Research*, *IEEE Transactions on Systems, Man, and Cybernetics*, *The Engineering Economist*, and *IEEE Transactions on Evolutionary Computation*. She won the E. L. Grant Award in 1999 for the best paper of *The Engineering Economist*, volume 43. Dr. Smith holds editorial positions on *INFORMS Journal on Computing*, *IEEE Transactions on Evolutionary Computation* and *IIE Transactions*. Dr. Smith is a senior member of IIE, IEEE and SWE, a member of Tau Beta Pi, INFORMS and ASEE, and a Registered Professional Engineer in Industrial Engineering in Alabama and Pennsylvania. She has been elected to the College Industry Council on Material Handling Education (CIC-MHE) of the Material Handling Institute for the term of 1999 through 2004.

Contributed by the Facilities Layout and Material Handling Department.