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Comparison Examination of Building Shape for Multi-Floor Factory using Genetic Algorithm

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Abstract: At present, because of diverse user needs, types and construction of products tend to be fractionated and complicated. Material handling costs at large-scale production facilities, regarded as an important factor, are said to account for about 15%–75% of all factory costs. Therefore, to achieve higher efficiency and lower production costs, conventional single floor buildings are being replaced by multi-floor buildings. Recently, when a new factory is designed, a few circular buildings are included in addition to rectangular buildings, which are still used frequently. Nevertheless, little development of multi-floor layouts has occurred for circular buildings. As the number of work sites at factories increase, the number of combinations of work sites (factory layout designs) is expected to increase exponentially. Therefore, a longer time is necessary for precise solutions using mathematical programming. Finding an optimal solution within a realistic calculating time is difficult. Therefore, to obtain a nearly optimal layout that approximates the best solution with high accuracy, some optimization method (meta-heuristic) must be used. For this study, a technique to produce a layout for a rectangular building and a circular building for a multi-floor factory using genetic algorithms (GAs) is used as one optimization method. The building shape is then subjected to comparative examination. Productivity values obtained according to the building shape, as calculated by the total material handling costs between work sites, are compared using numerical experiments to clarify the effectiveness of layout techniques for rectangular buildings and circular buildings.

Keywords: Circular building, Factory layout issue, Genetic algorithm, Multi-floor factory, Rectangular building

1. Introduction

Because of diverse user needs, types and construction methods of products are fractionated and complicated. To accommodate those needs, production facilities are built on a large scale. The overseas production ratio of Japanese manufacturing in 2018 was 25.4%. The overseas facility capital investment ratio was 40.9%, which has remained mostly level in these several years, although the possibility exists of their increase in the coming years. Regarding factory layout issues, minimization of material handling costs, waiting times, and lead times have been generally described in the literature (Anjos and Vieira, 2017). Of those, material handling costs are considered important, representing about 15%–75% of total factory costs (Tompkins, White, Bozer, and Tanchoco, 2010). Therefore, from viewpoints of higher efficiency and lower costs of production, conventional single floor buildings have been replaced by multi-floor buildings.

For factory layout issues such as the arrangement of work sites, machinery and facilities, many studies have been reported: the model by van Camp, Carter, and Vannelli (1992) has nonlinear restrictions of work site areas; the model by Sherali, Fraticelli, and Meller (2003) has linear restrictions. Moreover, column layouts and multi-floor layouts have been examined in several studies (Anjos and Vieira, 2017; Irohara, Fujikawa, and Shirai, 2007; Kusiak and Heragu, 1987; Sherali et al., 2003; Tompkins et al., 2010; van Camp et al., 1992). When a factory is newly designed, in addition to frequently used conventional rectangular buildings, circular buildings have become more common in recent years, although they remain small in number (Volkswagen factory; Volkswagen Interactive). Nevertheless, development of multi-floor layout techniques for circular buildings has only slightly progressed.

Factory layout is known as a non-deterministic polynomial (NP) hard problem (Anjos and Vieira, 2017). As the number of work sites increases in a factory, the number of combinations of work sites (factory layout ideas) increases in exponential fashion. Using rigorous calculations using mathematical programming, such problems take a longer time for calculations. It is difficult to obtain an optimum solution within any practical time frame. To obtain a layout idea representing a high accuracy approximate solution or best solution that is close to the optimum solution within a practical calculating time, some optimization method (meta-heuristic) must be used.

Various methods are applicable to meta-heuristic including genetic algorithms (GAs) and advanced algorithms, (Goldberg, 1989; Munakata, 2008), evolutionary strategy (Munakata, 2008), ant colony optimization (Dorigo and Stutzle

2004) using swarm intelligence, particle assemblage optimization (Clerc, 2006), differential evolution (Price, Storn, and Lampinen, 2005), tabu search (Glover and Laguna, 1977), and simulated annealing (van Laarhoven and Aarts, 1987). Of those, if the random nature of GA is incorporated into the solution method, then a wide range of applications can be maintained as the solution method. One can design a peculiar shape for every problem for composition of a solution and computational procedures. This ensures an efficient search for a solution.

Therefore, for this study, comparative examination of building shape is applied to assess layout techniques of rectangular buildings and circular buildings in a multi-floor factory using a GA as one optimization method. Productivity, as assessed by total material handling costs between work sites, associated with the buildings is compared using numerical experiments to identify the effectiveness of layout techniques for rectangular and circular buildings.

2. Factory Layout Problem

2.1 Setting of the problem

Basic conditions of the factory layout problem examined for this study are set as follows: a multi-floor building is considered. For a rectangular building, one passage (main passage) is set at the center. One passage (sub-passage) is set at each end. The aspect ratio of each work site is variable. For a circular building, a circular passage is set as internally connected in a torus-shaped arrangement area such that each work site is produced by cutting the torus shape by radial rays. One elevator is installed at each end of a rectangular building. Two elevators are provided at a center vacant area for the circular building.

2.2 Formulation

For these two types of factory layouts including rectangular and circular buildings, for minimization of total material handling costs between work sites, the following equations are established.

$$\text{min.} \quad f = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} \, (d_{ij} + e_{ij}) \quad (i \neq j) \tag{1}$$

$$\text{subject to} \quad a_{ij} = 0 \quad (i = 1, 2, \ldots, n-1; \quad j = i+1, \ldots, n) \tag{2}$$

$$b_i = 0 \quad (i = 1, 2, \ldots, n) \tag{3}$$

$$e_{ij} = p_{iE_k} + p_{E_k j} + h \times |l_i - l_j| \quad (i, j = 1, 2, \ldots, n; \quad i \neq j) \tag{4}$$

For those equations, the following variables are used.

- n: Number of work sites
- c_{ij} : Cost of movement from work site *i* to *j*
- d_{ij} : Distance from work site *i* to *j* when both are arranged on the same floor (Manhattan distance)
- e_{ij} : Distance from work site *i* to *j* through the nearest elevator when work site *i* and *j* are arranged on the different floor (Manhattan distance)
- a_{ij} : Overlapping area of work site *i* and *j*
- b_i : Area of protrusion of work site *i* from the arrangement area
- p_{iE_k} : Distance from work site *i* to nearest elevator E_k
- h: Floor height
- l_i, l_j : Floor on which work site *i*, *j* are arranged

When target two work sites are arranged on the same floor, for a rectangular building, Manhattan distance from gravity center to the center line of the passage is considered. For circular buildings, the passage portion is a circular arc, whereas the description given above is followed. When two target work sites are arranged on the different floor, from the gravity center of the target work site, passage through the passage and the nearest elevator (floor height is added) and passage from that elevator to the gravity center of another work site is considered.

3. Layout Technique for this Study

3.1 Expression of rectangular building layout

For expression of the rectangular building layout, a flexible multi-floor structure (FMS) is used [6]. Using this method, the main passage divides the building into an upper part and a lower part; work sites are arranged one-by-one to each part. Each work site area is set so that it increases/decreases by ±10% of the standard area as the area rate of change and the arrangement possible area of each floor is therefore adjusted. The aspect ratio of the work site is variable. The work site number of [permutation] shows the order of alignment sequence of the work site (generated randomly) whereas the lower left on the first floor is used as the base. [Breakpoint 1] shows that the work site immediately before the main passage enters at each floor and is located at what number. [Breakpoint 2] shows that the work site immediately before the floor is changed and is located at what number. [Breakpoint 1] and [Breakpoint 2] are determined by the order of [permutation] work site, area rate of change of each work site, and adjustment of the area on each floor where arrangement is possible. Figure 1 shows a case of two stories rectangular building with 20 work sites arranged.

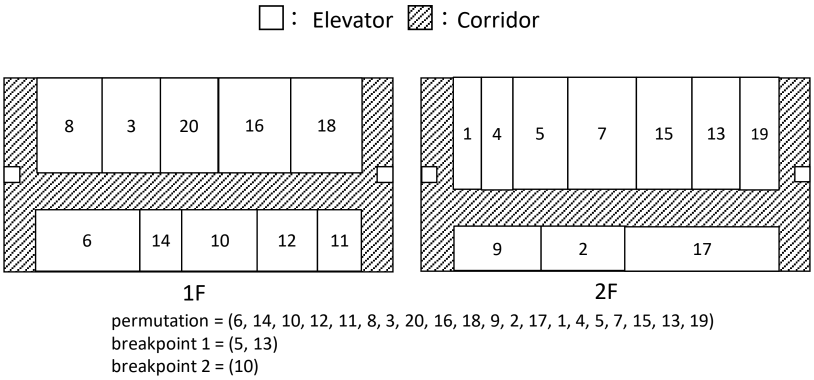

Fig. 1 Best layout of two stories rectangular building in which 20 work sites are arranged

3.2 Expression technique for the circular building layout

As the expression technique used for the circular building layout, work sites are arranged counterclockwise from 0 degrees according to the order of [permutation] work site number (generated randomly) while the passage provided in the arrangement area is referenced. [Breakpoint 2] shows that the work site immediately before the floor level is changed and is located at what number similarly to the information for the rectangular building. Figure 2 presents an example of 20 work sites on two stories in a circular building. With a circular building, area rate of change of the work site is not set, although possible arrangement areas are adjusted at each floor using surplus space. (In Fig. 2, the space between work site 7 and work site 17 are arranged on the first floor (shaded area) and space between work site 16 and work site 5 arranged on the second floor (shaded area)). [breakpoint 2] is determined by the order of [permutation] work site and adjustment of arrangement possible area at each floor. With a circular building, each floor need not be split into upper and lower halves. Therefore, [breakpoint 1] is unnecessary.

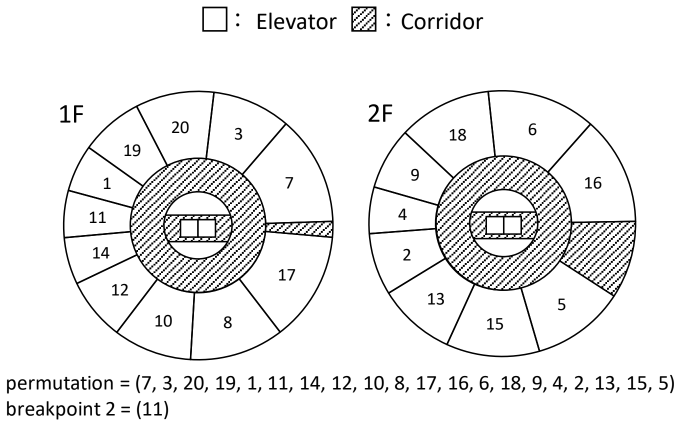

Fig. 2 Best layout of two stories with 20 work sites in a circular building

3.3 Technique using GA

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A technique following genetic processes, GA is used as a combination optimization method. By repeating genetic operation [selection], [crossover] and [mutation] (generation change) for individuals (solution candidates), an individual suited for the environment can be generated. For this study, in the layout expression technique, for a rectangular building and circular building layout explained in section 3.1 and section 3.2, the elite conservation option and roulette option are applied to [selection], which is genetic operation of GA. For crossover, Uniform Crossover (UX) is applied to the work site number of [permutation,], as for [mutation], translocation (gene at two locations selected randomly are permutated) is applied to the work site number to obtain the best solution (best layout).

4. Numerical Experiments

4.1 Conditions of numerical experiments

For conditions of numerical experiments, the number of stories and number of work sites were set with the following parameters: [two stories, 20 work sites], [three stories, 30 work sites] and [five stories, 50 work sites]; with standard external dimensions of rectangular buildings are 25 × 60 [m]; road width of 5 [m]; radius of standard external dimensions of circular building as 22 [m]; radius of internal diameter of 12 [m]; and road width set to 5 [m]. The floor height is 5 [m] for both buildings. The GA parameters are the following: 30 population size, 200 generations, 0.6 crossover rate, and 0.1 mutation rate. A trial run was performed 50 times. The best result was selected as the best solution (best layout).

4.2 Results of comparisons between rectangular building and circular building layouts

Results of numerical experiments under conditions shown in section 4.1 (minimum value, maximum value, average value and standard deviation of total material handling costs) are presented in Table 1. The best layout for two stories and 20 work sites obtained by numerical experiments is presented in Fig. 1 (rectangular building) and Fig. 2 (circular building). The best layout of three stories and 30 work sites is depicted in Fig. 3 ((a) rectangular building, (b) circular building). That for five stories and 50 work sites is portrayed in Fig. 4 ((a) rectangular building, (b) circular building). Numerals in the figure show the work site number. Diagonal lines denote passages. A square on the passage denotes an elevator.

In Table 1, comparison of the minimum value of total material handling costs of both shapes reveals that those of rectangular building are smaller for two stories and 20 work sites. Those of a circular building are smaller for three stories and 30 work sites and five stories and 50 work sites. The same might be said for the average of total material handling costs. For the standard deviation of total material handling costs, it is known that scattering occurs less with circular buildings for all cases.

From these results, one can consider that if the number of stories and number of work sites increase, the circular building productivity is probably higher than that of a rectangular building. Factory productivity is known to depend not only on the building shape, but also on the number of stories and number of work sites. For rectangular buildings, the area rate of change of the work site is set, with arrangement of possible areas of each floor adjusted. For circular buildings, the area rate of change of the work site is not set, but arrangement of work sites is made using the standard area. Arrangements of possible areas of each floor are then adjusted using surplus space. It is therefore considered that results of each numerical experiment might differ depending on differences of concepts of both buildings. Accordingly, the area rate of change of work sites for circular buildings should be added. Extensive numerical experiments should be conducted while changing the number of stories and the number of work sites.

Table 1 Comparison of layouts of rectangular and circular buildings

Number of Floors	Number of Departments	Building Shape	Minimum Value	Maximum Value	Average Value	Standard Deviation
2	20	Rectangle	49277.57	51698.25	50410.97	646.31
		Circular Shape	50529.50	51670.44	50800.12	184.94
3	30	Rectangle	132050.31	135929.69	133508.91	775.56
		Circular Shape	131104.35	133207.26	132071.91	457.34
5	50	Rectangle	430044.14	442123.74	435721.89	2730.15
		Circular Shape	415684.34	424409.76	419795.44	1820.06

5. Conclusions

For layout design of rectangular and circular buildings in multi-floor buildings using GA, our optimization method, the building shape is subjected to comparative examination by numerical experiments. Results of numerical experiments revealed that total material handling costs of circular building are lower than those of rectangular buildings if the number of stories and the number of work sites are increased. Factory productivity is shown to be dependent not only on the building shape but also on numbers of stories and work sites. Future studies should be conducted to assess the area rate of change of work sites with regard to circular buildings, setting of building parameters such as the number of stories and of work sites, and optimum elevator and column positions.

6. References

Anjos, M.F. and Vieira, M.V.C. (2017). Mathematical Optimization Approaches for Facility Layout Problems: The State-of-the-art and Future Research Directions. *European Journal of Operational Research*, 2017; 261(1): 1-16.

Clerc, M. (2006). *Particle Swarm Optimization*, Wiley-ISTE.

Dorigo, M. and Stutzle, T. (2004). *Ant Colony Optimization*, The MIT Press.

Glover, F.W., and Laguna, M. (1997). *Tabu Search*, Springer.

Goldberg, D.E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Publishing Company.

Irohara, T., Fujikawa, H., and Shirai, Y. (2007). Multi-floor Facility Layout Problem Considering Initial and Running Cost Simultaneously. *Journal of Japan Society of Logistics Systems*, 2007; 7(1): 67-78.

Kusiak, A. and Heragu, S.S (1987). The Facility Layout Problem. *European Journal of Operational Research*, 1987; 29(3): 229-251.

Munakata, T. (2008). *Fundamentals of the New Artificial Intelligence: Neural, Evolutionary, Fuzzy and More*. Springer.

Price, K., Storn, R.M., and Lampinen, J.A. (2005). *Differential Evolution: A Practical Approach to Global Optimization*, Springer.

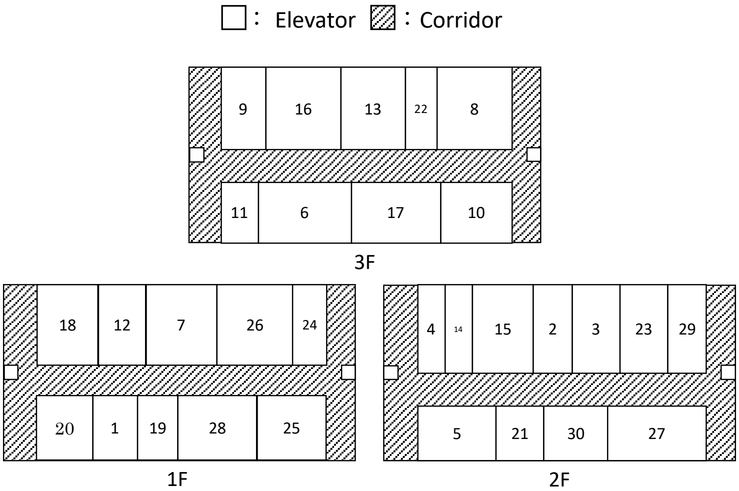
Sherali, H.D., Fraticelli, B.M.P., and Meller, R.D. (2003). Enhanced Model Formulations for Optimal Facility Layout. *Operations Research*, 2003; 51(4): 509-679.

Tompkins, J.A., White, J.A., Bozer, Y.A., and Tanchoco, J.M.A. (2010). *Facilities Planning, Fourth Edition*. Wiley.

van Camp, D.J., Carter, M.W., and Vannelli, A. (1992). A Nonlinear Optimization Approach for Solving Facility Layout Problems. *European Journal of Operational Research*, 1992; 57(2): 174-189.

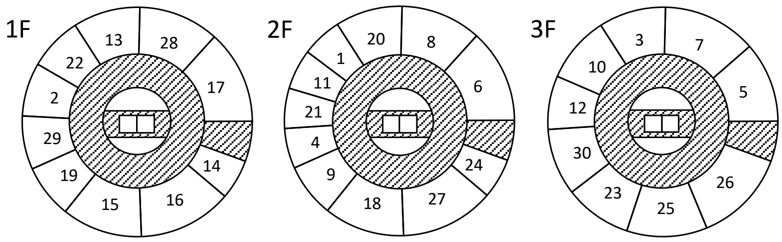
van Laarhoven, P.J.M., and Aarts, E.H.L. (1987). *Simulated Annealing: Theory and Applications*, Springer Netherlands.

Volkswagen Interactive. https://www.volkswagen-newsroom.com/en/volkswagen-sachsen-gmbh-the-transparent-factory-dresden-5906.



permutation = (20, 1, 19, 28, 25, 18, 12, 7, 26, 24, 5, 21, 30, 27, 4, 14, 15, 2, 3, 23, 29, 11, 6, 17, 10, 9, 16, 13, 22, 8)
breakpoint 1 = (5, 14, 25)
breakpoint 2 = (10, 21)

(a) Rectangular building layout

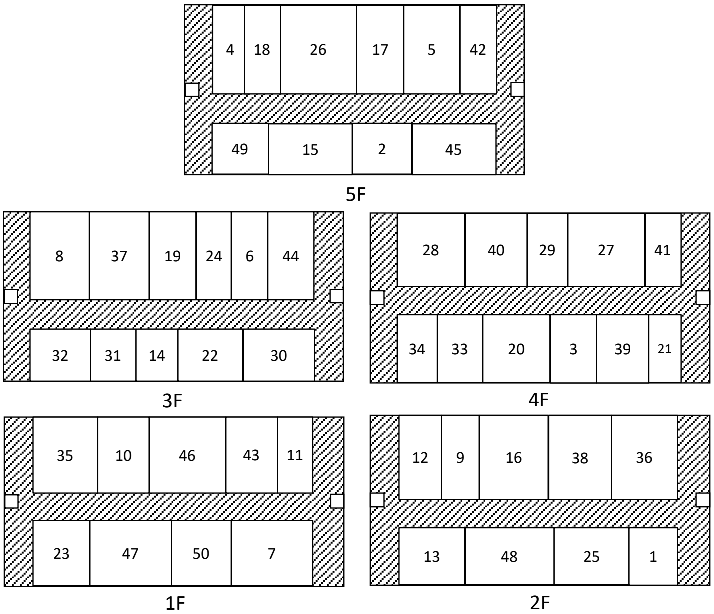


permutation = (17, 28, 13, 22, 2, 29, 19, 15, 16, 14, 6, 8, 20, 1, 11, 21, 4, 9, 18, 27, 24, 5, 7, 3, 10, 12, 30, 23, 25, 26)
breakpoint 2 = (10, 21)

(b) Circular building layout

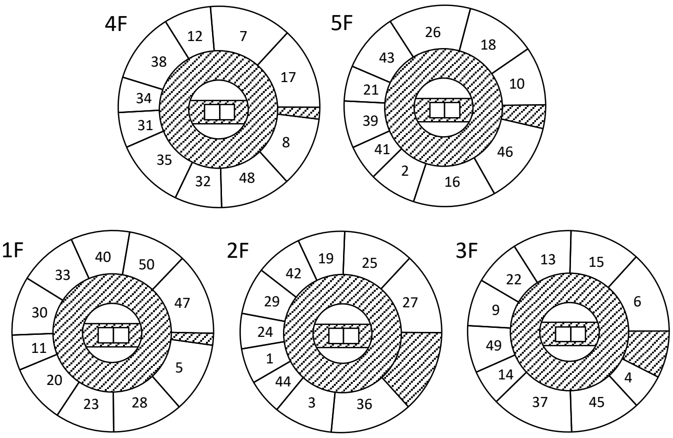
Figure. 3 Best layout for three stories and 30 work sites

☐ : Elevator ▨ : Corridor



permutation = (23, 47, 50, 7, 35, 10, 46, 43, 11, 13, 48, 25, 1, 12, 9, 16, 38, 36, 32, 31, 14, 22, 30, 8, 37, 19, 24, 6, 44, 34, 33, 20, 3, 39, 21, 28, 40, 29, 27, 41, 49, 15, 2, 45, 4, 18, 26, 17, 5, 42)
breakpoint 1 = (4, 13, 23, 35, 44)
breakpoint 2 = (9, 18, 29, 40)

(a) Rectangular building layout



permutation = (47, 50, 40, 33, 30, 11, 20, 23, 28, 5, 27, 25, 19, 42, 29, 24, 1, 44, 3, 36, 6, 15, 13, 22, 9, 49, 14, 37, 45, 4, 17, 7, 12, 38, 34, 31, 35, 32, 48, 8, 10, 18, 26, 43, 21, 39, 41, 2, 16, 46)
breakpoint 2 = (10, 20, 30, 40)

(b) Circular building layout

Figure. 4 Best layout for five stories and 50 work sites