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A Space Syntax Analysis of the Relationship between Function and Form in Facility Layout

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***Abstract*— This paper explores the relationship between a facility's operation and its form using quantitative techniques provided by Space Syntax. Space Syntax provides quantitative metrics for characterizing the spatial traits of the locations within a facility which can then be related to operational metrics. Instances of the quadratic assignment problem are used to perform spatial and operational analyses on different flow matrices to study the resulting layouts. The effects of different objective functions on facility shapes are also studied.**

Keywords—facility layout design, quadratic assignment problem, Space Syntax

I. Introduction

Facility design is concerned with the relationship between the function of a facility and its shape and arrangement, or form. Most facility design research has not fully explored this aspect for the sake of developing solvable models. To keep models simple, researchers usually restrict the form of the facility to rectangular shapes. A second obstacle for studying this relationship is the absence of quantitative metrics for describing the spatial characteristics of a facility. In addition, new objective functions such as those required for facility design in the service sector also raise important questions about how they are affected by a facility's shape.

The purpose of this paper is to propose an analytical framework for studying the impact of function on form. The framework is built using the principles, techniques, and metrics of Space Syntax [6]. This framework provides tools for characterizing the spatial traits of a facility. This paper uses the framework in three different experiments which study how the shape of a facility affects the value of the objective function, and how different facility shapes reflect the properties of different flow matrices.

II. Literature Review

A. *Studying facility shape in facility layout design*

Research into the effects of shape in the design of facilities has been scarce. By studying how changing the length to width ratio of different floorplans affects the mean trip time, [8] concludes that square-shaped floors are better than rectangular floors. However, this study does not consider any other possible floor shape. In [13] there is a brief discussion on the use of hexagons as the shape of the modules that form a Volvo plant in Sweden. No details on why such shape was chosen are provided, nor is there any discussion of its advantages (or disadvantages) with respect to other shapes. The only study we have found that discusses the role that different shapes can have on travel distances is [3]. Using a computer simulation model, they study the travel distances across floorplans with different shapes, but equal area. There findings coincide with some of the findings we present in this paper. Specifically, they found that a circular shape is the most distance minimizing, though they argue in favor of hexagons, as they pack better when incorporated into a larger tile-like pattern while still outperforming rectangles and squares.

B. *A brief primer on Space Syntax*

Space Syntax is defined as "a set of techniques for the representation, quantification, and interpretation of spatial configuration in buildings and settlements" [7]. It provides a set of metrics for quantifying the spatial traits of the different components of a building, a capability which, as we mentioned in the introduction, is lacking in the current facility layout literature. See [6] for a thorough discussion of the principles behind Space Syntax, as well as its basic techniques.

The basic approach to a Space Syntax analysis can be described by the following steps:

1. Define a set of spatial units.
2. Define a set of spatial relations among those units.
3. Construct a graph of the facility in terms of each spatial relation.
4. Define a set of spatial metrics to be computed from the spatial relation graphs.
5. Compute the values of the spatial metrics.

The Space Syntax literature has focused on the description and comparison of already existing facilities. A wide range of spatial units (convex spaces, axial lines, visibility polygons), spatial relations (adjacency, permeability, visibility), and spatial metrics (depth, integration, control) have been used for studying the configuration of varying types of facilities and spatial systems (e.g., houses, hospitals, universities, urban settlements).

What the facility layout literature is lacking in spatial analysis, the Space Syntax literature is lacking in operational analysis. Space Syntax was first used to study the "social logic" of space, that is, how social behaviors manifested themselves spatially. Since then, it has evolved to study how many different types of functions relate to space. However, as far as we know, no study has been done relating the organization of space to specific operational functions, nor to the way operational processes manifest themselves spatially. Therefore, combining the analytical tools of Space Syntax with those of facility layout can bring some valuable ideas for better, more realistic facility models.

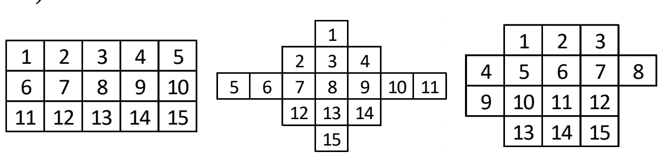
In this paper, the primary concern is with those Space Syntax metrics that capture some spatial characteristic of the locations within the facility. The basic spatial element is a facility location, represented as a square within which a department can be placed. The fundamental spatial relation considered is the relationship of adjacency. The spatial metric used is adjacency depth, which is defined as the number of hops to go from location i to location j along the adjacency graph.

III. Experiments

A. Experiment 1: Effect of Facility Shape

To test whether the facility's shape has any significant effect, the following experiment was set up: the objective function values of the known optimal solutions of three of the QAP instances described by [10], which presuppose a rectangular facility, were compared with those of facilities that do not conform to the rectangularity constraint. The hypothesis was that better values of the objective function can be obtained with shapes other than the rectangle.

This hypothesis arose from an analysis of the total adjacency depth of different facility shapes. This metric is very closely related to travel distance. It represents a measure of topological distance and is obtained by calculating the number of spaces that must be crossed to go from location i to location j. The sum of the depth values for each location gives us the total depth of the facility. Therefore, it is reasonable to assume that facilities with different depth values should result in different travel distances. A facility with a lower total depth should also result in a lower total travel distance. Fig. 1 shows three different facility shapes for a 15 location facility with their corresponding total depth (TD) values.

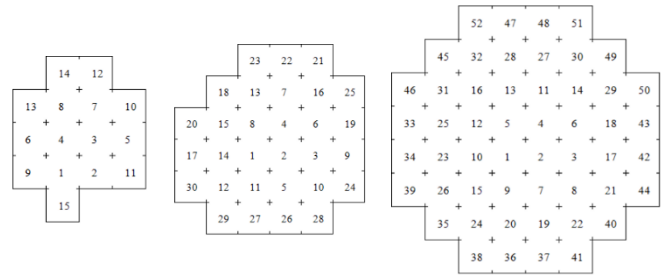


a) TD = 560 b) TD = 590 c) TD = 544

Fig. 1. Facility shapes and their depth values

To find which facility shape has the lowest total depth, a total depth minimizing algorithm (described in section III.C) was run. The results showed that minimum depth facilities tend towards a circular shape. Examples of such shapes can be seen in Fig. 2 for varying facility sizes.

The flow matrix data from three sample problems, Nug15, Nug25 and Nug30 [10], all of which can be found in the QAPLib [2] were used to compare optimal solutions. The optimal solution for these three instances is known for the rectangular case. A tabu search (described in the Appendix) was used to solve the QAP using the same flow matrix data, but with different distance matrices corresponding to the near-circular shape of the facility.

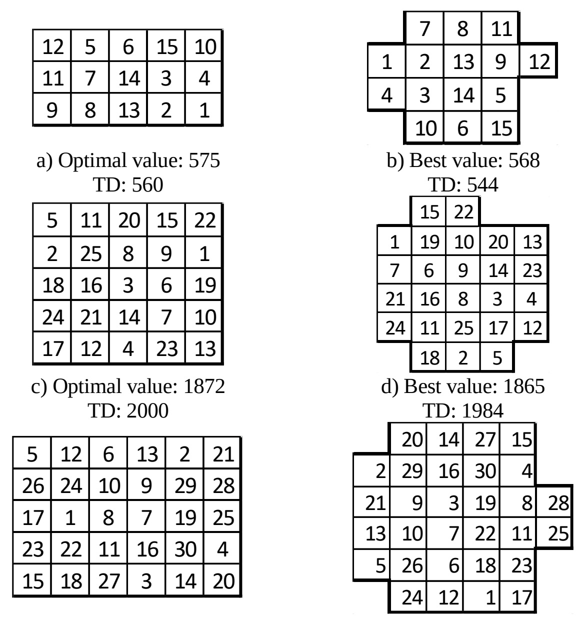


a) 15 locations b) 30 locations c) 52 locations

Fig. 2. Depth minimizing shapes

The results are summarized in Fig. 3. (Since the objective values obtained for the non-rectangular facilities were the result of a meta-heuristic, they are not guaranteed to be optimal.)

From these results, it follows that the shape of the facility has an important impact on the optimal solution to the problem. In addition, it seems that a lower value of the facility's depth results in an improved optimal solution regarding minimizing total distance. Subsequent research revealed that this is not always the case, as will be discussed below.



a) Optimal value: 575 TD: 560
b) Best value: 568 TD: 544
c) Optimal value: 1872 TD: 2000
d) Best value: 1865 TD: 1984
e) Optimal value: 3062 TD: 3190
f) Best value: 3057 TD: 3142

Fig. 3. Rectangular vs. Circular facility shape comparison

B. Experiment 2: Shapes resulting from different flow matrices

For experiment 2, additional spatial metrics were considered. These were the radius-1 and the radius-2 neighbor counts of each department. The radius-n neighbor count, as used here, is defined as the sum of the departments that are n steps away from the current department along the adjacency graph. Radius-1 counts all the immediate neighbors of the original department. Radius-2 counts the neighbors of its immediate neighbors. Whereas the total depth of a department measures its global connectivity, these quantify its local connectivity.

In addition to the new metrics, different flow matrices were also used. These were designed to represent different types of traffic patterns. Two of them represent matrices with local flows, that is, facilities where there are interactions between only a few departments. Two of them have globalized flows, where every department interacts with all or almost all the other departments in the facility. A last matrix presents a highly-structured and ordered flow. Table I summarizes the differences between each matrix used in our study.

For each matrix, the optimal (or close to optimal) solution for travel distance was found with three facility shape specifications: (1) rectangular shape, (2) depth-minimizing shape, and (3) free form. The correlation and coefficient of determination (R2) between the operational and spatial metrics were calculated and compared across facility shapes. Operational metrics were denoted FV (Flow volume) and NF (number of flows). Spatial metrics were denoted by D (depth), R1 (radius-1 neighbor count), R2 (radius-2 neighbor count). Interactions were indicated by combining terms, for instance, the interaction between FV and NF is denoted by FVNF.

TABLE I. MATRIX CHARACTERISTICS

Matrix	FV	NF
Nug15	Highly variable	Many, very similar
Global All	Moderately Variable	Many, all equal
Local Flow 1	Low, similar	Few, similar
Local Flow 2	Low, very similar	Few, very similar
Ordered	Highly variable	Few, variable

1) Highly-ordered flows

The network representation of this matrix is seen in Fig. 4. Each node in the graph stands for a department, and each arc for an interaction between departments.

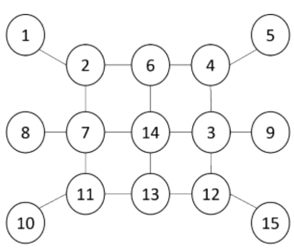


Fig. 4. Highly ordered flows

This matrix was expected to perform well with the rectangular shape, as it seems to fall naturally into that arrangement, and it did. But it also produced several non-rectangular shapes that were equally good. These shapes are shown in Fig. 5.

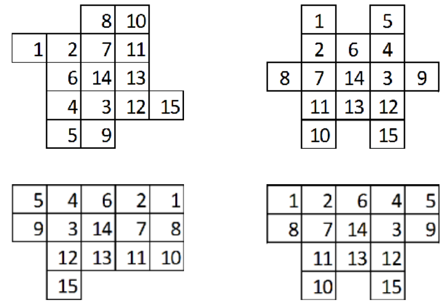


Fig. 5. Non-rectangular optimal solutions for highly-ordered flows

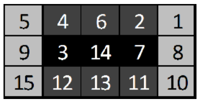
In this instance, the operational metrics correlated with the spatial metrics, as can be seen in Fig. 6. The figure also contains the combination of operational and spatial factors that resulted in the highest correlation and R2 values. For such a well-ordered operation, the most significant operational factor is the number of flows that each department has. In the spatial dimension, it is the immediate neighborhood structure of the locations that has the most effect. Intuitively this makes sense; a department will seek locations where it has enough room to accommodate its immediate neighbors.

These results also make clear the role that facility shape can have, not only in terms of affecting the optimal value, but also in terms of department placement. It seems that certain shapes (with their corresponding distribution of depth and local neighborhood structures) force departments into placements that they would not necessarily favor in the absence of the shape constraint. In this instance, the circular shape of the facility does this, so that the correspondence between operational and spatial metrics is altered significantly, as is seen in the lower R2 value. Fig. 6 shows the best solutions found for each facility shape, together with the map of the spatial metric that performed best. For the optimal solution maps, the departments were ranked by NF, where a darker shade represents a better placement in the ranking. For the rectangular shape, the spatial map corresponds to the location depths, while for the other two cases it corresponds to the R1 value of each location, with a darker shade representing the better values (lower for depth, higher for R1). In a), we observe that the ranking matches well with the depth distribution (the top ranked departments all fall into the locations with the lowest depth), and in e) it matches perfectly. For the circular shape, however, we observe a noticeable mismatch, indicating that the facility shape disrupts the natural arrangement of the departments.

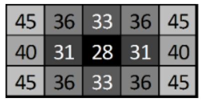
2) Global flows

Two instances of globalized flows were evaluated. The first instance is the Nug15 problem, the second instance was generated by randomly assigning flow values among the departments. The network representation of these two matrices can be seen in Fig. 7.

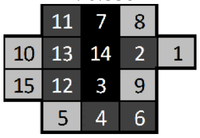
In both cases, the best solutions that were found had the depth-minimizing shape. The results are summarized in Fig. 8. For the Global All instance, given that the NF across departments is equal, the determining factor from an operational point of view is FV alone. For the Nug15 case, there is enough variation in NF so that the interaction between both operational metrics becomes the most significant factor. In terms of the spatial factors, it makes sense that depth should be the most significant, given that it captures very neatly the behavior of the departments, which interact with every, or almost every, other department.



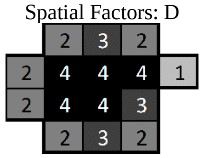
a) Optimal solution
Optimal value: 94
R^2: 0.8867



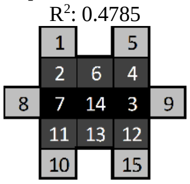
b) Depth map
Operational factors: NF
Spatial Factors: D



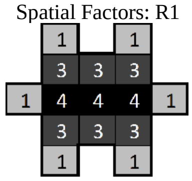
c) Optimal solution
Optimal value: 102
R^2: 0.4785



d) R1 map
Operational Factors: NF
Spatial Factors: R1



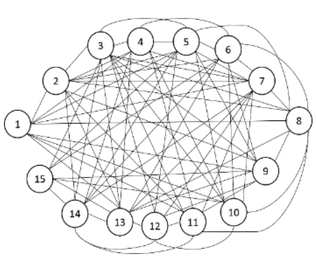
e) Optimal solution
Optimal value: 94
R^2: 1.0000



f) R1 map
Operational Factors: NF
Spatial Factors: R1

Fig. 6. Best solutions with corresponding spatial maps (NF = number of flows, R1= radius-1 neighbor count)

For the rectangular shape in the Global all instance, however, R1 outweighs depth. We believe that the rectangular facility, by having more differentiated depth values, especially in the central part of the facility, ends up forcing the departments to arrange themselves with respect to their location's neighborhood structure. Since all departments have equal NF, the ones with higher FV seek to locate themselves in areas with more neighbors, so as to maximize their direct access to other departments.


a) Nug15

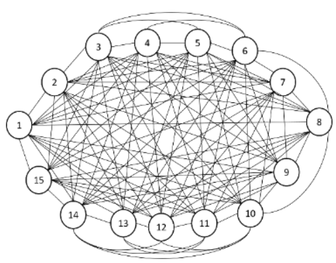
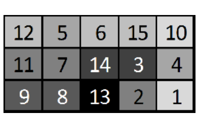
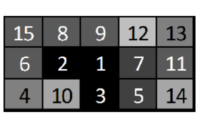

b) Global all

Fig. 7. Global flow matrices

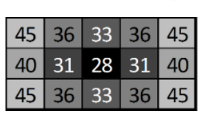
The optimal solutions with depth maps, are shown in Fig. 8.



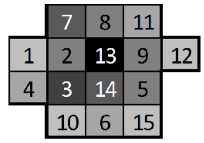
a) Nug15
Optimal value: 575
Operational factors: FVNF
Spatial factors: D
R^2: 0.3949



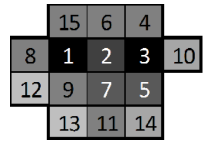
b) Global all
Optimal value: 1309
Operational factors: FV
Spatial factors: R1
R^2: 0.5639



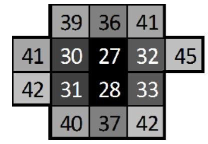
c) Depth map



d) Nug15
Optimal value: 568
Operational factors: FVNF
Spatial factors: D
R^2: 0.7121



e) Global all
Optimal value: 1263
Operational factors: FV
Spatial factors: D
R^2: 0.7306

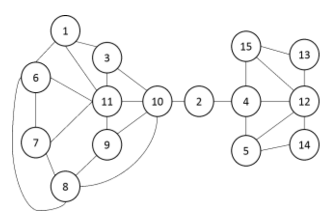


f) Depth map

Fig. 8. Globalized flow solutions and depth maps (FV = flow volume, FVNF = interaction between flow volume and number of flows, D = depth, R1= radius-1 neighbor count)

3) Local flows

The two last flow matrices analyzed are local flow matrices. In these, each department interacts with only a few other departments, forming small functional groups. The first instance has two functional groups, and the second one, three. The network representation of these two matrices is found in Fig. 9.


a) Local flow 1 (two groups)

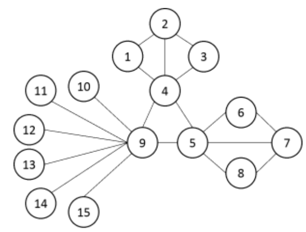

b) Local flow 2 (three groups)

Fig. 9. Local flow matrices

The free-form in both instances reached the lowest value of the objective function. However, for the first instance, so did the rectangular shape. The circular shape, in both cases, failed to reach the lowest objective value. In terms of the mapping between operational factors and spatial factors, we had the lowest performance overall. Even the free-form had relatively low values of R2. The summary of these results is presented in Table II.

TABLE II. LOCALIZED FLOW RESULTS

Instance	Shape	Optimal Value	Operational Factors	Spatial Factors[a]	R^2
2 group	Rectangle	160	FV	DR1R2	0.4478
	Circle	171	FVNF	R1R2	0.1831
	Free Form	160	FVNF	R1	0.5776
3 group	Rectangle	56	NF	R1	0.3924
	Circle	56	NF	R1R2	0.5057
	Free Form	54	NF	R1	0.2776

a. FV = flow volume, NF = number of flows, FVNF = interaction between flow volume and number of flows, R1 = radius-1 neighbor count, R2 = radius-2 neighbor count, R1R2 = interaction between neighbor counts, DR1R2 = interaction between depth and radius-1, radius-2 neighbor counts

These results show that, in most cases, the local spatial metrics are the most influential in determining the final placement of the departments. This stands in contrast with the globalized matrices where the predominant spatial metric is global depth. Even then, though, their effect seems to be relatively low. Why the poor performance? If we look more closely at the placement of departments in the optimal solutions, we notice immediately that the functional groups have arranged themselves in clusters. See Fig. 10 for some examples.

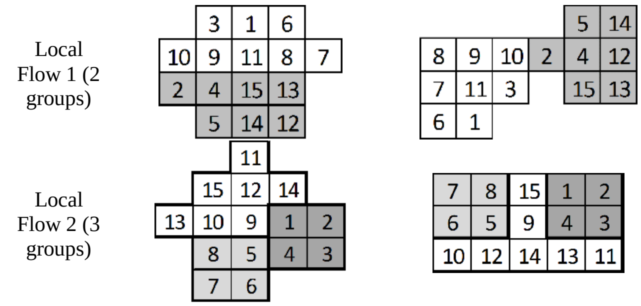


Fig. 10. Functional group clustering

The reason behind the poor correspondence between the operational and the spatial metrics is that department placement in these instances is governed by the spatial traits of the locations within each cluster, not by those of the overall facility. Any interaction with the rest of the facility takes place in the connection point with other clusters. Consider the facilities in Fig. 11. The optimal function value is the same for all three. The department placement is essentially the same within each cluster and the connection between clusters takes place between departments 2 and 10.

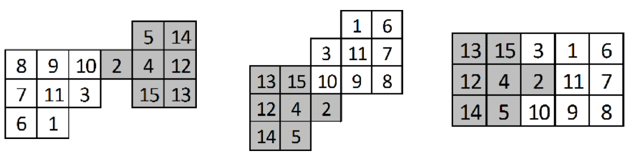
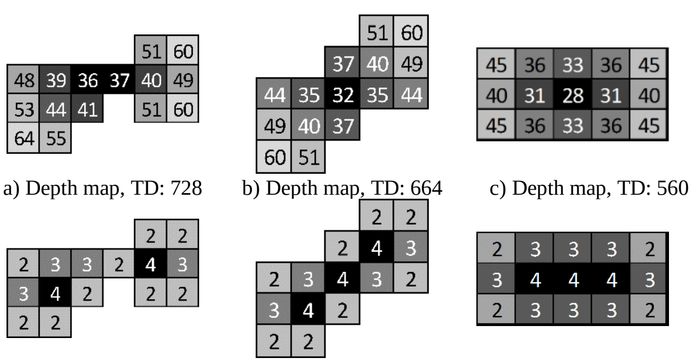


Fig. 11. Different cluster arrangements (Local Flow 1 – 2 groups). Objective function value = 160 for all shapes.

The only difference among the layouts is the orientation of the second cluster around the connection point. This small difference has a noticeable impact on the spatial metrics of the overall facility, as can be seen in Fig. 12.

This is a telling example of how sensitive spatial metrics can be and explains why there is not a strong correlation among the spatial and operational metrics when considering the entire facility. It is also worthy of note that with this specific flow matrix (Local flow 1 - 2 groups) the clusters can fit in a rectangular facility without any negative effect on the optimal value.

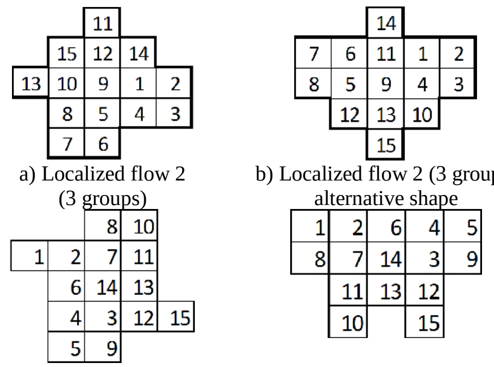


a) Depth map, TD: 728 b) Depth map, TD: 664 c) Depth map, TD: 560

d) R1 map e) R1 map f) R1 map

Fig. 12. Differences in spatial metrics (Local Flow 1 – 2 groups) Objective function value = 160 for all shapes

These results also reveal the importance of local processes in shaping a facility's layout. An advantage of local behaviors is that they allow greater freedom in terms of facility shape. Globalized flows lead to a single, distance minimizing form. Localized flows, on the other hand, produce a variety of distance minimizing forms. Even when combined with other more globalized flows, the parts of the facility that have localized flows can arrange themselves in different shapes, without affecting the quality of the solution. Consider the various optimal free-forms generated for the localized flow matrices and the well-ordered matrix (which had several local flows) in Figs. 5 and 13.



a) Localized flow 2 (3 groups) b) Localized flow 2 (3 groups) alternative shape

c) Highly-ordered d) Highly-ordered alternative shape

Fig. 13. Localized flow facility shapes for Local Flow 2 (3 groups) and Well-Ordered

If we look at the relationship between spatial and operational metrics within the clusters for Localized Flow 1 (2 groups), we obtain the results shown in Table III.

TABLE III. IN-CLUSTER RESULTS

Facility Shape	Cluster	Operational factors	Spatial factors	R^2
Rectangle	1	NF	R2	0.5704
	2	NF	R1R2	0.9557
Circle	1	NF	R2	0.3451
	2	NF	DR1	0.1281
Free-form	1	NF	DR2	0.4897
	2	NF	R1R2	0.9557

[b] FV = flow volume, NF = number of flows, FVNF = interaction between FV and NF, R1 = radius-1 neighbor count, R2 = radius-2 neighbor count, R1R2 = interaction between radius-1 and radius-2 neighbor counts

C. *Experiment 3: Effects of different objective functions on facility shape*

The two previous experiments revealed that the travel distance minimization objective favors certain shapes depending on the flow matrix. The last experiment sought to find whether different objective functions produce different shapes. Two alternative objective functions and their resulting effects on facility shape were tested. These were maximization of visibility and contact with the outside. The former is important for many practical reasons that vary from setting to setting, e.g., to respond promptly to the needs of their patients, nurses need to be able to see that they are in need; to guard valuable art pieces in a museum, security guards must have visual access to them. The more a facility's surface is in contact with the exterior, the more windows/doors can be installed that allow access of natural light. Natural light has psychological benefits that should not be disregarded, especially in medical settings.

Facility visibility is calculated by summing the visibility of each location over all the locations in the facility. For each location, we project straight visibility lines in every direction. Any location that falls along one of the visibility lines is counted as visible. Fig. 14 shows the visibility line method used to calculate visibility, together with the visibility polygon that it approximates. All the shaded locations are visible from the source location. This process is repeated for every other location in the facility. This is a simplistic measure of visibility, as the addition of walls and other visual obstructions will affect it, however, it captures the visibility potential that a facility can have due to its shape.

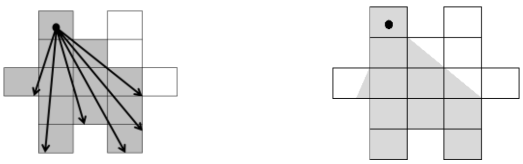


Fig. 14. Location visibility

Contact with the exterior of the facility is calculated by summing the access to the exterior of each location. For each location, we sum the number of sides where there is no neighboring location (see Fig. 15).

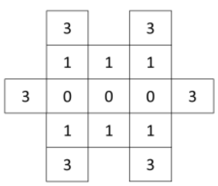


Fig. 15. Access to the outside

To generate the different facility shapes, a constructive greedy heuristic algorithm was used. It offers a quick and easy method for generating good solutions for the purposes of this paper. The algorithm progresses by adding new locations to the current facility sequentially until the desired number of locations have been placed. New locations must be adjacent to at least one of the previously added locations. At each iteration, a list of possible placements for the next location is generated. The change in the objective function that would result from each placement is calculated and then the placements are sorted from best to worst. The best placement is selected (if there are more than one best, one is selected randomly). The multi-objective version of the algorithm cycles through the objectives in a predetermined sequence. Each new placement is determined by the objective function that is being optimized at that iteration. Using this algorithm, a variety of function maximizing shapes were generated, some of which are shown in Fig. 16.

Some general principles can be deduced from these results. In the case of visibility, any convex shape, however irregular it may be, will represent a good facility shape. With respect to contact with the outside, those shapes that maximize it will tend to have thin, elongated “branches”, such as the ones seen in e) and g); they might also develop “courtyards”, as seen in f) and g); or they might just be composed of long sequences of single file locations (not necessarily in a straight line).

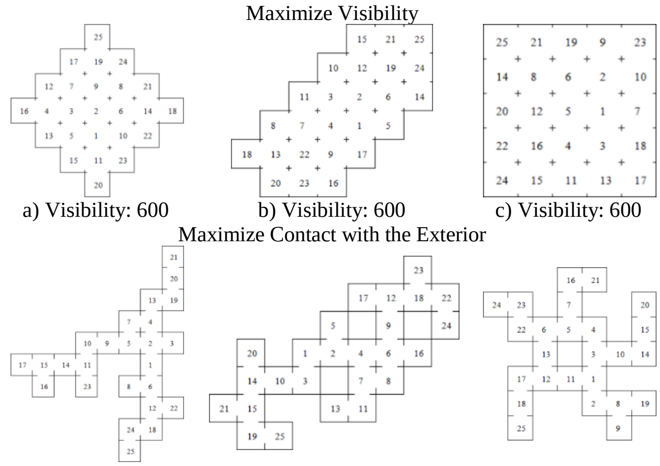


Fig. 16. Single objective maximizing shapes (numbers indicate placement order)

An interesting case is that of a straight sequence of locations, such as the one seen in Fig. 17. This facility shape maximizes both visibility and contact with the outside simultaneously.

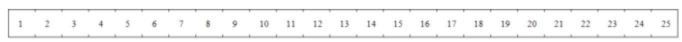


Fig. 17. Straight sequence of departments, visibility: 600, CWE: 52

IV. Conclusions

In this paper, a framework for analyzing the relationship between function and form in facility layout design using principles from Space Syntax was proposed. It was found that facility shape can have a significant impact on the value of the objective function. Another finding was that there are important correlations among the operational characteristics of a department and the spatial characteristics of its final location within the facility. Different structures in the flow matrix (different operational patterns) manifest themselves spatially in different facility shapes. Lastly, the role of the objective function in generating facility shapes was studied. The shaped produced by three different objective functions were analyzed. The framework that Space Syntax offers for spatial analysis represents a valuable tool for gaining a deeper insight into the way operations relate to the organization of space. Both the Space Syntax literature and the facility layout literature can mutually benefit from the application of these principles to engineering design problems.

This work represents a first step in the right direction and that further, more detailed, studies into the relationship between function and form are needed to invigorate the field of facility layout design.

References

[1] T. Arnold, “The Use of Space Syntax Methodology to Design an Architecture of Visual Relations,” Journal of Space Syntax, vol. 2, no. 2, pp. 201–222, 2011.

[2] R. E. Burkard, S. Karisch, and F. Rendl, "QAPLIB-A quadratic assignment problem library," European Journal of Operational Research, vol. 55, no. 1, pp. 115–119, 1991.

[3] J. Chung and J. Tanchoco, "Layout design with hexagonal floor plans and material flow patterns," International Journal of Production Research, vol. 48, no. 12, pp. 3407–3428, 2010.

[4] H. Dalke, J. Little, E. Niemann, N. Camgoz, G. Steadman, S. Hill and L. Stott, "Colour and lighting in hospital design," Optics & Laser Technology, vol. 38, no. 4–6, pp. 343–365, 2006.

[5] B. Hillier, Space Is the Machine: A Configurational Theory of Architecture. Cambridge University Press, 1998.

[6] B. Hillier and J. Hanson, The Social Logic of Space. Bell & Bain, 1993.

[7] B. Hillier, J. Hanson, and H. Graham, "Ideas are in things - an application of the Space Syntax method to discovering house genotypes," Environment & Planing B: Planning & Design, vol. 14, no. 4, pp. 363–385, 1987.

[8] R. V. Johnson, "Finding building shapes that minimize mean trip times," Computer-Aided Design, vol. 24, no. 2, pp. 105–113, 1992.

[9] D. Leaf, P. Homel, and P. Factor, "Relationship between ICU design and mortality.," CHEST, vol. 137, no. 5, pp. 1022–1027, 2010.

[10] C. E. Nugent, T. E. Vollmann, and J. Ruml, "An experimental comparison of techniques for the assignment of facilities to locations," Operations Research, vol. 16, no. 1, pp. 150–173, 1968.

[11] A. Penn, "Space syntax and spatial cognition or why the axial line?," Environment and Behavior, vol. 35, no. 1, pp. 30–65, 2003.

[12] J. Peponis and J. Wineman, "On the description of shape and spatial configuration inside buildings: Convex partitions and their local properties," Environment & Planning B: Planning & Design, vol. 24, no. 5, p. 761, 1997.

[13] J. A. Tompkins, Facilities planning. J. Wiley, 2003.

[14] R. S. Ulrich et al., "A review of the research literature on evidence-based healthcare design," HERD Health Environments Research & Design Journal, vol. 1, no. 3, pp. 61–125, 2008.

[15] T. E. Vollmann and E. S. Buffa, "The facilities layout problem in perspective," Management Science, vol. 12, no. 10, p. B-450–B-468, 1966.

APPENDIX. TABU SEARCH ALGORITHM FOR RECTANGULAR AND NON-RECTANGULAR QAP

The algorithm was run with 25 different initial solutions for each flow matrix/facility shape combination. About half of these solutions were generated randomly at the beginning of each run, and the remaining ones were seeded from the initial solutions used in [10].

A. Solution encoding

Layouts were encoded as arrays. The value j at index i, means that department j is placed in location i. The locations are numbered from left-to-right and top-to-bottom. For the cases in which the facility's shape is determined beforehand, the number of locations and the number of departments is equal ($m = n$). The encoded array, then, is a permutation of n departments. For the cases without any shape constraint, there are many more available locations than departments ($m > n$). In the array, locations where there are no departments have the value zero. For the 15 department instances presented in this paper, an array with 40 possible locations, such as the one shown in Fig. 18 was used.

For the free forms, each new facility required the generation of a new distance matrix corresponding to its shape. These matrices were constructed so as not to allow travel through zero-valued locations. Once the matrix was generated, evaluation of the objective function proceeded as with the fixed shape cases.

B. Neighborhood structure

The neighborhood was generated using a full-neighborhood, deterministic procedure based on a two-way swap between the departments located j locations apart. That is, the department in location i is swapped with the department in location $i + j$, for $i = 1,2, \ldots, m-1$ and $j = 1,2, \ldots, m-1$, where m is the number of locations. We prohibited swaps between locations where both values were zero, so that only swaps that included at least one department were allowed.

C. Parameter configuration

The parameter configuration was chosen based on previous testing with the QAP. The search stops after a maximum of 5000 iterations or 1500 iterations without improvement. A fixed tabu list of size 20 was used, together with a frequency-based list for increased diversification of the solutions being explored.

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

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

Fig. 18. Solution encoding