A Study of the Effects of Multi-level Layouts on Quality

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ABSTRACT

Layout has been commonly studied as a single-level problem. Even though single-level layouts are common, locations where land is expensive, multi-level layouts are still practical. Also, because of several existing multi-level layouts, the redesign of multi-level layouts is of considerable interests to manufacturers. Very few researchers have studied the multi-level layout problem. Researchers who have studied the multi-level layout problem have often considered quantitative criteria such as minimizing cost of material handling. In this research, we develop propositions related to quality based on Juran's framework. In addition, we study the effects of multi-level layouts on quality.

Keywords: Layout, Multi-level, Single level, Quality, Measures

1. Introduction

Facility layout is concerned with allocating limited building spaces to departments to optimize certain criteria (such as cost of material handling), given information such as the flows between departments, the required department sizes, and the building size and shape. While most manual or computerized procedures deal with the facility layout in a single-level structure, new procedures have been developed for multi-level structures. This development in facility layout recognizes the fact that many manufacturing and services facilities are multi-level. This is particularly true in urban areas where land is scarce and/or expensive. Chrysler Corporation's Toledo facility moves material from one floor to another on 22 elevators and 66 miles of conveyor [Rae (1998)]. Similarly, the manufacturing process in Allen Bradley's facility in Milwaukee requires movement of material across 7 floors. The authors of this research visited several factories in Southern China where lightweight products (e.g. consumer electronics) are assembled in facilities that are organized at multiple levels. Material handling vertically seems far more difficult than handling materials in the same level. However, advances in material handling equipment and lack of space have made construction of and/or redesign of multi-level structure more desirable in the recent years.

The research in the area of facility layout has been primarily analytical in nature. Francis et al. [1992], Bozer and Meller [1994] and Meller and Bozer [1997] have presented analytical approaches to solve the multi-level layout problem. However, very little attention has been given to the effects of layouts on product and services quality. In this research, we present a systematic analysis of the effect of single-level and multi-level facilities on quality. Such an analysis is important, as it can help facility planners in anticipating quality problems related to different layouts and thereby help in designing ways to prevent the problems related to specific layouts.

The remainder of the paper is organized as follows. Section 2 gives a brief description of single-level and multi-level facility layouts. Section 3 organizes quality into three categories based on the Juran quality framework and provides some propositions related to quality for each category. Section 4 gives a computational study of a realistic problem. Section 5 concludes with a summary.

2. Facility layout

In facility layout, the primary concern is to minimize the cost of material, information, and human flows between departments. This cost depends mainly on the frequency of flows and the distance between two departments. In a single-level building, the distance between two departments may be measured by departmental centroids. However, in a multi-level building, the distance between two departments in two different floors may involve the traveling length between the starting department to an access point (e.g., an elevator) in the same floor, the traveling length between floors, the traveling length between the access point to the ending department.

Figure 1 (A), (B), and (C) show the 1-level, 2-level, and 3-level facility layouts for 12 departments, respectively. The 1-level facility has 3 by 4 departments. The 2-level facility has 2 floors, each of which contains 2 by 3 departments. The 3-level facility has 3 floors, each of which contains 2 by 2 departments. The 1-level structure has several entry/exit doors, each located at one side of the building. Access to each department can be done through any entry/exit door. We assume that access to a department is always done through the closest entry/exit door. In the 2 and 3-level layouts, access to a department on the ground floor may be done through the entry/exit door closest to the department. Access to a department on other floors must involve a lift that is located at the center of a facility.

To formally describe the facility layout problem, we define the following notation:

i,j - index for departments

N - total number of departments

l - index for lifts (i.e., vertical handling devices)

f_{ij} - flow per time unit from i to j

$$\delta_{ij} = \begin{cases} 1 \text{ if } i \text{ and } j \text{ are on the same level} \\ 0 \text{ if } i \text{ and } j \text{ are on different levels} \end{cases}$$

$d^{(H)}_{i \text{ or } l, j \text{ or } l}$ - (H)orizontal distance between i or l to j or l

$d^{(V)}_{ij}$ - (V)ertical distance between i and j

c_{ij} - Unit cost to move one unit of flow, one distance unit from *i* to *j*

Then the *distance* between departments *i* and *j* is,

$$d_{ij} = d_{ij}^{(H)}\delta_{ij} + (1-\delta_{ij})[\min_l\{d_{il}^{(H)} + d_{lj}^{(H)}\} + d_{ij}^{(V)}] .$$

That is, when departments *i* and *j* are on the same level (i.e., $\delta_{ij} = 1$), the distance between them is the horizontal distance between their centroids. When they are on different levels, the distance between them consists of the horizontal distance from the centroids of *i* and *j* to the nearest lift *l*, plus the vertical distance between the levels on which *i* and *j* are located.

The *total travel time* between *i* and *j* is equal to the product of the flow f_{ij}, the cost c_{ij}, and the distance d_{ij}. Horizontal travel time will be different from vertical travel time because of factors such as different material handling equipment is used for horizontal and vertical travel, waiting time at an elevator, and capacity of elevator. This is modeled by assigning different weights to horizontal and vertical distance. Let

$w^{(H \text{ or } V)}$ - weight per unit of (H)orizontal or (V)ertical distance

In a typical manufacturing facility $w^{(V)} > w^{(H)}$, where-as in a service facility $w^{(V)} \approx w^{(H)}$. So total travel time between departments *i* and *j* is,

$$t_{ij} = \delta_{ij} f_{ij} c_{ij} w^{(H)} d_{ij}^{(H)} + (1-\delta_{ij}) f_{ij} c_{ij} [w^{(H)} \min_l\{d_{il}^{(H)} + d_{lj}^{(H)}\} + w^{(V)} d_{ij}^{(V)}] .$$

and the total travel time in the facility is,

$$T = \sum_i \sum_{j \neq i} t_{ij} .$$

Facility layout algorithms try to allocate building spaces to departments to minimize the total travel time in the facility. Heuristics for single-level layout include research presented by Armour and Buffa [1963], Seehof and Evans [1967] and Tompkins and Reed [1976]. Multi-level facility layout heuristics have been presented by Cinar [1975], Johnson [1982] and Bozer et al. [1994].

3. Analysis with examples

To systematically examine the effect of quality in a single-level and multi-level facility layout, frameworks such as those of Crosby, Deming, Feigenbaum, and Juran may be used. An overview of frameworks is presented in Dean and Evan [1994]. In this study, we use Juran's framework because it is easily understood, widely used, and provides a suitable organization for this study. Cheng *et al.* [2000] adopted some features of Juran's framework to analyze straight and U-shaped production lines on quality. In this research, we consider several features of the framework and compare the effect of single-level and multi-level facility layouts on quality.

Juran [1986] organizes quality activities into three elements: quality planning, quality control, and quality improvement. For each of these elements we develop several propositions related to quality, which can be used to gauge the effect of a single-level versus multi-level facility layout on quality.

3a. Quality planning

Quality planning is the process of establishing quality goals and defining the approach to meeting those goals. Juran and Gryna [1993] organize quality planning into six categories: establish goals, identify customers, identify customer needs, develop product features, develop process features, and establish process controls for operations. In what follows we develop measures for these categories for the purpose of determining the effect of layouts on quality.

1. Total travel time as a quality goal

A goal of quality planning is to minimize the total travel time *T*, because the smaller the value of *T*, the smaller will be the opportunity for damage due to material handling. A multi-level facility inevitably requires vertical flows between two departments located in different floors and hence, its total travel time *T* is often more than that of a single-level facility. In other words, a multi-level facility creates an adverse effect on quality. This adverse effect on quality is more severe, when the time required for vertical travel is significant relative to that for horizontal travel.

Proposition 1: A single-level facility provides a higher level of quality. When $w^{(V)} >> w^{(H)}$, the benefit of a single-level facility is more significant.

<u>Example</u>: Consider **Figure 1.** Suppose each department has a length and width of one distance unit, the distance between levels is one unit, all distances are rectilinear, there is one unit of flow between all pairs of departments, unit cost between all pairs of departments is one, and the lift is located in the middle of the floor. Further suppose $w^{(H)} = 1$. Now we consider $w^{(V)} = 1$. The total travel times, *T*, for the 1-level, 2-level, and 3-level facilities are 308, 340, and 368, respectively. The l-level facility requires fewer material handling and hence reduces damage. The total travel times, *T*, of the three facilities are 308, 412, and 496, respectively when $w^{(V)} = 2$. A multi-level facility, the total travel time, *T*, increases as $w^{(V)}$ increases from 1 to 2. We may infer that the benefit of a single-level facility is more significant when $w^{(V)} >> w^{(H)}$.

Proposition 1 hypothesizes that a single-level facility provides a higher level of quality than a multi-level facility given the same flows between departments. Following this proposition, we may also infer that as the number of floors increases in a facility, quality also deteriorates. In the same example, the total travel time, *T*, increases from 340 to 368, and from 412 to 496, when the number of floors increases from 2 to 3, for $w^{(V)} = 1$ and 2, respectively.

2. Identify customers

Customers are one of the sources of information for product/process changes and innovations. A firm and its divisions should be in constant contact with customers for new ideas. Customers include external customers and/or internal customers (Evans and Lindsay [1993]).

Proposition 2: A facility, manufacturing or services, has to interact with external and internal customers in satisfying customer needs.

3. Discover customer needs

The needs of the internal customers of department *i* can be better identified when they are located adjacent to the department. Departments are adjacent when they touch. The average number of adjacent departments is almost always larger when the facility is a single-level than when it is a multi-level for the following reason. When *N* departments of equal size are located in a facility with *L* levels then, at most *(N-1)/L* can be adjacent to department *i*. In a single-level facility, the number is *N-1*.

Proposition 3: The needs of the internal customers can be better identified in a single-level facility because the average number of adjacent departments is usually larger than in a multi-level facility.

Example: *Twelve* departments of equal size are to be located in a 1-level facility of size three departments by four departments, a 2-level facility of size two departments by three departments, or a 3-level facility of size two departments by two departments. Consider first, the 1-level facility in Figure 1(A). The number of adjacent departments for departments 1,2,3, … are 3,5,3, …, and the average number of adjacent departments is (3+5+3+…)/12=4.83. In the 2-level facility, the number of adjacent departments for departments 1,2,3,… are 3,5,3,…, and the average number of adjacent departments is 3.67. In the 3-level facility, the number of adjacent departments for departments 1,2,3,… are 3,3,3,…, and the average number of adjacent departments is 3.00. The 1-level facility has a much higher number of adjacent departments.

Suppose that department *j* is a customer of department *i*. Then it is more difficult to identify the needs of customer *j* when the time to travel to *j*, t_{ij}, is large. In other words, an internal customer is better served when he/she is located closer to the servicing department.

Proposition 4: The average $\bar{t}_{ij}$ is smaller for a single-level facility, and hence it is easier to identify customer needs, than for a multi-level facility. The benefit of a single-level facility is more significant when $w^{(V)} >> w^{(H)}$.

Example: Recall the example in Figure 1. Suppose also that $w^{(H)}=1$. Now consider two values of $w^{(V)}$: 1 and 2. Then it is easy to calculate $\bar{t}_{ij}$=25.6 for the 1-level facility. For the 2-level facility $\bar{t}_{ij}$=28.3 and 34.3, when $w^{(V)}=1$ and 2, respectively and for the 3-level facility $\bar{t}_{ij}$ = 30.6 and 41.3, when $w^{(V)}=1$ and 2, respectively. That is, when $w^{(V)}=2.0 >> w^{(H)}=1.0$ average travel time between departments and their internal customers is better by 50 percent when the layout is single-level.

Now consider the needs of an external customer. Customer relation and satisfaction may be a challenge particularly when a customer directly interacts with a facility or involves in the production and provision of products and services. A facility must be designed in a way to facilitate its interaction with external customers. A multi-level facility provides legitimate compartments each of which may be designated to provide a particular type of products, or services. This is similar to the concept of "plants within a plant" in manufacturing. This concept may be a solution to a large facility (a single-level facility) that gradually loses its customer focus over time. Hence, in a multi-level facility, departments in each level can be focused on the needs of particular external customers. This makes it easier for a multi-level facility to respond to the needs of an external customer than a single-level facility.

Proposition 5*:* A multi-level facility may be better able to focus departments in particular levels to respond to the needs of particular customers.

Example: One possible measure for customer services quality in a department store is search time required for finding a product. The worst case for search time in a single-level facility may be approximated by the traveling time required for searching through each department in the facility. In Figure 1(A), the total traveling time is $11 \times w^{(H)}$ to search every department. In a multi-level facility, a customer is only required to search through each department in a level in the worst case. The traveling times are $5 \times w^{(H)}$ and $3 \times w^{(H)}$ for the 2-level and 3-level facility in Figure 1(B), and 1(C), respectively. Therefore, a multi-level facility is better able to address to the needs of a customer.

4. Develop product features

Significant efforts have been devoted to the developments and modifications of product features to increase product sales. Information from market researches is used to define changes in product features. This process requires formal and informal communication and coordination among various departments.

A multi-level facility naturally divides a facility into partitions (i.e., levels). These boundaries and spaces contribute positively to employer's association to group identity. For these reasons, a multi-level facility makes the facility more focus on specific products and services. Activities relevant to product features is better coordinated and executed. A single-level facility, however, gives a wide and open environment. Unless efforts have been taken to foster format and informal communication and coordination, this openness often adversely affects group identity.

Proposition 6: Changes in product features require communication and coordination between various departments. In a multi-level facility each level these departments can be located on the same level. Hence, changing product features can be easier in a multi-level facility.

Example: Consider the layouts in **Figure 1** with departments of equal size. The numbers of departments in a floor are 12, 6, and 4, respectively for a 1-level, 2-level, and 3-level facility. With a smaller number of departments interacting in a level, a multi-level facility foster better formal and informal communication and coordination and hence, contributes positively to changes in product features.

5. Develop process features

The departments that comprise a facility may represent a product layout, process layout, or cellular layout. A product layout requires a larger continuous area than a process or cellular layout because the departments that comprise a product layout are usually organized into a line. Facilities with a single-level layout have a larger continuous area (because all departments are on the same level) than a multi-level layout where the largest continuous area is the size of the largest floor in the facility. Certain manufacture processes such as chemical processes and steel-making use multi-level facility layouts to use gravity in facilitating material flow from upper levels to lower levels as they undergo processing.

***Proposition** 7:* Single-level facilities are better suited to a product layout than multi-level facilities because product layouts require large continuous areas. Some manufacturing require multi-level facilities because materials must flow from upper levels to lower levels during processing.

Maintenance activities are simplified when the facility has a single-level layout because 1) equipment breakdowns are more visible when equipment is located on the same level, 2) it is easier for maintenance personnel to move to areas requiring maintenance, 3) maintenance of vertical movement equipment such as elevators is not needed in single-level layouts.

***Proposition 8**:* Maintenance activities are simplified when the facility has a single-level layout and so quality is improved.

Because a multi-level facility has a fewer number of possible process arrangements than a single-level facility, there is a smaller number of possible routings in a multi-level facility. This means that there are fewer flexible routings and there is less volume flexibility in a multi-level facility.

***Proposition 9**:* A single-level facility layout has more routing flexibility and volume flexibility than a multi-level facility layout.

***6. Establish process controls, transfer to operations**:*

According to Juran and Gryna [1993], as these quality plans are put into production, the coordination among all functions continues and will result in final refinements to the product and process design. It is well known that people are more likely to communicate and co-ordinate with people in other functions if they are located close to one another, say, working on the same floor.

Proposition 10: A single-level facility layout encourages communication and coordination with different functions.

Example: Consider **Figure 1**. The average number of adjacent departments for the 1-level, 2-level, and 3-level facilities are 4.83, 3.67, and 3.00, respectively. The more adjacent departments a department has, the more likely it interacts with functions performed by other departments. Hence, a single-level facility layout encourages more communication and coordination with other functions.

3b. Quality Control

Quality control is directly concerned with meeting goals and preventing adverse changes. The process focuses on sporadic quality problems rather than chronic problems by acting on quality measurement. It consists of observing actual performance, comparing this to a standard, and taking appropriate action if the observed performance is significantly different from the standard. Workers should play an important role in detecting and solving quality problems (Ebrahimpour and Withers [1992], Harrison [1992], and Hernadez [1993]).

According to Juran and Gryna [1993], the control process involves seven activities: choose control subjects, choose units of measure, set goals, create a sensor, measure actual performance, interpret the difference, and take action on the difference. We now show specific measurement for each of these activities and the impact on single and multi level facility layouts.

7. Number of quality resource personnel required as control subjects and measure

Quality resources refer to supervisors, maintenance crew, and quality inspectors who are responsible for solving sporadic quality problems that occur in a manufacturing facility. In a multi-level layout, the facility needs to either designate quality resource personnel for each level or share them among different levels. For example, suppose that a single level requires two personnel for handling quality control activities. Then, a four level facility layout would require these two individuals to be responsible for all four levels, which results in waste of time required for travelling among floors.

Proposition 11*:* In a single level facility, the amount of travelling time required for solving quality problems is lower.

Example: Consider again the facility layouts in **Figure 1**. Assume the facility has 1 quality resources personnel who is currently working at department 1 and quality problems requiring his/her attention occur in the following departments: 1, 8, 7, 2, 12, 11, 5, 6, 7, 9, 10, and 1. In the 1-level facility, it would take the quality resources personnel 24 time units for travelling to complete the above quality problem sequence. In the 2-level facility, the same quality problem sequence would require 21 horizontal moves, and 6 vertical moves. Therefore, this facility layout will result in 33 time units for travelling when $w^{(V)} = 2.0 >> w^{(H)} = 1.0$. In the 3-level facility, we need 18 horizontal moves and 8 vertical moves to complete all quality problems. Therefore, this facility layout will result in 34 time units for travelling.

Using the same logic, we may argue that in a single level facility, quality resources personnel may react more quickly to a quality problem. This is possible because a single level facility does not need any vertical material handling equipment. This advantage is more apparent in a single level facility in comparison with a multi-level facility with $w^{(V)} = 2.0 >> w^{(H)} = 1.0$.

Proposition 12*:* A single level facility is more responsive to quality problems.

Example: Consider the same facility layouts. Suppose the quality resources personnel is currently is working in department 1 and a quality problem arises in department 12. It would take him/her 5 time units to travel to the quality problem area in the 1-level facility whereas 5 time units in the 2-level facility, and 6 time units in the 3-level facility with $w^{(V)} = 2.0 >> w^{(H)} = 1.0$.

In a multi-level structure, the facility could hire an individual at each level dealing with quality problems. This option would certainly increase the cost of prevention and help in preventing defects. However, the level of quality will still be adversely affected due to lack of visibility of quality errors on different levels.

8. Visibility as a sensor

According to Hall [1993], the level of visibility has a positive effect on quality. In a single-level facility, an entire sequence of operations is done at one level and therefore can be entirely followed. When quality problems occur, they can be made visible, spotted quickly and can be attended to immediately. This makes it easier for operators to help each other fix quality problems as they arise. In a multi-level facility, the level of visibility is generally lower. In line with this analysis, Meller and Bozer [1997] have recommended against locating departments that often interact with each other on different floors.

Proposition 13**:** Visibility is higher in a single level facility.

When a sequence of operations is split among different floors of a multi-level facility, quality problems occurring in a floor are generally harder for personnel in other floors to know about. It is intuitively obvious that when the number of floors increases in a facility, the level of visibility decreases, and thereby adversely affecting the level of quality. The level of quality can partially be improved, however, at the expense of high quality cost.

Proposition 14: Visibility is adversely affected when the number of floors in a facility increases without increasing the number of quality resource personnel.

Example: Consider the same problem in Figure 1. It takes 25.7 time units on average to get one department to another in the 1-level facility, while it takes 34.3 and 41.3 time units on average in the 2-level and 3-level facility, respectively for $w^{(V)} = 2.0 >> w^{(H)} = 1.0$. Hence, visibility is higher in the single level facility. Visibility may be improved for a multi-level facility by increasing the number of supervisors at an increased cost of prevention.

9. Measure actual performance of suppliers

In a traditional one level facility, the number of specialized points where suppliers can enter a facility is more than a multi-level facility, thus making it easier for deliveries to be made to specific user departments. Delivering parts directly to the user departments helps the department perform inspection when delivery is made, thus ensuring good quality control mechanism. On the other hand, in a typical multi-level facility, there is one general purpose receiving area or one entry point. This entry point prevents suppliers from delivering parts directly to the user departments, thus restricting a direct feedback from the user department.

Proposition 15**:** Better supplier quality can be achieved in a single level facility on account of direct shipment of parts to the user departments.

Another disadvantage associated with the delivery of shipment in a multi-level facility pertains to additional handling of parts caused by vertical movement from the entry point to the user departments on high levels. This additional movement and handling may result in internal failure costs related to quality.

Proposition 16**:** Total travel time and potential part damages are higher in a multi-level facility on account of additional handling of parts.

Example: In **Figure 1(A),** the 1-level facility has four entry points, each of which serves neighbouring departments. In Figure 1(B), the 2-level facility also has four entry points. However, delivery to departments on higher level requires vertical movement of parts, and hence, increases total travel time and potentially creates part damages.

3c. Quality Improvement

Quality improvement is the part of the quality trilogy that identifies and corrects chronic quality problems (Juran and Gryna [1993]) for the purpose of moving the current level of quality to a new, higher level. In Juran's trilogy of quality processes, the quality improvement phase plays a dominant role in reducing costs associated with poor quality. A typical quality improvement process involves the following steps: prove the need, identify projects, organise project teams, diagnose the causes, provide remedies and prove that these are effective, deal with resistance to change, and control to hold the gains.

10. Number of suggestions as a proxy for proving the need and identifying projects

In general, visibility in a single level facility is greater due to the closeness of related departments and work stations, awareness of quality problems arising in the facility, and formal and informal communications occurring among workers and supervisors. As a result of this closeness, the volume and quality of suggestions are improved. The increase in the number of suggestions leads to identify more possible needs, improvement, and remedies resulting in better quality.

Propositions 17: Due to greater visibility, a single level facility tends to encourage more suggestions than a multi-level facility.

Example: The level of visibility may be approximated by the average number of adjacent departments. Since the average number of adjacent departments in the 1-level, 2-level, and 3-level facility are 2.8, and 2.3, and 2.0, respectively, visibility in the single facility is better and hence increases the potential for the number of quality improvement suggestions.

11. Material handling as a means to diagnose the causes

The average travel time between departments in a single level facility are less than in a multi-level facility because of the proximity of departments and the absence of vertical travel requirements. In the example facilities in Figure 1, it takes 25.7 time units on average to get one department to another in the 1-level facility, while it takes 34.3 and 41.3 time units on average in the 2-level and 3-level facility, respectively for $w^{(V)} = 2.0 >> w^{(H)} = 1.0$. It is well known that better product quality and lower failure cost can be achieved, as the travel time associated material handling reduces.

A smaller area in each floor of a multi-level facility provides fewer routing options. Human and material traffics on the same floor are restricted to the number of available routes and therefore, may congest those routes when they are heavy. The limited number and capacity of vertical material handling equipment further amplify the congestion problem on each floor. Damages to products are more likely in a multi-level facility.

Proposition 18**:** Quality problems, related to material handling, are greater in a multi-level facility.

Typically, heavy equipment and receiving/shipping departments must be located on the lower floors in a multi-level facility. Because of this limitation, optimal routing and material flows cannot be achieved. For example, a department requires very heavy machinery and must be located on the ground. As a result, material flows in and out of this department are inevitably increased. This also increases wastage and thus impacts quality.

Proposition 19**:** Better routing and material flows can be achieved in a single level facility.

Example: Consider the same example in Figure 1. Suppose departments 2, and 3 require heavy equipment and must be located on the ground floor. Consider a routing sequence as follows: 1, 4, 5, 6, 2, 10, 3, 4, 1, 11, and 3. The sequence requires 24 time units (24 horizontal moves), 26 time units (18 horizontal moves and 4 vertical moves), and 38 time units (18 horizontal moves and 10 vertical moves) in the 1-level, 2-level, and 3-level, respectively, when $w^{(V)} = 2.0 >> w^{(H)} = 1.0$.

12. Cross-functional teams and cross-functional training: organising project teams

The literature suggests that cross-functional teams are needed to better identify causes associated with quality problems within a facility (Juran and Gryna [1993]). Since more departments are closer in proximity in a single level facility, it is easier for workers from different departments to work together co-operatively and solve quality problems as a group. A single-level facility brings remote departments together.

Proposition 20**:** Proximity in locations of departments in a single level facility facilitates the formation of cross-functional teams.

In a multi-level facility, departments with high interactions are located in the same floor because of commonalties in human, information, and material flows. As a result, it is more meaningful and feasible to cross-functionally train workers for a variety of tasks. This training helps identifying and resolving quality and other problems. As there are fewer activities on each floor in a multi-level facility, workers tend to be more familiar with the activities occurring on their floor, resulting in assisting co-workers in quality improvement activity projects.

***Proposition 21*:** A multi-level facility provides a better opportunity for cross-functional training on account of commonalties in the jobs.

Example: The departments in the same floor tend to interact with each other continuously because of their proximity and commonalties. This regular interaction fosters a co-operative environment for exchanging ideas, and cross-functional training.

13. Resistance to change

In a single floor of a multi-floor facility, there are fewer processes, machines, and people in relation to a single-level facility. Workers are likely to develop their association with products. They are directly in touch with suppliers, internal customers and external customers. Changes in product, process, and technology may be easier for the supervisors/project leaders to "sell" and implement.

Proposition 22: A multi-level facility encourages selling of new ideas.

On the other hand, proven ideas can be sold to and shared among other departments in a single level facility because it is easier to communicate success among departments (due to the proximity). The average number of adjacent departments can be used as a measure of the proximity of different departments.

***Proposition 23*:** A single level facility encourages sharing of proven ideas.

4. Analysis of a problem

In the previous section, we discussed the various aspects of quality problems related to different layouts. Propositions and examples were used to demonstrate the problems. Tables 1 through 3 summarise the quality propositions, measures, and arguments. In this section, we apply our framework to a realistic layout problem taken from LayOPT ^{TM}

Training Manual, and examine how layouts affect the product quality. The problem is solved by LayOPT ™ version 1.2.

We adopt the problem from LayOPT ™ training manual for our use. The facility is a two-level structure (Figure 2): a ground level and a mezzanine. The mezzanine is 14′ above the ground. Two 50′x50′ grids (at the south-east corner of the building) are marked as fixed obstacles both on the ground level and the mezzanine, respectively. They will not accommodate any departments.

Table 4 gives the descriptions of 17 departments, and their required areas. Some departments (for example the shipping and receiving departments) must be assigned to fixed locations. Also, some departments cannot be assigned to the mezzanine level probably due to safety reasons.

Unit cost to move one unit of flow one foot from department *i* and *j* (i.e., c_{ij}) is 1 second. The horizontal weight is $w^{(H)} = 1$ and the vertical weight is $w^{(V)} = 5$. The larger vertical weight value reflects the difficulty of a vertical movement of materials, parts, and products.

The plant operates one shift a day. A material handler (e.g. a lift truck) only deals with one load per trip. The number of loads handled per shift is given in Table 5 between a pair of departments.

First, we assume that we do not allocate any department to the mezzanine level. All production departments are placed on the ground level. Thus, this becomes a single floor layout problem. The spacefilling curve (SFC) (Bozer et al. [1994]) for this layout problem and the solution are given in Figure 3. No other grid exchanges and readjustments are needed. Total travel time for material handling is 114,448.55 seconds.

For a 2-level problem, we block out the west section of the building to reduce the free space on the ground floor for layout planning (see Figure 4). The SFC used by the manual to solve this problem is adopted. Notice that some departments are not allowed on the mezzanine level. The layout solution we obtain is the same as the one presented in the training manual. Minor no gain/loss exchanges of grids are done between departments 5 and 8 and departments 5 and 12 to make departments 5 and 8 contiguous. Total travel time for material handling is 113,755.24 seconds.

LayOPT ™ cannot solve a problem with more than 2 levels. To examine the 3-level solution, we further divide the departments of the first level into two levels. In other words, the departments in the third level are those in the second level of the 2-level problem above. The SFCs used in the first and second levels are given in Figure 5. The layout solution for the 3-level problem is given Figure 6. Minor no gain/loss exchanges of grids are done between departments 2 and 14, departments 2 and 16 to make departments 2 and 14 contiguous. Total travel time for this solution is 209,010.86 time units.

Table 6 reports how the vertical weights and the number of floors in a building affect the total travel time. Since the level of mezzanine is not used in the single level example, the value of the vertical weight does not affect total travel time. The total travel time increases as the value of the vertical weight increases. This result is consistent with proposition 1. The total travel time increases as the number of floors used for layout planning increases.

Proposition 2 states that a facility serves two types of customers: internal and external. The internal customers will be served better when the average number of adjacent departments is high. Proposition 3 suggests that the average number of adjacent departments is larger in a single-level facility. This claim is supported by our example layout. The average number of adjacent departments in a 1-level, 2-level, and 3-level is 4.59, 3.35, and 2.41, respectively in this example.

It is easier for a serving department to identify the needs of internal customers if he/she is closer to the serving department. Proposition 4 suggests that the average travel time is smaller and hence that it is easier to identify the needs of internal customers. This benefit is more significant when the vertical weight is larger than the horizontal weight. Table 6 is supportive of proposition 4. In general, the average travel time increases as the number of floors in the facility increases and also it increases as the vertical weight increases.

Each level of a multi-level facility may be designated to provide a particular type of products and services and hence, a multi-level facility better serves external customers (i.e., proposition 5).

The 2-level facility in our example layout has 14 and 3 departments in the first and second levels, respectively. The 3-level has 7, 7, and 3 departments in the first, second, and third levels, respectively. The 1-level facility has all 17 departments. With a smaller number of departments in a level, a multi-level facility fosters better communication and co-ordination, and hence, facilitates the process of changing product features, as suggested by proposition 6.

A single-level facility provides a 600′×450′ - 50′×50′ contiguous space for layout planning. With the exception of certain industries, a single-level facility facilitates product layout (i.e., proposition 7). The openness of a single-level facility also simplifies maintenance activities (i.e., proposition 8). In addition, a single-level facility provides more routing flexibility and volume flexibility (i.e., proposition 9).

Proposition 10 suggests that a single-level facility encourages communication and co-ordination. For example, the average number of adjacent departments in a 1-level, 2-level, and 3-level is 4.59, 3.35, and 2.41, respectively. We expect a single-level facility encourages more communication and co-ordination.

Proposition 11 postulates that the amount of travel time required for solving quality problems is lower. In this example, suppose a quality problem requires quality resource personnel to visit these departments in the following sequence: 1, 3, 6, 7, 3, 8, 4, 2, 1, 12, 14, 12, 1. In a 1-level structure, it takes the quality resource personnel 3208.44 feet of horizontal moves to complete the sequence. He/she has to commit 3474.65 feet of horizontal moves and 28 feet of vertical moves in a 2-level structure. In a 3-level structure, the same sequence requires 3412.26 feet of horizontal moves and 112 feet of vertical moves. When $c_{ij} = 1$, $w^{(H)} = 1$, and $w^{(V)} = 5$, a 1-level, 2-level, 3-level structure requires 3208.44 seconds, 3614.65 seconds, and 3972.26 seconds, respectively to complete the sequence.

In proposition 12, a single-level facility is said to be more responsive to quality problems. This can be established by measuring how quick the quality personnel responds to a quality problem. In a 3-level facility, a quality problem occurring in the third level will require vertical moves committed by the quality personnel who do not happen to be on the same level.

Proposition 13 suggests that visibility is higher in a single level facility. In one level, all operations are visible. When quality problems occur, they can be quickly spotted and immediately attended. In other words, a multi-level facility tends to hide quality problems. The level of quality associated with a multi-level facility can be partially improved by increasing the number of quality resource personnel. This is consistent with proposition 14.

Proposition 15 deals with the supplier quality and proposition 16 deals with the quality of materials and parts. As described earlier, a multi-level facility makes receiving shipments to using departments difficult because of vertical movements of materials and parts. Hence, we expect the quality of materials and parts from the suppliers to be adversely affected.

In proposition 17, we propose that a single level facility tends to encourage more suggestions due to its greater visibility. The higher is the level of visibility, the more is the level of communication and co-ordination, and hence the larger is the possible number of suggestions. The visibility for a single level facility is higher. This can be established by the fact that the average number of adjacent departments is larger in a single level facility. In this example layout, the average number of adjacent departments in a 1-level, 2-level, and 3-level facility is 4.59, 3.35, and 2.41, respectively.

Material and part handling is more complicated in a multi-level facility partially because of the separation created by floors and the use of vertical transport equipment. In proposition 18, we suggest that quality problems due to material and part handling are more severe in a multi-level facility. The separation created by floors also limits the flexibility of routing and material flows. In this example layout, the locations of the receiving department and the shipment department are fixed. Some departments are not allowed on the 2-level for the safety reason. This adversely affects the flexibility of routing and material flows, as suggested by proposition 19.

The average number of adjacent departments is larger and the average distance between a pair of departments is smaller for a single-level facility. Proximity in locations of departments in a single-level facility facilitates the formation of cross-functional teams (i.e., proposition 20). On the other hand, a multi-level facility facilitates cross-functional training (i.e., proposition 21). This is due to the fact that highly interacting departments are often assigned to the same level.

Proposition 22 suggests that selling of new ideas is easier in a multi-level facility while proposition 23 suggests that a single level facility encourages sharing of proven ideas.

5. Conclusion

In this paper, we examine the effect of the facility layout on quality. For the purpose of systematically studying the effect, we use Juran's three-stage trilogy as a framework – quality planning, quality control, and quality improvement. In addition, we develop several measures of quality. At each stage, we introduce several propositions. These propositions are carefully examined and analysed. We use a realistic problem to illustrate several propositions. In general, we show that a single level facility produces better quality.

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Table 1 Quality Planning

Quality Planning	Measure	Arguments
Establish Quality Goals	Total Travel Time	The smaller the value of total travel time, the smaller the amount of material handling, and the better will be the quality.
Identify Customers	External & Internal Customers	Customers are one of the sources for product and process changes and innovations.
Discover customer needs	Average number of adjacent departments	The needs of the internal customers can be better identified when a layout has a higher average number of adjacent departments.
	Average travel time	The needs of the internal customers can be better identified when a layout has a lower average travel time.
	Worst case of search time	The needs of the external customers can be better identified when a layout has a lower worst case of search time.
Develop product features	Number of departments interacted with on the same floor	Changes in product features are easier to implement when they involve a smaller number of interacting departments.
Develop process features	Continuous area in a floor	The size of continuous area in a floor favors a process layout.
	Use of vertical equipment	Maintenance activities are simplified when a facility does not need the use of vertical equipment.
	Number of possible routings	The fewer the possible routings, the smaller will be the volume flexibility.
Establish process controls, transfer to operations	Average number of adjacent departments	Communication and coordination among different functions are easier with a higher average number of adjacent departments.

Table 2 Quality Control

Quality Control	Measure	Arguments
Choose control subjects	Quality resource personnel	Quality resource personnel directly address quality problems.
Choose measure	Travelling time involved in solving quality problems	The smaller the amount of travelling time required for solving quality problems, the fewer will be the number of quality resource personnel required and the lower will be the quality cost.
Create a sensor	Level of visibility	The higher the level of visibility, the quicker the quality problems be identified and attended.
Measure actual performance of suppliers	The number of access points to the facility	The larger number of access points the facility, the better will be the performance of the suppliers.

Table 3 Quality Improvement

Quality Improvement	Measure	Arguments
Prove the need	Level of visibility	The higher the level of visibility, the higher will be the number of suggestions for improvement.
Diagnose the causes	Material handling	The higher material handling, the worse will be quality problems.
	The flexibility of routings	The more flexible the routings, the better will be the quality.
Organizing project teams	Number of adjacent departments	The higher the number of adjacent departments, the easier cross-functional teams will be formed.
	Closeness of departmental functions	The closer the departmental functions, the more meaningful and feasible will be cross-functional training.
Deal with resistance to change	Closeness of departmental functions	The closer the departmental functions, the less sever will be the resistance.
	Number of adjacent departments	The higher the number of adjacent departments, the easier will be the selling of proven ideas.

Table 4 Department Data Summary

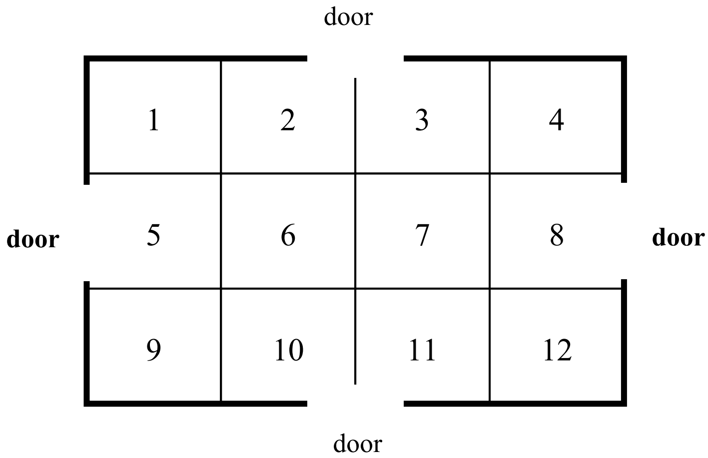
Department Number	Department Description	Department Area (Sq. Feet)	Department Type	Located on the Mezzanine level
1	Receiving	5,000	Fixed	No
2	Steel Storage	20,000	Free	No
3	Purchased Parts Storage	15,000	Free	
4	Machining and Milling	20,000	Free	No
5	Flexible Cell A	15,000	Free	
6	Flexible Cell B	15,000	Free	
7	Flexible Cell C	15,000	Free	
8	Flexible Cell D	16,000	Free	
9	Job Shop Cell	15,000	Free	
10	Final Assembly 1	20,000	Free	
11	Final Assembly 2	18,000	Free	
12	Final Assembly 3	18,000	Free	
13	Decorative Finishing	15,000	Free	
14	Wood Shop	18,000	Free	No
15	Electrostatic Cost/Paint	18,000	Free	No
16	Finished Goods Storage	22,000	Free	No
17	Shipping	5,000	Fixed	No

Table 5: Interdepartmental Flow Summary

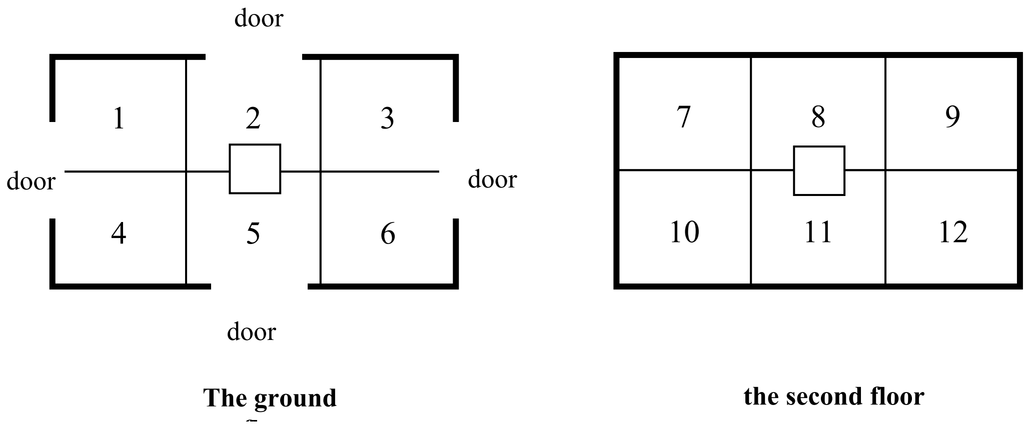
		TO																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	1		10	24							30		30	5	18			
	2				10													
	3					1	1	1	2	3	10	2	8					
	4					10	5		5	12								
	5																	20
F	6							10										10
R	7																16	
O	8																	30
M	9															34		
	10																44	
	11																20	
	12																30	
	13							4			3							
	14							4				10	10					
	15										14	20						
	16																	55

Table 6: The effect of the vertical weight and the number of floors on total travel time

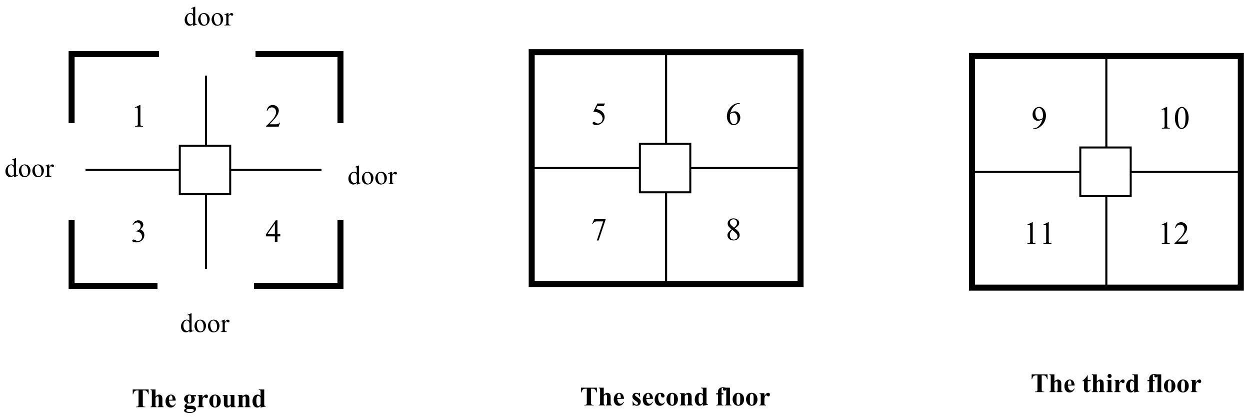
	Total Travel time			Average Travel time		
	1-level	2-level	3-level	1-level	2-level	3-level
$w^{(v)}=5$	114,448.55	113,755.24	180,450.86	6,732.27	6,691.48	10,614.76
$w^{(v)}=10$	114,448.55	116,905.24	209,010.86	6,732.27	6,876.78	12,294.76
$w^{(v)}=15$	114,448.55	120,055.24	240,370.86	6,732.27	7,062.07	14,139.46
$w^{(v)}=20$	114,448.55	123,205.24	270,330.86	6,732.27	7,247.36	15,901.82



A) A single-level facility layout



B) A 2-level facility layout



C) A 3-level facility layout

Figure 1: Facility Layout

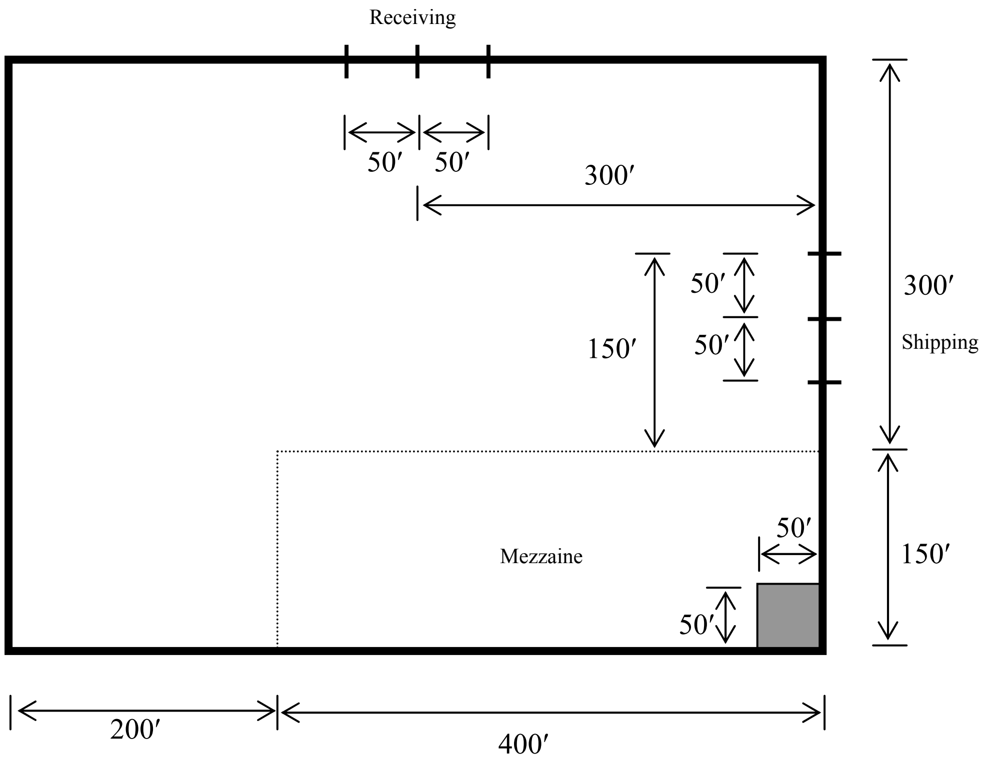
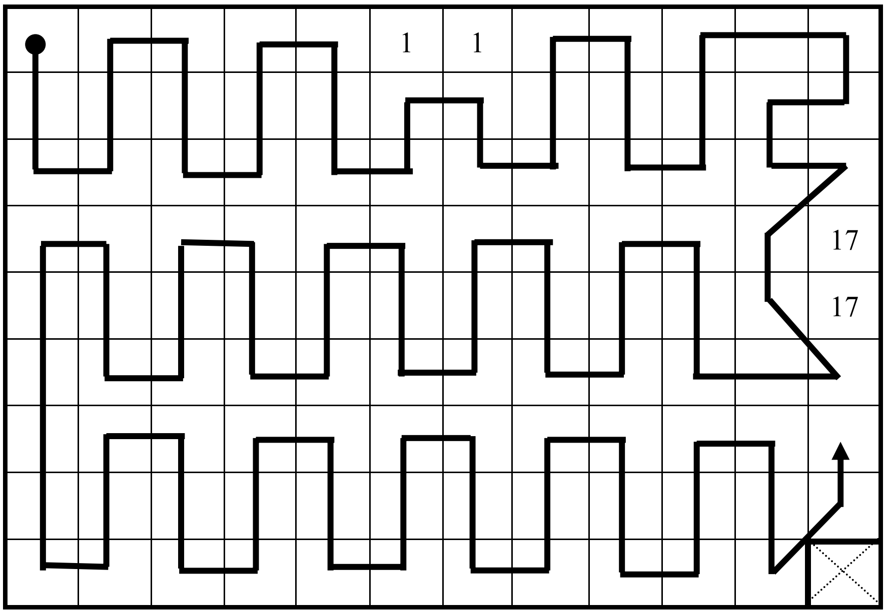


Figure 2: Building Outline

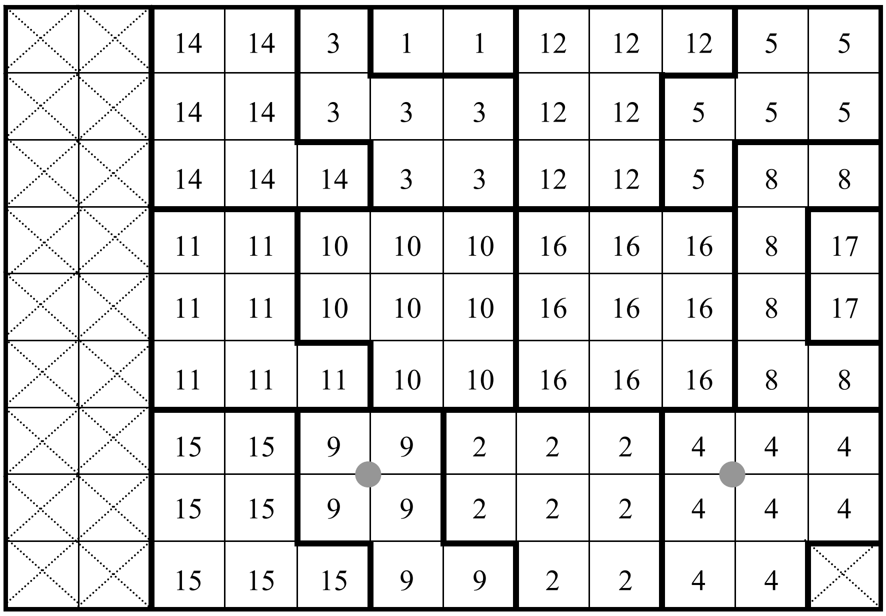


The SFC used in the ground floor

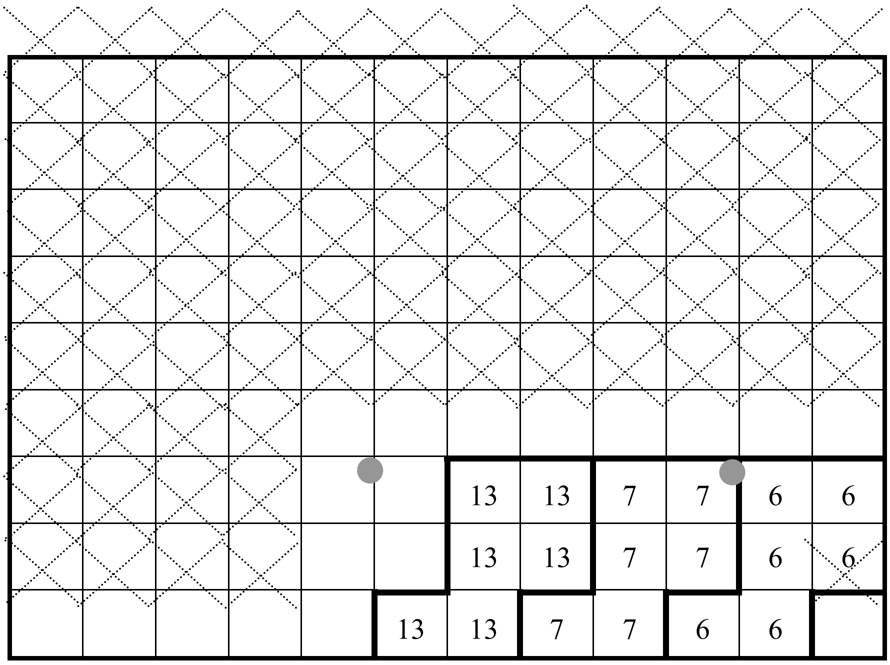
14	14	14	3	3	1	1	7	7	6	6	6
14	14	3	3	12	12	12	7	7	6	6	6
14	14	3	3	12	12	12	12	7	7	8	8
11	11	13	13	10	10	10	16	16	16	8	17
11	11	13	13	10	10	10	16	16	16	8	17
11	11	11	13	13	10	10	16	16	16	8	8
15	15	15	9	9	2	2	4	4	5	5	5
15	15	9	9	2	2	2	4	4	4	5	5
15	15	9	9	2	2	2	4	4	4	5	

The ground level layout

Figure 3: All production departments are located on the first level

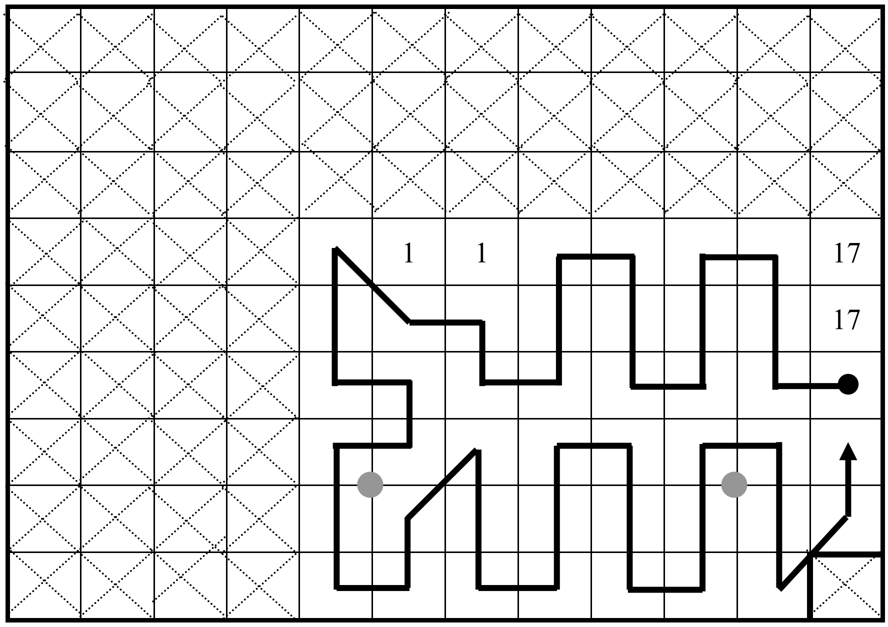


The ground

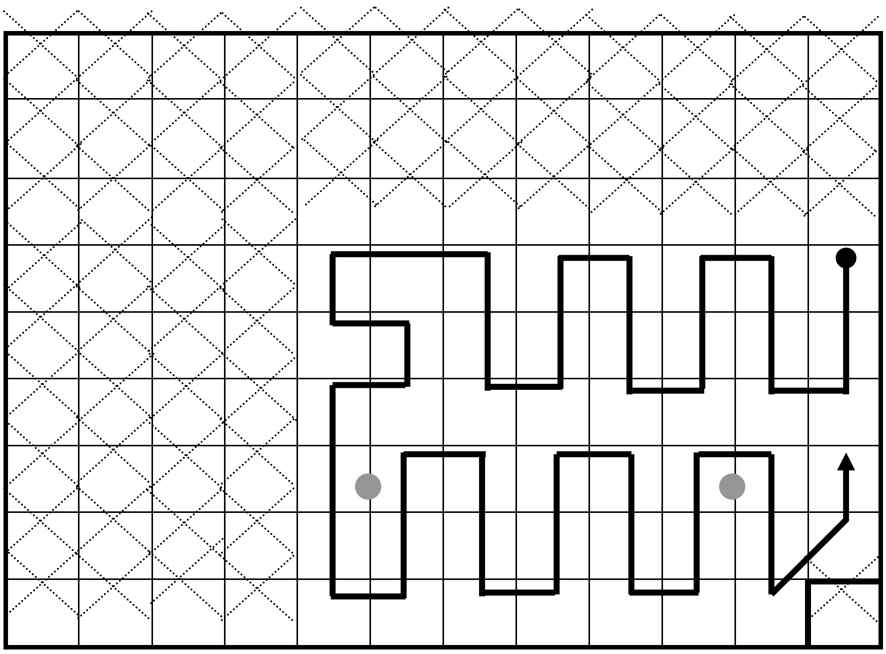


The mezzanine

Figure 4: A two level solution (with some production departments on the mezzanine)



The ground



The 2nd level

Figure 5: The SFCs used in the first and second levels

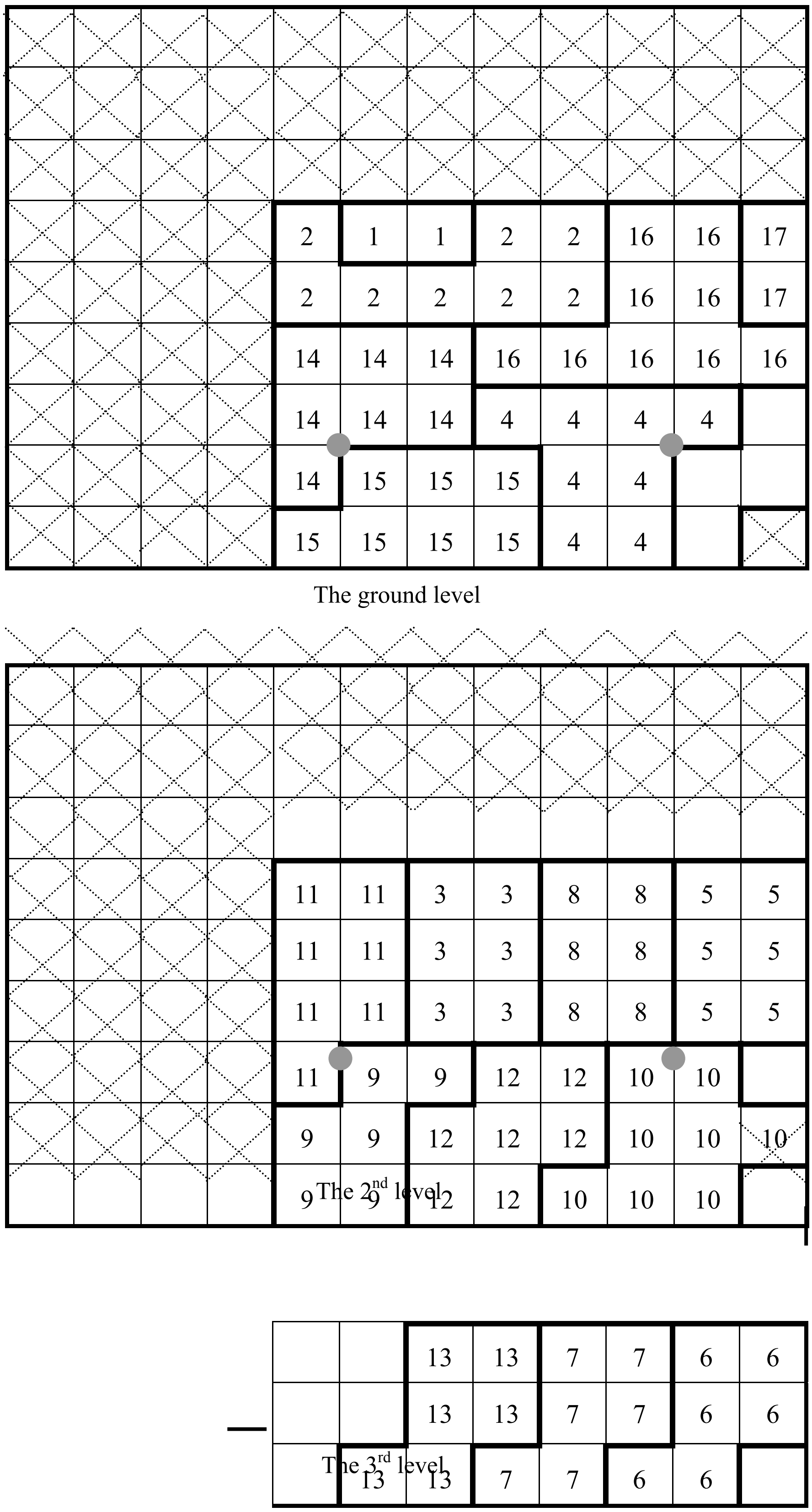


Figure 6: A three level solution