THE DESIGN REQUIREMENTS OF MULTI-PURPOSE FACTORY BUILDINGS

by

Arthur G. Aldersey-Williams

B. Arch., University of Liverpool, A.R.I.B.A.

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Master of
Architecture
at the
Massachusetts Institute of Technology
September, 1957

Signature of Author

Department of Architecture, September 16, 1957

Head of Department of Architecture
September 16, 1957

Pietro Belluschi, Dean
School of Architecture and Planning
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

I herewith submit my thesis entitled "The Design Requirements of Multi-Purpose Factory Buildings" in partial fulfillment of the requirements for the degree of Master of Architecture.

Sincerely yours,

Arthur G. Aldersey-Williams
"Knowledge is the raw material for design. It is not a substitute for architectural imagination; but it is necessary for the effective exercise of skill and imagination in design. Inadequate knowledge handicaps and trammels the architect, limits the achievements of even the most creative, and depresses the general level of design."

Richard Llewelyn Davies
TABLE OF CONTENTS

Introduction - page 1
   Architect's role in industrial building design - need to understand function of factories - large specialist firms - scope of industrial architecture - standard type of factory - purpose of the thesis - method used.

Chapter 1 - Present Practice
   The Plan - page 3
   Trend toward single-story construction - reasons for - shape of building - location of offices - size of factories - area of warehouse space - population density - vertical location of toilets - locker rooms - separate level access.

Structure - page 6
   Frame material - bay size - clear internal height - trend toward higher factories - height for different kinds of products - provision for hanging loads - floor loading of single-story factories - multi-story - provisions for relocating machinery requiring special foundations - press shop foundations - floor finish - no satisfactory finish - external walls - provisions for expansion - internal wall finish - roof deck material - use of sound absorbing material not widespread - trend away from natural overhead light - arguments against natural light - industries which still use natural light - side lighting- type of window.

Fire Precautions - page 14
   No increase after General Motors Livonia Plant fire - description of plant fire - reasons for - precautions in new General Motors and Ford plants - use of sprinkler protection - use of heat vents - use of fire walls - use of fire curtains.

Power Distribution - page 17
   Cost of power system - power size of plant - amount of power used by different industries - type of distribution - when used - type of circuit used - means of secondary distribution - voltage.

Artificial Lighting - page 20
   Type used - levels for different industries.

Heating and Ventilating - page 21
   Same air system used for both - exceptions - use of air conditioning - means of exhaust - use of natural ventilation - air change rate - recirculation.

Materials Handling Equipment - page 22
   Influence of - universal use of fork lift trucks - use of overhead conveyors - use of cranes - floor conveyors - hand trucks.
Speed of Construction - page 23


Chapter 2 - The Factors Influencing the Design Requirements

Bay Size - page 25


Clear Internal Height - page 26

Determined by - stacking height of fork lift trucks - recommended heights in manufacturing areas - height of machine tools - clearance required for cranes - clearance for overhead monorail hoists - height of mezzanines and overhead walkways.

Provision for Hanging Loads - page 28

Depends on - load carrying capacity of overhead conveyors - monorail hoists - weight of machine tool parts - weight of ventilation equipment - weight of power distribution equipment.

Floor Loading - page 30

Determined by - weight of machine tools - weight of laden fork lift trucks.

Chapter 3 - Conclusions

Existence of standard factory - arguments for using multi-purpose buildings - industries which cannot.

The Problem - page 33

Possibility of prefabrication - basic structural components - heavy not easily adapted floor - light adaptable superstructure - material for structural system.

The Plan - page 35

Shape of building - vertical disposition of employee facilities.

Bay Size - page 36

Span proposed - type of structure for economical square bays.

Provision for Hanging Loads - page 36

Difficult to meet - two-way span solution - load limits required - centers of panel points.

Clear Internal Height - page 38

Height required - adaptability provided - percentage of sample adequate for.
Floor Loading - page 38
No problem - maximum load required - bearing capacity of soils - percentage of sample floor loading would meet.

Natural Lighting - page 39
Most buildings without - provision for - method of adding monitors - vision strip recommended - low sill.

Fire Precautions - page 41
Sprinkler protection - heat vents required - built-in fire walls not possible.

Heating and Ventilating - page 41
Flexible system essential - reasons why - proposed solution - ease of changing.

Power Distribution - page 43
Suspended from roof - expected plant demand - type of circuit arrangement - location of master substation - artificial lighting.

Service Line Distribution - page 44
Location - gravity waste removal.

Scope of Prefabricated System - page 44
Percentage of sample these standards satisfy.

Appendix 1 - The Questionnaire Survey of Existing Factories

Introduction - page 1
Purpose of survey - sample desired - selection of sample - source - addressed to - limitations of questionnaire - number of replies received - composition of sample.

The Figures - page 2
Method of plotting.

The Questions and Answers - page 3
General questions - reasons for - table of products manufactured - table of examples by specialized designers.

Plan - page 6
Aim of questions - reasons for questions - confusion of wording - lack of definite answers.

Structure - page 7
Number of multi-story examples - effect of multi-story construction on answers - details of structure - provision for expansion - trend away from overhead natural light.

Fire Precautions - page 9
Basis of questions - description of terms.
Power Distribution - page 9
   Complexity of subject - reasons for questions.
Heating and Ventilating - page 10
   Reasons for degrees of air conditioning - system in majority of plants.
Materials Handling Equipment - page 11
   Difficult questions to answer - reasons for.
Costs - page 11
   Reasons for questions - unreliability and lack of answers - buildings rented.
Inadequacy of Building Services - page 12
   Complaints.
INTRODUCTION

The architect's role in industrial building design is somewhat tenuous, and the reasons for this are not difficult to discover. There are no clients more cost-conscious than industrialists, and on part experience and their own intuition they are likely to think that the architect is a person who will involve them in unnecessary expense, at best somebody to be called in for aesthetic advice or to add "dignity" to the offices and entrance hall. Furthermore, even now the opinion exists in industry that the building is unimportant, merely a shed to house the production machinery, and that the best person to design this efficiently is a structural engineer. In most cases, however, factory buildings are something more than sheds and they do, to a very great extent, determine the efficiency of the manufacturing process inside. The effect of the process on the building, and vice versa, is very much part of the architect's responsibility. He is the only person whose training enables him to integrate the complex requirements of a modern industrial building to produce an efficient and economically sound solution. But before this is possible, it is essential that the architect fully understand the function of a factory building, since he will seldom persuade industry to accept a design on anything but its own terms.

There are of course exceptions to this rule, the most prominent being the large specialist firms who have accumulated considerable experience in the design of factories. The existence of these firms, which have no counterpart in other parts of the world, has undoubtedly influenced present practice profoundly.

The field of industrial architecture is very large; it extends from special buildings which enclose processes of vast scale such as the manufacture of steel to a small, simple, single-story structure. To try to cover all the different types of building in one limited study would mean that the material would be too superficial to be of any use. However, in spite of the extent of industrial architecture, the bulk of factory buildings are of a fairly
standard type and capable of housing many of the manufacturing operations in use today.

The purpose of this thesis is to discover the factors influencing the design of the standard factory and the requirements that the building must satisfy.

The main method which has been used to achieve this purpose is a detailed survey of a large number of existing factories to discover the basis of present factory design practice. By comparing the buildings manufacturing the same product, it is possible to find the building requirements for the manufacturing process and by this means the facilities needed for all the processes represented in the survey. From this can be found the scope and range of adaptability required of a multi-purpose factory. Because of the number of factories necessary to give a representative sample, this survey was conducted by questionnaire.

In the second chapter of this report the requirements established by the survey have been checked against the dimensions or weights of the equipment which determine them.
CHAPTER 1 - PRESENT PRACTICE

From the questionnaire survey of existing buildings described in detail in Appendix 1, we can obtain an accurate and detailed picture of present factory design practice in the United States. In general the picture is consistent, and it is easy to come to conclusions on the location of employee facilities, the structure of the building, the arrangements made for natural or artificial lighting, and the heating and ventilating systems used; in fact, those aspects of design which make it possible to identify the "standard" factory. In detail, however, this consistency breaks down and it is difficult to discover on what bases decisions were made.

The Plan

The majority of factories represented in the sample are single-story. Of a hundred buildings only 16 were of two floors or more, and twelve of these were built prior to 1955. When it is considered that half the sample was built later than this, the trend toward single-story construction becomes more obvious. As one studies factory design, the reasons for this dominant trend become clear. Briefly they are as follows:

To avoid the congestion of densely built-up areas, factories are increasingly located in suburban or rural areas where land is plentiful and cheap;

A single-story building can be expanded more easily than a multi-story one;

Materials handling equipment for most manufacturing requirements is far better developed for operating in a single horizontal plane;

The floor loading required for machine tools and fork lift trucks is high and would make multi-story construction expensive;
A single-story plant of steel framed construction is not normally fireproofed and can therefore be built much more quickly than a multi-story example with suspended reinforced concrete floors;

The ventilation of a large single-story factory is easier because fresh air inlets and exhaust fans can be located anywhere on the roof;

The economical bay sizes are bigger in single-story construction.

In conclusion, it might be said that multi-story construction is applicable only when the site is very expensive and the process suited to this type of building.

It was not possible by questionnaire to obtain any information on the shape of the building, but from the few aerial photographs that respondents enclosed with their replies and from the many more than have appeared in the architectural press from time to time, this is normally a simple rectangle. The rectangle is far more adaptable to changes in machinery layout or even to different products than an E, H, or more complicated shaped building. The two-story office block is usually located across the short side of the rectangle, which faces the street to give the main façade of the factory a more imposing appearance. In most cases the office building shares a common wall with the manufacturing space, with frequent doors and openings through. In about a third of the examples, the offices were detached from the factory but probably connected by bridges. In another arrangement which is not common the offices are entirely within the factory. Although this may be considered "democratic", it does not seem to be very sound to place any more people than absolutely necessary within the noise and confusion of the manufacturing space. Even the common wall arrangement suffers in this respect.

The area of the factories included in the sample varied from 7,000 to 3,000,000 square feet. Forty-five examples had manufacturing
space less than 100,000 square feet and another nineteen less than 200,000 square feet. From 200,000 square feet to the upper limit quoted above, the distribution was more or less uniform. Thus it would appear that the normal factory—even those belonging to large organizations—is less than 200,000 square feet in area. In most cases to this manufacturing space is added a proportion of warehouse space which may vary from almost nothing to an area as large as the manufacturing space itself. Normally it is less than 100,000 square feet, but its size bears no constant relationship to the area of manufacturing space. This emphasizes the advantages of having the two kinds of space interchangeable to facilitate the expansion of either.

The population density within the factories varies from less than one person to every 1,000 square feet to more than one person to every 100 square feet, depending on the type of process. Table 1 below shows the normal range of population density for the various manufacturing processes represented in the survey.

Table 1

<table>
<thead>
<tr>
<th>Process</th>
<th>Density (sq. ft./person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clothing and shoe manufacturers</td>
<td>100-200</td>
</tr>
<tr>
<td>Radio and electronic equipment, etc.</td>
<td>100-200</td>
</tr>
<tr>
<td>Drugs and surgical goods</td>
<td>125-200</td>
</tr>
<tr>
<td>Light assembly - household appliances</td>
<td>200-400</td>
</tr>
<tr>
<td>Medium assembly - cars, etc.</td>
<td>250-500</td>
</tr>
<tr>
<td>Heavy assembly - aircraft, etc.</td>
<td>200-500</td>
</tr>
<tr>
<td>Machine tools, electric tools, etc.</td>
<td>150-500</td>
</tr>
<tr>
<td>Mills - woolen fabrics</td>
<td>250-350</td>
</tr>
<tr>
<td>Processes - detergents, plastics</td>
<td>250-500</td>
</tr>
<tr>
<td>Food products</td>
<td>250-500</td>
</tr>
<tr>
<td>Building products</td>
<td>200-700</td>
</tr>
</tbody>
</table>

From this table we can see that a "standard" factory of 200,000 square feet will employ anywhere from 400 to 2,000 persons.

The position in the vertical plane of the toilets, locker rooms, and employee access is one of the most important factors in a
single-story factory layout, where all manufacturing and material movement takes place on the main floor. The usual location of the toilets in the plants surveyed is on the main floor, but there is a significant number of factories in which the toilets were placed on a separate level. Where another level is used, a mezzanine is preferred to a basement location, probably because it is less expensive and more flexible. Both locations have the advantage of removing the toilets from the main manufacturing level where they would interfere with layout changes.

The location of the locker rooms is not as important as the toilets, since they are usually grouped near the entrances where they do not interfere with layout changes so much. In thirty-six out of the hundred examples a mezzanine or basement location is used, but normally the locker rooms are located on the main floor.

Separate level access for employees, either by basement or overhead walkways, occurs in about a third of the factories represented in the sample. The basement level is preferred, by more than two to one, to the overhead alternative. This is surprising in view of the expense involved and the complete lack of flexibility in relocating basement walkways. As one would expect, separate level access is more common in plants which use line assembly and in those that make frequent layout changes. There is also some indication that it is used more in densely populated factories, but it is certainly not limited to these cases. Basement or overhead walkways are not limited to large factories either; in fact half the examples in which they are used are under 100,000 square feet in area, but in the smaller plants the basement alternative is even more popular.

One of the most irreconcilable facts which was brought up by the survey is that there is no correlation between overhead walkways and mezzanine toilets and locker rooms or between basement walkways and a basement location for toilets, etc.

Structure

The structure of the vast majority of American factories is remarkably consistent, and there appears to be much more agreement between
manufacturers on this aspect of design than on any other.

In the single-story examples the frame is nearly always of steel. Only eight examples use a reinforced concrete frame exclusively, and four of these are multi-story buildings. It appears that reinforced concrete frame construction is more frequently used in conjunction with steel, presumably for basements where the load above is heavy or for columns if some fire resistance is required.

The bay size varies from about 20 x 20 feet to 35 x 160 feet, depending on whether the building is single- or multi-story, on the size of the product manufactured, and on the degree of flexibility required for changes. The most common size is 20 x 20 feet, and these dimensions are by far the most popular in multi-story examples. For single-story construction the next most common size is 40 x 60 feet, which might well be considered a standard for this type of factory. There is, however, a preference for square bays. In addition to the 20 x 20 foot size, there are at least two examples each of 30 x 30 foot, 35 x 35 foot, 40 x 40 foot, and 50 x 50 foot column spacing, and in one instance a bay of 64 x 64 feet. This preference for square bays is difficult to understand because this form of construction is not the cheapest, except in multi-story buildings with reinforced concrete slab floors. A square bay does have the advantage of being "directionless" and giving the same degree of flexibility in both directions; perhaps this accounts for its popularity. The range, and the normal bay size where there are enough examples, is given in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Category</th>
<th>Bay Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food products</td>
<td>20 x 20-45 x 50, 20 x 20</td>
</tr>
<tr>
<td>Processes - detergents, plastics</td>
<td>20 x 20-25 x 80, 20 x 20</td>
</tr>
<tr>
<td>Clothing and shoe manufacturers</td>
<td>20 x 20-28 x 56, 25 x 25</td>
</tr>
<tr>
<td>Drugs and surgical goods</td>
<td>20 x 25-40 x 40, 35 x 35</td>
</tr>
<tr>
<td>Light assembly - household appliances</td>
<td>20 x 20-40 x 60, 20 x 40</td>
</tr>
<tr>
<td>Radio and electronic equipment</td>
<td>20 x 20-40 x 60, 20 x 40</td>
</tr>
<tr>
<td>Machine tools, electric tools, etc.</td>
<td>20 x 20-25 x 90, 20 x 40</td>
</tr>
<tr>
<td>Medium assembly - cars, etc.</td>
<td>20 x 20-40 x 60, 40 x 60</td>
</tr>
<tr>
<td>Heavy assembly - aircraft, etc.</td>
<td>24 x 25-35 x160, 40 x 60</td>
</tr>
<tr>
<td>Paper products</td>
<td>20 x 20-40 x 60, 30 x 50</td>
</tr>
</tbody>
</table>
The clear internal height is perhaps the most important dimension affecting the flexibility and adaptability of a factory, and this is a fact which is not always realized. The height to the underside of the roof depends on the size of the product, the height of machinery, the type of materials handling equipment, and whether mezzanines are used. The average height of the factories surveyed was 18 feet and the range from 10 to 40 feet. Post-war factories are noticeably higher than the pre-war examples, but there is little indication that the trend is still to go higher. The table below gives the range and the average clear internal height for the various types of manufacturing represented in the sample.

<table>
<thead>
<tr>
<th>Type of Manufacturing</th>
<th>Range and Average Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clothing and shoe manufacturers</td>
<td>10-18', 12'</td>
</tr>
<tr>
<td>Radio and electronic equipment</td>
<td>14-17', 14'</td>
</tr>
<tr>
<td>Drugs and surgical goods</td>
<td>11-20', 15'</td>
</tr>
<tr>
<td>Machine tools, electric tools, etc.</td>
<td>12-38', 16'</td>
</tr>
<tr>
<td>Food products</td>
<td>11-23', 18'</td>
</tr>
<tr>
<td>Paper products</td>
<td>14-20', 18'</td>
</tr>
<tr>
<td>Processes - detergents, plastics</td>
<td>14-20', 18'</td>
</tr>
<tr>
<td>Light assembly - household appliances</td>
<td>10-27', 18'</td>
</tr>
<tr>
<td>Medium assembly - cars, etc.</td>
<td>12-32', 18'</td>
</tr>
<tr>
<td>Heavy assembly - aircraft, etc.</td>
<td>16-40', 30'</td>
</tr>
<tr>
<td>Mills - woolen fabrics</td>
<td>12-22', --</td>
</tr>
<tr>
<td>Warehouses</td>
<td>15-16', --</td>
</tr>
<tr>
<td>Building products</td>
<td>18-28', --</td>
</tr>
</tbody>
</table>

If a factory is to have the maximum amount of adaptability for layout or product changes, it is important to have not only adequate bay size and internal height but also adequate provision for hanging loads anywhere from the roof structure. These loads may be overhead walkways, mezzanine toilets, unit substations, ventilating equipment, overhead monorail conveyors or hoists, and from time to time pieces of machinery which are being replaced. Since
this is such an important part of factory building design, it was a surprise to find that only half the factories in the sample had any provision for hanging loads. It was thought that this was standard practice in modern American factory design.

The load-hanging capacity can be stated in many different ways. Those normally used are the maximum loads at panel points on the trusses, the maximum load that can be supported anywhere, and a loading in lbs./sq. ft. of floor area. In this last case it is impossible to find what the maximum load at any point can be without more information. The range of loading at panel points varies from 35 lbs. to 10,000 lbs., but 2,000 lbs. is a much more normal figure. The panel points are usually from 8 to 12 feet apart, but sometimes they are much more. The maximum load which can be supported at any point is of course less; it varies from 100 to 2,000 lbs. with 500-1,000 lbs. an average capacity. Where the capacity for hanging loads is given in lbs./sq. ft., the range is from 5 to 35 lbs./sq. ft. and 15 lbs./sq. ft. the average. Assuming that these figures may be multiplied by the panel point centers given above, it will be seen that this is approximately equivalent to a load of 1,000-2,000 lbs. at panel points.

One of the most marked advantages of a single-story factory is the much higher floor loading that is possible without excessively expensive construction. If the factory is built on good subsoil, the limiting floor load may well be the load bearing capacity of the soil, and in some cases this may be as high as ten tons per square foot. The maximum allowable floor loading encountered in the survey was 10,000 lbs./sq. ft. This was the limit in about 10 per cent of the sample. The figure was usually qualified by the respondents stating that the soil conditions governed the loading. In contrast, for multi-story buildings the maximum floor loading was 500 lbs./sq. ft. and the normal range 100-300 lbs./sq. ft. It appears that most single-story factory floors are designed to withstand a superimposed load of 500 to 1,000 lbs./sq. ft. where they are on grade. For limited areas over basement corridors, etc., this is frequently
reduced to 200-300 lbs./sq. ft., though it may considerably hamper the use of fork lift trucks and the moving of machinery.

In one reply it was stated that the floor structure included permanent trenches sixty feet apart for flexibility in utility distribution. It is not known what the normal provisions are for gravity waste disposal though when a wood block floor finish is used, it can be chased for small pipes and conduits.

Only one factory had any provision for relocating machinery requiring special foundations, and it is worth describing in detail, since it shows the lengths to which industry will go when flexibility is absolutely necessary. The plant was a press shop forming automobile parts where minor changes are probably made annually and major changes every two years. The floor at press operating level is suspended, with a basement underneath which is used for toilets and unit substations. The presses are supported on heavy steel beams, which in turn rest on girders spanning between concrete columns. The presses are moved by overhead cranes when the beams have been moved aside. After the presses have been moved, the operating floor has to be rebuilt, but this of course is far less trouble than casting a new foundation.

The floor finish in the vast majority of plants is concrete incorporating some form of hardener and sealer. In some cases the surfacing treatment can be quite elaborate involving many troweling operations with special machines. The next most popular floor finish is wood blocks usually laid with the end grain showing. This is primarily used by the manufacturers of machine tools, etc., and to a limited extent in the assembly industries--cars, household appliances, electronic equipment, etc. Wood is less damaging to accidentally dropped tools and is more comfortable to stand on, but it gets dirty easily and is difficult to clean. In all the factories in the sample in which drugs or surgical goods are made, vinyl or asbestos tile floors are used, and two of the food products plants have quarry tile. The use of these relatively expensive flooring materials is no doubt because of their better appearance, cleanliness, and in the case of the drug factories, the com-
fort of the employees.

There does not seem to be any floor finish which is reasonable in first cost and satisfactory for industrial use. If a finish is comfortable, it will not stand up to the extremely hard wear imposed—or if it does, it is uncomfortable and damaging to dropped tools. All the respondents who complained that their finish was unsatisfactory had concrete floors, and the majority of them were the industries where wood block would otherwise be used.

The external walls of factories are normally faced in brick and backed up with concrete block. This frequently stops at about five feet, or sill level in the case of continuous strip windows, and the space above is covered with a light sheet material. This sheathing may be steel, corrugated cement-asbestos, or more recently, aluminum. In some cases the brick is omitted and the masonry wall is all concrete block. A wall may be built more quickly with the bigger blocks, but brick is no doubt preferred because of its better appearance. If small windows are used, the wall is often completely built of masonry, but here too in recent examples a sheet material is more usual. There are a few examples with reinforced concrete external walls which are normally cast on the ground and tilted up into place and a few more which use precast concrete panels, but these two forms of construction are not common.

Provision is usually made for easily removing walls or parts of them for expansion. One clever and very simple idea which came to light was a continuous lintel in a solid masonry wall so that door openings could be knocked out anywhere.

On the inside the wall finish is normally painted concrete block though in earlier buildings where the wall is solid brick this material also forms the internal finish. An alternative to concrete block is a hollow-clay block glazed on the inward face, and this or plaster are the wall finishes used in the drugs and surgical goods factories. The light-weight sheathing of the upper part
of the wall is usually faced on the inside with sheets of metal, cement-asbestos, or other wallboard, with a layer of insulation between. The insulation itself may also form the internal finish in some cases.

In the newer buildings only two types of roof decking are used extensively. One is a pressed steel ribbed sheet from 18 to 30 inches wide with ribs 1 1/2 inches to 2 inches deep and 6 inches apart. These sheets come in lengths up to 20 feet and are made so that adjacent sheets can be interlocked. The decking is usually spot-welded on the site to the steel frame. The alternative is a precast concrete channel slab about 4 inches deep, two feet wide, and up to 12 feet long. These units can also be obtained with a sound-absorbing material facing on the underside. Precast or poured-in-place gypsum roof decks are also used to a limited extent, and there are one or two examples of both cement-asbestos and aluminum roof decking.

The use of sound-absorbing material either in the form of a suspended ceiling or in baffles hung down from the roof is not at all widespread in manufacturing areas in factories. Of the nine examples which use acoustical material, five are drugs and surgical goods manufacturers, and two make radios, electronic equipment, etc. The use of sound-absorbing ceilings by the drug manufacturers, in fact all of those included in the sample, is remarkable. It is not a noisy industry and one comes to the conclusion that the material is used to give better working conditions to attract high-grade female labor which would otherwise be employed in offices. This agrees with the other high standards of internal finish that these factories have; for example vinyl or asbestos tile floors and tile or plaster walls.

The latest factories in the United States do not normally have any overhead natural lighting, and in this respect they stand out in contrast to the earlier examples in which monitor or sawtooth lighting was normally incorporated as part of the structure. If 1952 is taken as the dividing line, only 15 per cent of the factories built since then have overhead natural lighting against about 60 per cent
before this date, and before 1937 the completely artificially
lit plant was almost unknown. The arguments against natural
overhead lighting are outlined below:

A steel truss frame and the increasing accumulation of over-
head gear seriously reduces the effectiveness of natural light;
The inclusion of monitors, etc., does not reduce the cost of
installing artificial lighting which is still required for dark
days and night work;
Overhead glazing requires constant maintenance to prevent it
from leaking;
The glass gets dirty easily and has to be cleaned frequently,
which adds to the maintenance cost;
The heat loss in winter and the gain in summer when air condi-
tioning is used increases the running cost of the heating or
cooling system appreciably;
The psychological advantages of natural lighting do not compare
with those of air conditioning and good artificial light.
It would be worth investigating the economic aspects of these argu-
ments further.
The factories built after 1952 which had overhead natural lighting
were primarily the metal working assembly industries, the biggest
single group being machine tool manufacturers. The areas of the
factories varied uniformly from 25,000 square feet to 500,000 square
feet, so there does not appear to be any appreciable increase in
natural lighting for small factories. In some of these cases the
respondents stated that the overhead lighting was by glass reinforced
plaster material, and this presumably eliminates some of the mainten-
ance disadvantages of glass. Monitors are the most popular method
of overhead lighting, but sawtooth (or north light) glazing is not
as rare as was supposed. In the later examples there is an indica-
tion that other forms of lighting are becoming more popular—pro-
bably plastic dome lights. Colored glass to reduce the heat gain
in summer is not used much in overhead lighting.
The arrangements made for side lighting the factories do not show such a dominant trend, nor would it be expected since the economic arguments against overhead glazing do not apply so much and the psychological advantages of a view out of the building are stronger. A quarter of the recent buildings do not have any side lighting at all, but there is no indication that this is increasingly common practice. Half of these factories were air conditioned, and all of them were of course mechanically ventilated. When side wall glazing is used, there are signs that the all-glass wall is no longer as popular as it once was. Instead recent practice is to use either small individual windows or a continuous strip of glazing at eye level. The small window solution is rather more common. Colored glass, either blue or green, to control heat gain and sky glare is used more in side lighting than in overhead lighting, though even here it is not very common. Where the factory is large in area, the usefulness of small windows would seem to be limited to the inhabitants who are near the external walls. In these cases the continuous strip of window at eye level or even the glass wall if the heat gain and sky glare can be controlled should be better, but there is no indication that the decision is made on this basis.

Fire Precautions

The structural provisions for fire protection made in the factories represented in the sample present a confusing picture and one which defies analysis. It was expected that there would be an appreciable increase in the degree of fire protection in the buildings built after the disastrous General Motors Livonia Plant fire of 1953, but this is not apparent. Since this fire illustrates so well the hazards in the modern industrial building, it will be described in detail. The fire started by sparks from an oxy-acetylene torch igniting a rust-inhibiting liquid in a long drip tray. Although the fire was immediately attacked with hand extinguishers, hot gases and heavy smoke from burning oil condensate and oil-soaked wood block flooring became trapped under the continuous unventilated steel roof deck and forced the fire fighters to retire. The hot
gases then melted the asphalt built-up roofing which dripped through the steel deck and was spontaneously ignited below, causing the fire to spread throughout the plant. The fire was then out of control, and in less than an hour the whole 1,500,000 square feet of factory was ablaze. The direct losses were estimated at $55 million, and the indirect losses may have been five times that amount.

The National Fire Protection Association has said that the main factor in the Livonia Plant fire was an undivided fire area of 1,502,500 square feet in which the absence of fire walls and roof vents denied access for fire fighting and prevented the localization of heat and smoke. Other factors in order of importance were: lack of sprinkler protection where the fire started; lack of carbon dioxide fire protection over the drip tray and the unprotected steel construction, in particular the poor insulation provided by the steel roof deck between the heat below and the built-up asphalt roofing above.

In an older factory building where overhead lighting is incorporated as part of the roof structure, a fire would probably not be so serious because the glass would break and allow the hot gases to escape. The new General Motors plants have automatically opening heat vents with an area equal to 2.5 to 5 per cent of the floor area they serve installed in the roof and the plant divided into areas of 250,000 square feet (10,000 square feet for hazardous areas) by fire curtains. These are incombustible barriers extending from the underside of the roof to the bottom of the truss and which contain the smoke and hot gases in the limited area they enclose. Fire curtains do not interfere with production line layout or with subsequent changes. In addition especially high fire load areas are protected by full-height non-combustible fire walls, and there is sprinkler protection over the whole factory area. The Ford Motor Company's new plant at Mahwah, New Jersey,\(^1\) has automatic heat vents which are equal to .3 per cent of the floor area, the factory being divided into 72,000 square foot areas by fire curtains.

Again there are fire walls around especially hazardous areas and complete sprinkler protection.

Most of the factories surveyed had sprinkler protection over all, or almost all, the floor area, but there are significant exceptions. Of the plants which had no sprinkler protection three were food product factories and four primarily the metal working industries. In addition there were nine examples with less than half the floor area sprinkled, and these too produced mainly metal goods. In such cases the sprinklers are limited to the hazardous areas, and probably the fire load in the rest of the plant does not warrant their use. In most of the factories with limited sprinkler protection there are other forms of fire protection, generally heat vents, but sometimes fire walls or curtains. Each sprinkler head usually serves 100 to 120 square feet of floor area, but there are examples where there is one head to every 50 square feet or even less in high fire load areas.

About half the factories in the sample have heat vents generally located in the roof, and it seems to be growing practice to make these automatic in operation. The standard vent area appears to be about 2 to 3 per cent of the floor area served by the vent, but the size varies from .01 per cent to 20 per cent or more especially in early examples where the vent area is the overhead glazing. Each heat vent serves about 5,000 to 10,000 square feet of floor area though this figure too varies widely. The buildings with heat vents are not limited to one group of industries or to large plants.

In spite of the disadvantages of fire walls in obstructing layout changes, they are more common than fire curtains. There is some indication however that they are not used in plants that have line production processes and those that make frequent layout changes. Generally, fire walls enclose the hazardous areas, but where they are used to break the floor area down into smaller fire zones, the walls divide the plant into 50,000 to 150,000 square foot areas. Surprisingly, from the survey fire walls appear to be more common in smaller plants than in large ones.
In more than half the examples where fire curtains are used, they subdivide the area enclosed by fire walls into smaller zones. Fire curtains enclose anything from 10,000 to 100,000 square feet, but in most cases the area is 30,000 to 50,000 square feet. They are normally used in conjunction with heat vents. Only five factories in the sample have the full fire protection advised by the National Fire Protection Association, which is similar to that in the latest General Motors and Ford plants.

Power Distribution

The cost of the power distribution system in a factory represents some 10 to 20 per cent of the total capital expenditure. It is therefore one of the most expensive single items aside from the structure and one of the principal factors in determining the adaptability of a plant.

The size of a plant in terms of power used is indicated by the total plant demand in kilovolt amperes (KVA) which is the amount of electrical energy normally required. It is on this basis that the power distribution system of a factory should be examined. The installed capacity of the substations, switchgear, etc., will normally be a figure in excess of the plant demand, and the ratio between the two indicates the reserve available for increased mechanization or expansion. The total connected load of a plant is the power required if everything was running at once; it is normally more than the plant demand and may be more than the installed capacity.

To show the power required by different industries and to give some idea of the machine density, the total plant demand may be expressed in terms of KVA/1000 sq. ft. which is roughly equivalent to watts/sq. ft. The amount of power used by the factories in the sample varies from 2 to 37 KVA/1000 sq. ft., depending of course on the manufacturing process, the degree of mechanization, and the machine density. The range and the normal figure for the different types of manufacturing represented is shown in Table 4.
There are four different methods used by the factories in the survey for distributing the power to the utilization points. The choice of method depends on the total plant demand and the incoming voltage. The methods are tabulated below.

Table 5

1. Incoming power to master substation to unit substation to machines.
2. Incoming power to unit substation to machines.
3. Incoming power to master substation to machines.
4. Incoming power to machines.

The first two methods are used when the total plant demand is relatively high, i.e. over 2000 KVA. The use of a master substation depends on whether the power supply is higher than voltage which codes and economics allow to be transmitted through the buildings. The master substation is usually located outside the plant either in the open or in a power house. In some cases it belongs to the utility company. From the master substation the primary cable is usually taken overhead to the unit substations which are located near areas of high power consumption. This system gives the maximum flexibility with low cost because there are no long secondary runs from the main transformer to machines, the voltage drop is lower, and less copper is used. The short runs of secondary
feeders make machine relocation easier and if necessary for production line changes, the unit substations can be moved. The last two methods of power distribution are used when the total plant demand is less than 2000 KVA. Again the installation of a master substation depends on the voltage of the incoming power. Where several utility voltages are available, the choice is based on the relative cost of power and the distribution system the voltage requires.

The type of circuit used is usually determined by the reliability required in the power distribution system; for instance, a higher reliability factor may be needed if the type of manufacturing in the plant involves continuous processes. The primary circuit runs from the master substation or main switchgear to the unit substations, and the secondary distribution system feeds the machines from the unit substations or in the case of small plants, from the main substation. Either circuit may be of three types. In a simple radial circuit, which is by far the most popular and also the lowest in first cost, one feeder serves each substation or utilization network. A selective radial system has an alternative feeder to each substation or busduct, and in a looped system all substations or distribution networks are connected together. The looped circuit layout is not common in industrial buildings, and it is only used where the power load varies appreciably from place to place. In the sample there is no indication that the plants which have continuous processes favor any particular type of circuit, though they frequently locate the primary cable under the floor for increased reliability.

The means of secondary distribution is almost evenly divided between busduct and cable in conduit, but the factories that use busduct are primarily the assembly and metal-working industries and those which make frequent layout changes. Busduct, especially the plug-in type, is extremely flexible. To relocate a machine, it is simply disconnected, moved, and reconnected without any changes in the machine power supply if the busduct is at the same height throughout the factory. The secondary distribution voltage
is usually 480 or 440, though in many cases lower voltages are used. The higher voltages are becoming more common, and two respondents complained that their 208-volt system was inadequate. The distance between the utilization busduct in the industries where it is primarily used for secondary distribution varies from 20 to 100 feet with about 40 feet being the usual spacing.

Artificial Lighting

As one would expect, fluorescent lighting is the normal means of lighting modern factories, but there are still plants, even recent ones, which have incandescent or mercury vapor lighting. The factories that use mercury vapor are chiefly the assembly and tool-making industries, and incandescent tends to be installed where the population density and the lighting levels required are low. These forms of lighting are not limited to the factories which have overhead natural light, which makes it surprising that mercury vapor is used in the industries which often have critical visual tasks. The average level in the manufacturing areas of the factories in the sample is 40 foot candles, but it varies ten foot candles each side of this for different processes. The average figure for different types of manufacturing is given below.

Table 6

<table>
<thead>
<tr>
<th>Processes</th>
<th>35 foot candles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mills - woolen fabrics</td>
<td>35 &quot; &quot;</td>
</tr>
<tr>
<td>Heavy assembly - aircraft, etc.</td>
<td>35 &quot; &quot;</td>
</tr>
<tr>
<td>Paper products</td>
<td>35 &quot; &quot;</td>
</tr>
<tr>
<td>Building products</td>
<td>35 &quot; &quot;</td>
</tr>
<tr>
<td>Machine tools, electric tools, etc.</td>
<td>40 &quot; &quot;</td>
</tr>
<tr>
<td>Clothing and shoe manufacturers</td>
<td>40 &quot; &quot;</td>
</tr>
<tr>
<td>Light assembly</td>
<td>40 &quot; &quot;</td>
</tr>
<tr>
<td>Medium assembly</td>
<td>40 &quot; &quot;</td>
</tr>
<tr>
<td>Food products</td>
<td>45 &quot; &quot;</td>
</tr>
<tr>
<td>Radio and electronic equipment</td>
<td>50 &quot; &quot;</td>
</tr>
<tr>
<td>Drugs and surgical goods</td>
<td>50 &quot; &quot;</td>
</tr>
</tbody>
</table>
Heating and Ventilating

The heating and ventilating of American factories is almost always by the same air circulating system. In the sample there were only three exceptions to this norm, and they were all relatively early plants which used a low temperature radiant heating system, and two were multi-story. There are rather more examples which used a mixed heating system, but this too is far from common, and in many cases the respondents may have included the heating system of the office space. The normal system of heating, where there are no other climatic control complications, is by unit heater, drawing fresh air in through the roof and frequently blowing directly into the manufacturing space but sometimes distributing the air through a duct system. Ducts tend to be used when the ceiling height is low and the population density high to achieve proper distribution. The use of more complete climatic control—filtered air, humidity control, and cooling—depends primarily on the process. For instance, the plants which manufacture precision instruments and those that require extreme cleanliness have most of the manufacturing area supplied with filtered air. The processes which use material on which moisture has an adverse effect—for example, the cardboard container manufacturers—have humidity control, and so on. In addition there are other factories of course where all or part of the area is air conditioned for the employees' benefit. These examples tend to be concentrated in the types of manufacturing which demand a high population density. Of the hundred factories in the sample, 28 had more than a quarter of the area filtered, 15 a quarter under humidity control, and 18 a quarter of the area cooled.

The exhaust side of the ventilation system is usually by roof exhaust fans when a simple unit-heater system is used. There are however a considerable number of factories which have part natural ventilation and a few which rely completely on this means. Most of the recent examples which rely on natural ventilation are under
50,000 square feet in area, though some of the earlier ones are much bigger. A ducted air exhaust system with provision for recirculation is necessary of course when the factory is air conditioned. Very little information on the rate of air change and the amount of recirculation was given in the completed questionnaires. The air change rate appears to vary from 1/2 to 20 air changes per hour with 5 to 10 being the average. The highest rates of air change occur in the factories which do not have air conditioning, of course. The maximum recirculation of air varies from 10 per cent to 100 per cent, but about 75 per cent is the normal figure.

Materials Handling Equipment

The type of materials handling equipment used in a factory has an important influence on the structure. For instance, if fork lift trucks are necessary to the process, the clear internal height must be adequate to allow them to stack to the limit of their capacity and the floor strong enough to carry the load. Again, if overhead conveyors are used, the structure must be strong enough to support the weight of the conveying system and its load in addition to the roof.

From the answers given to this section of the questionnaire, the most striking thing from the building design aspect is the almost universal use of fork lift trucks. These appear to be used as much as the rest of materials handling equipment put together. Beyond this it is difficult to generalize, and the appendix giving the detailed answers to the question should be studied. It seems that the industries which primarily use fork lift trucks are paper product manufacturers, building products, processes such as detergents, and woolen mills. There are of course other plants which use fork lift trucks a great deal, but they do not seem to be used by the particular industry as a whole.

Overhead conveyors are used in 37 of the 100 plants, but only five manufacturers use this means of handling more than any other.
The industries which use overhead conveyors appreciably are radio and electronic equipment manufacturers, light assembly such as household appliances, and medium assembly--cars, etc. Overhead handling is also used to some extent by the manufacturers of tools. The heavy assembly industry is the only one which uses cranes for most of its materials handling, but 43 plants have a limited amount of overhead handling by this method. In fact there are only 20 factories in the survey which do not have some form of overhead-moving equipment. Floor conveyors--roller, wheel, or belt--are not often actually fixed to the structure, but in some factories this is the case. Only six plants do more than 50 per cent of their handling by this method. Elevators of course are mainly used in multi-story factories, and since they are normally installed at the time the structure is built, they need not be considered here. The only other type of materials handling equipment which is used a great deal by the factories in the sample is hand trucks, and these and power trucks do not affect the structure as much as the fork lift type.

Speed of Construction

The speed with which a factory building can be constructed is one of the most important factors in the design, since once the decision to build is made, the manufacturer's capital is unproductive until the plant is in operation. The need for fast erection may lead to compromises in the design of the structure, and it is undoubtedly the prime reason why a steel frame is the most popular construction. The duration of construction of the factories in the sample varies considerably, partly as one would suppose with the size of the building, but this does not account for every case. Multi-story buildings generally take longer to build than single-story examples because the construction is normally reinforced concrete or fire-proofed steel frame. The multi-story factories for which this information is given vary from 15,000 to 600,000 square feet and the construction time from 8 to 30 months for the same buildings. The
normal construction time for a multi-story building of 200,000 square feet is 15 months. Single-story factories of course are frequently built much more quickly. The shortest time reported in the survey is 3 months for a 50,000 square foot factory, and the longest 35 months for a 600,000 square foot factory. On the average a 200,000 square foot factory can be built in 10 months, though if required, this can be reduced to 8 months. Bigger factories do not take much longer to build; there are examples in the survey where 500,000 square feet have been built in 11 months and 780,000 square feet in 12 months, but 16 months would be a more reasonable time.
CHAPTER 2 - THE FACTORS INFLUENCING THE DESIGN REQUIREMENTS

A survey of existing buildings is one way of arriving at the design requirements of multi-purpose factory buildings, but for some of the most important criteria it is possible to check the conclusions against the equipment which determines them. In this chapter the factors which influence the major decisions are tabulated and discussed, and where standardized equipment determines the criteria, the critical dimensions or weights are given.

Bay Size

The bay size is determined by:

1. The adaptability required;
2. The size of product;
3. The type of assembly;
4. Amount of load-hanging capacity required;
5. Bridge crane sizes.

In most factories the bay size is not the most important design factor, as many people believe. Where the size of the product controls the column spacing, as for instance in a factory making heavy road machinery or aircraft, the dimensions must obviously be big enough for the product to pass through. In addition, there must be enough space between the lines of columns for easy access by machines, materials, and men. But there are very few products which are large enough to influence the bay size, and then the most important factor is the desire for clear floor space for a good production layout, and subsequent changes. The ideal is a factory with no internal columns at all, but this is seldom if ever possible and the cost prohibitive. Thus the bay size is a balance between the adaptability required and the cost of framing the span, for beyond a certain limit the weight of steel required increases out of all proportion to the usefulness of the bigger bay size. In this respect it should be remembered that the capital costs of the factory building are only 5 to 7 per
cent of the total production costs, and if an increased bay size results in higher productivity, it may well pay for itself. It has been said that every column wastes 10 square feet of floor space, and this should be taken into account when calculating the relative costs of different bay sizes.

From the survey there appears to be a preference for square bays, and although these are normally more expensive than rectangular ones, they do have the advantage of permitting the maximum flexibility for production line layouts in both directions.

If the amount of load-hanging capacity required is substantial, it will reduce the economical bay size in proportion to the extra load to be carried.

Where overhead bridge cranes are used, the column spacing in one direction is usually considerably less than the maximum span, to reduce the weight and size of the crane rails which span between the columns along the short dimension. The maximum span may also be influenced by the size and cost of the bridge cranes that are available. The large capacity models come in spans up to 100 feet, but the small load type, which use an I-beam girder, are limited to 50 feet.

Clear Internal Height

The clear internal height is determined by:

1. Working height of stacking equipment and load;
2. Height of machine tools;
3. Clearance required for overhead handling equipment;
4. Use of mezzanines and overhead walkways;
5. Size of product.

The clear height to the bottom of the roof structure is the most important dimension to be decided in designing a factory, since it is the main factor in determining the adaptability of the building. The average height of present factories is about 18 feet, and this is four feet higher than the average of a few years ago.
The standard stacking height of the smaller fork lift trucks is 10 feet, but most of them can also be obtained with a 12-foot stacking mechanism. If to this is added a load height of 8 feet, which is not unreasonable, the top of the stack of material is 20 feet high. In addition, some clearance is essential, and this establishes the clear height of the factory at 21-22 feet. The larger high-lift fork trucks stack to a height of 18 or even 24 feet. These are not often used inside the normal factory, but nevertheless the possibility remains. Of course, it is probable that vertical stacking space will only be required in the warehouse areas of the factory, but if the space is to be adaptable to changing requirements, adequate height for stacking is important everywhere.

The following table gives the recommended heights required in manufacturing areas.1

<table>
<thead>
<tr>
<th>Type of Production</th>
<th>Without Overhead Equipment</th>
<th>With Overhead Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-product assembly</td>
<td>9-14 feet</td>
<td>10-18 feet</td>
</tr>
<tr>
<td>on benches</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large-product assembly</td>
<td>Max. height of product + 75%</td>
<td>Max. height of product + 125%</td>
</tr>
<tr>
<td>on floor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small-product forming</td>
<td>Height of machinery + 100%</td>
<td>Height of machinery + 150%</td>
</tr>
<tr>
<td>Large-product forming</td>
<td>Height of machinery + 125%</td>
<td>Height of machinery + 125%</td>
</tr>
</tbody>
</table>

The height of machine tools may be anything up to 18 feet for heavy, large capacity units, but 12 to 14 feet is a more reasonable figure for the higher machine tools which are likely to be used in general manufacturing areas. Many tools of course are less than the height of the operator.

The clearance required for normal bridge cranes is 7 feet for up to 15 tons capacity, but for heavier cranes this will be increased to 10 feet. If to this is added the height of the load and that of machine tools, it gives a minimum clear internal height of about 30 feet.

1. Practical Plant Layout, Muther, McGraw Hill Book Company
Overhead monorail hoists require at least 4 feet clearance, and with a load the minimum height to clear machine tools must be about 22 to 24 feet. Neither overhead cranes nor hoists are common throughout most of the manufacturing areas covered by the survey, but provision must be made in an adaptable factory for overhead monorail conveyors. The clearance required for these is difficult to establish. The depth of the track and trolley is seldom more than 18 inches, but the track cannot normally be placed hard against the underside of the structure, and the load may vary considerably. For normal loads the clearance required will be 6 to 8 feet, but for bulky objects or small loads in tiered baskets the clearance may well be 10 feet. This gives a clear internal height of about 20 feet.

If mezzanine toilets or overhead walkways are suspended below the bottom of the trusses, they will require about 9 feet, including the depth of the floor structure. Another 9 feet must be considered the absolute minimum headroom under the mezzanine, and this should be much more if it is not to hamper layout changes. This gives a minimum height of 18 feet, but 22 would be considerably better. It is of course probable that more than two of the factors described above will occur at the same place. This is especially true if overhead walkways and overhead monorail conveyors are used. In this case a minimum height of 26 feet will be required unless the production floor is interrupted by the conveyor dipping down.

Provision for Hanging Loads

The load capacity of the structure depends on:

1. Weight of overhead conveyors and load;
2. Weight of monorail hoists and load;
3. Weight of parts of machines to be lifted out for repair;
4. Whether mezzanines or overhead walkways are required;
5. Weight of unit substation and busduct;
6. Weight of ventilation equipment.
The factories in the sample had a hanging load capacity varying from 100 to 10,000 pounds at panel points and 100 to 2,000 pounds anywhere. The average, however, is 2,000 pounds at panel points and 500 to 1,000 pounds anywhere, and this appears to be the absolute minimum that is acceptable. The load centers are normally from 8 to 12 feet apart, but they are sometimes much more.

The load carrying capacity and the weight of overhead monorail conveyors is normally up to 200 pounds per linear foot, but there are conveyor trollies made which will support much more. Since the normal support centers are 10 feet apart, this gives a point load of 2,000 pounds.

Monorail hoists, which are suspended from the roof, handle considerably heavier loads, in fact up to 30,000 pounds, although 10,000 pounds is probably an average figure. The weight of the hoist unit itself is also heavy, varying from 750 to 4,500 pounds with the 10,000 pound capacity units weighing about 2,000 pounds. This gives panel point loadings of 6,000 pounds for the average hoist and up to 13,000 pounds for the heavy capacity ones. Whether full provision for the largest hoists is required will depend on the weight of component parts of machine tools that have to be lifted out for repair or on the weight of the product. Monorail hoists are usually the only type of lifting equipment which is suspended from the roof. For heavier loads bridge cranes are used, and these rest on tracks supported by the columns.

The weight of the heaviest component parts of machine tools is one of the most important factors determining the load-hanging capacity. To be able to lift out the part of a machine needing repair overhead is frequently the only way of removing it without disturbing the production on adjacent machines. As factories become more mechanized and the machine density gets higher, this will become of increasing importance, especially where there are long continuous transfer machines alongside. Unfortunately, the manufacturers of machine tools do not have this information readily available. One of them, however, stated that the bare cast-
ings weighed up to 18,000 pounds.

One of the prime requirements of an adaptable factory is a flexible ventilating system, which means that unit heaters or unit air conditioners may be hung anywhere. Unit air conditioners are, of course, more complex and weigh considerably more. They vary from 6,000 pounds to 22,000 pounds for capacities of 8,000 to 35,000 cubic feet per minute. To this weight of the unit must be added a little for the weight of the supporting framework, but most likely the platform will be suspended from four panel points which gives a maximum load of approximately 6,000 pounds.

The power distribution equipment is usually placed overhead where it can be easily moved, and most of the factory busduct systems are designed for this mounting with the supports at 10-foot centers. The weight depends on the ampere rating of the busduct and on the number of lines in the circuit. It varies from 5 to 20 pounds per foot for copper bus and from 4 to 12 for aluminum. In 10-foot lengths this will give a load of 50 to 200 pounds at the supports. This of course is for a single busduct; if the runs are multiple, the load will be greater. Unit substations are among the heaviest objects which the roof may be required to support. The weights range from about 3,500 pounds for a 150 KVA transformer to 14,000 for one of 1,500 KVA capacity. In addition there is the weight of the high and low voltage switchgear which varies from 500 to 2,000 pounds, depending on the type. An average size substation of 750 KVA which is frequently used in factories weighs, with switchgear, about 10,000 pounds. If the platform supporting the substation is supported from four panel points, the load is 2,500 pounds.

Floor Loading

The live load which the floor may be required to support is determined by:

1. Weight of machine tools;
2. Weight of fork lift trucks, laden;
3. Weight of product and stacking height.
The maximum floor loading in the single-story factories surveyed was generally 500 to 1,000 pounds per square foot, and the multi-story examples varied from 100 to 300 pounds per square foot.

The weight of the standard production machine tools which do not require special foundations may be anything up to 500 pounds per square foot of base area. Detail figures are difficult to determine because the base dimensions are seldom given, but for extremely large machines the loading may be 1,500 pounds per square foot or even more. Even in "light" industry the trend is to use bigger machines performing multiple operations, so a high floor loading is to be expected.

The weight of laden fork lift trucks is also extremely high. If it is assumed that the weight is distributed over an area the size of the truck, the floor loading for a 4,000 pound capacity truck is about 600 pounds per square foot. The peak loads under the wheels are, of course, higher.

From this it seems that a floor loading of 500 pounds per square foot is barely adequate for many machine tools, and if fork lift trucks are used, the floor must be heavily reinforced to distribute the load over a wide area.
CHAPTER 3 - CONCLUSIONS

In this chapter the design requirements of a multi-purpose factory building are established and the scope of the design determined by comparing it with the facilities of the examples in the survey.

The existence of a "standard" factory building should not be in doubt since there are constant references to it in the literature on plant layout, and from architectural references it can be seen that a large proportion of the plants designed by the specialist firms are very similar to each other. In this respect it is worth quoting the report by W. Allen:¹

"The American scene stands out in marked contrast (to the European); instead of variety there is a dominant trend towards a single type of enclosure, developed to give a high degree of adaptability. Designers and clients alike support this move, declaring it to be in the best interests both of the country as a whole and of the individual firms. Adaptability, they say, is a national asset because it facilitates changes from war to peace production and vice versa, and by the same token it is an individual asset because it means a firm can look forward to a long useful life for its buildings without fearing that it cannot adapt them to industrial changes and because, should a sale become desirable, a unit can command a better price. The idea of adaptability will be found consequently to recur throughout this Report. The idea is the fruit of very expertly appraised experience and is already regarded as having added materially to the resilience and strength of American industry."

The arguments for using a multi-purpose building as against a specially designed and constructed factory are very strong. Briefly they are:

1. Lower initial cost;
2. Easier to sell, if necessary;
3. More adaptable to changes in layout or product;
4. Can be brought into operation more quickly.

From this it is apparent that for industries which have relatively simple manufacturing operations, as in the case of most consumer goods industries, the advantages of a multi-purpose building are quite overwhelming. For other industries with large or extremely heavy products or for the large-scale chemical processes, the multi-purpose building is not suitable.

The Problem

The possibility of prefabricating a multi-purpose factory building appears to be very good. It is probably not possible to design a complete "package" factory or even a series of "package" factories that would satisfy all the requirements of the consumer goods industries, but in any case this is not required. If we assume that the multi-purpose factory is to be a single-story structure—and the reasons given in Chapter 1 predetermine this—then the building may be considered to consist of two main parts:

1. A massive cast-in-place floor to resist the heavy loads of materials handling equipment and machine tools. This is "inert" and it must have all the adaptability required built in at the time of construction, since it is extremely expensive and time-consuming to alter afterwards. By its very nature this part of the structure cannot be standardized.

2. A superstructure supporting the roof, overhead handling equipment, electrical and other utility distribution, and from which other loads can be hung and moved about as required. This is the essential part of the multi-purpose factory which can be prefabricated.

The rest of the structure—the walls, etc.—is a small part of the structure and may be built in the conventional way.

The idea of a prefabricated framing system is not, of course, very different from the standard technique which is used at the moment, since the steel frame of the normal factory is shop fabricated—in fact some firms even keep their own stock of standardized trusses. There are, however, important differences in the requirements of the
Figure 1 - The Problem

The problem includes inadequate height for stacking with fork lift trucks, headroom for overhead walkways and monorail conveyors over machines, hanging loads from monorail conveyors, equipment hung from roof, power distribution system suspended from structure, and adequate height for mezzanines for toilets, substations, etc.

The basic structure consists of:

1. Light, adaptable superstructure supporting all services and overhead handling equipment; it may be changed easily to meet new conditions.
2. Massive cast-in-place floor slab to support heavy loads from trucks and machines; not easily adapted to changed conditions.
multi-purpose factory roof structure proposed here. Though the usual truss frame is a simple and flexible method of spanning large bays, it is not necessarily the best means of obtaining the adaptability required in a factory. Figure 2 illustrates this point.

The structure of the vast majority of factories is steel, and this material is well suited to a prefabricated system, though if the disadvantages of concrete can be overcome, there is no reason why it should not be used. These disadvantages are the increased construction time required for reinforced concrete and the difficulty of fixing suspended loads. A precast, prestressed system which is assembled on the ground and hoisted into place would overcome the first of these, and if adequate cast-in inserts are used, preferably of the continuous channel type, hanging loads may be easily fixed. Reinforced concrete does of course have considerably more fire resistance than the normal unprotected steel construction.

The Plan

The disposition of production lines and employee facilities in the horizontal plane is constantly being changed in factories, and ample provision for this must be incorporated in the design. For maximum layout flexibility the shape of the building should undoubtedly be rectangular. It is usual to make the plan with the dimensions in the ratio of 5:8 except in the larger factories where the long dimension is increased. This makes the normal size factory of 200,000 square feet approximately 360 by 540 feet. The ability to relocate if necessary limits the levels on which employee facilities can be placed to the main floor or the mezzanine because a basement location would be fixed. The provision of separate level access for materials and employees is desirable in all but the smallest factories. Thus the mezzanine level will be used for overhead walkways, toilets, locker rooms, etc. This position allows easy relocation, good supervision, and is cheaper than a basement location. Furthermore, if the headroom below is adequate, mezzanines interfere less with production lines than basement areas, where it is difficult
to make the floor strong enough and where the staircases create obstructions. The provision of suspended mezzanines does of course increase the required capacity for hanging loads, but the weight of these facilities will not be any greater than some of the other equipment which should be hung from the structure.

Bay Size

The main span in the factory building should be 60 feet, and for this distance the structure should be capable of carrying the full hanging load capacity described in a later paragraph. From the survey of existing buildings there appears to be a preference for square bays in spite of the extra expense this involves when conventional construction is used. To make a square bay economical, the structure should span in both directions—similar to a two-way concrete slab—which would naturally result in equal dimensions. The square bay will permit the same degree of adaptability for production line layout in both directions and allows the building to be extended in any direction while still maintaining the same degree of adaptability for the extra space. Figure 2 shows diagrammatically the structural system proposed for a multi-purpose factory.

 Provision for Hanging Loads

This is the most difficult requirement to meet in designing a factory. If each panel point is to sustain the maximum load that the manufacturer would like to hang from it and at the centers normally provided, the cost of the framing would be prohibitive. The solution to this is the second and major advantage of the two-way framing system described in the preceding paragraph. This allows the loads at panel points to vary, the heavier loads averaging out the points which are underloaded, since the full capacity is never required at all adjacent panel points. The load limit in this case is considerably more than that which a normal main and secondary truss frame would support. The system is explained in Figure 2.
Figure 2 - The Structural System

Beam loaded to limit
no load on this beam

panel points designed for
3000 lbs, unladen
adjacent beam is no help

standard framing system

the basic unit

panel points designed for
average load of 3000 lbs
if little load on adjacent
points load may be
increased because of two
way stress distribution

two-way framing system
For a multi-purpose factory the average design load at each panel point should be 3000 pounds, and any particular panel point should be capable of supporting 6000 pounds if the adjacent points are not loaded. Since practically all the equipment which is mounted overhead in a factory comes in ten-foot lengths with supports ten feet apart, the panel points should be ten feet in each direction. In addition, provision for supporting much lighter loads between these points is required for overhead electrical distribution and other service lines. This amount of load-hanging capacity, which is primarily based on the weights of components given in Chapter 2, is adequate for 96 per cent of the factories surveyed.

Clear Internal Height

The clear internal height to the underside of the roof structure should be 22 feet to give sufficient adaptability to the factory building design. This clearance is adequate for standard fork lift trucks to stack to the limit of their capacity, which is an important consideration, as this form of materials handling is universal in industry. A height of 22 feet also provides adequate headroom over normal machine tools for overhead monorail conveyors and mezzanine-level employee facilities. A lower internal height would not permit two-level circulation of materials and personnel, and a higher factory would be uneconomical for the majority of users. A factory building with a clear internal height of 22 feet would meet the requirements of 92 per cent of the factories surveyed.

Floor Loading

Since the multi-purpose factory is a single-story building, the main production floor will be on grade, and the provision of adequate floor loading does not present an insuperable problem. On the other hand, the bearing capacity is determined by the soil, and in selecting the site this should be taken into consideration. The floor slab should be capable of supporting a superimposed load of 5000 pounds per square foot, and this loading is adequate for 90
per cent of the factories in the sample. In addition, the floor construction must be sufficiently robust to distribute peak loads from trucks and heavy machines over a wide area without danger of cracking. The bearing capacity of various soils is given below.

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Allowable Bearing Value - 1000 lbs./sq. ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Massive bedrock without laminations, granite, diorite, and other granite rocks, gneiss, trap rock, folsite, and thoroughly cemented conglomerates</td>
<td>200</td>
</tr>
<tr>
<td>2. Laminated rocks such as slate and schist in sound condition</td>
<td>70</td>
</tr>
<tr>
<td>3. Shale in sound condition</td>
<td>20</td>
</tr>
<tr>
<td>4. Residual deposits of shattered or broken bedrock of any kind except shale</td>
<td>20</td>
</tr>
<tr>
<td>5. Hardpan</td>
<td>20</td>
</tr>
<tr>
<td>6. Gravel, sand-gravel mixtures, compact</td>
<td>10</td>
</tr>
<tr>
<td>7. Gravel, sand-gravel mixtures, loose; sand, coarse, compact</td>
<td>8</td>
</tr>
<tr>
<td>8. Sand, coarse, loose; sand, fine, compact</td>
<td>6</td>
</tr>
<tr>
<td>9. Sand, fine, loose</td>
<td>2</td>
</tr>
<tr>
<td>10. Hard clay</td>
<td>12</td>
</tr>
<tr>
<td>11. Medium clay</td>
<td>8</td>
</tr>
<tr>
<td>12. Soft clay</td>
<td>2</td>
</tr>
</tbody>
</table>

From this it will be seen that only two normal soil conditions do not have enough bearing capacity for the recommended floor loading. A floor loading of 2000 pounds per square foot, equal to the bearing capacity of the poorest soils, would meet the requirements of 80 per cent of the factories in the sample.

Natural Lighting

The majority of multi-purpose factory buildings constructed will be without any overhead natural lighting for the reasons given earlier in this report. However, since a limited number of manufacturers will require overhead lighting, the system should be

1. Boston Building Code
designed so that this can be added. It can take the form of a rigid frame unit standing on top of the main frame to form continuous monitors. The continuity of the main frame is required for hanging loads. This monitor arrangement is shown in Figure 4.

Side lighting is advantageous in all multi-purpose factories. The window area should be a continuous strip from a low sill, protected by a curb, to a height of eight feet. A continuous strip of glazing allows a wider horizontal angle of view than separate windows, which benefits the workers away from the wall. Limiting the height to eight feet reduces the sky glare and the solar heat gain in summer. This form of side wall glazing is illustrated in Figure 5.

Fire Precautions

Sprinkler protection throughout the factory will be required with one head between each of four panel points, i.e. ten foot centers in each direction. An automatic heat vent in the roof should be provided at the center of each bay with an open area of 5 percent of the floor area or 180 square feet, which meets the requirements of the National Fire Protection Association. Since fire walls and fire curtains enclose hazardous areas which move with layout changes, they cannot be built into the structure. Fire curtains and walls will be made of one of the demountable fire partitions which are commercially available.

Heating and Ventilating

A flexible heating and ventilating system is one of the prime requirements of a multi-purpose factory design. The degree of air conditioning and even the amount of air required cannot be standardized because it varies from one process to another and from place to place within the plant. Even if the building were specially designed for the manufacture of a particular product, the heating and ventilating system would still have to be adaptable to layout changes when, for instance, a heat-treatment area may be moved to another part of the plant. The normal method of
Figure 6 - Heating and Ventilating System

air circulation diagram

supply distribution ductwork

fresh air inlet

standard heater-air-conditioning unit on suspended platform

platform & unit lowered for alteration

cooling coil to be added

Figure 7 - Power Distribution System

load center unit substation on suspended platform

secondary voltage busduct feeder

plug-in busduct

high-voltage feeder

conduit machine drops

service pipes suspended

permanent underfloor trenches for gravity waste disposal
factory heating is by the standardized, commercially available unit heaters and air conditioning units. This system is ideally suited to the changing requirements of industry. In the simplest case where straight heating ventilating is required, the air can be brought in through an inlet in the roof, through the heating coils suspended directly below, then through the circulating fan and short duct runs to the positions required. The units incorporate a recirculating bypass for the majority of the return air, and the remainder which has to be exhausted to give the required air change rate is taken through roof fan units spaced between the heaters. In the summer the coils are not in use, but the fans are used to give simple ventilation. The next step, where the air is filtered, is exactly the same except that filter units are added to the intake side of the fan. For full or part air conditioning, cooling, humidity control, etc., the extra unit required is added to the basic heating unit. To make this system easily adaptable, the air-handling equipment should be mounted on a platform suspended from four panel points. The platform can then be lowered, the extra unit required for cooling, etc., added, the platform hoisted up again, and the ductwork and pipe connections made. Figure 6 shows diagrammatically the proposed system.

Power Distribution

The power distribution will also be suspended from the roof structure. This is the usual method since the busduct runs may be easily changed, and machinery may be moved from place to place without alteration to the connections if the distribution system is all at the same level. For factories designed for the manufacture of consumer goods where layout changes are frequently made, the power distribution will be entirely by a busduct system except for the actual connections to the machines. The average size multi-purpose factory is likely to have a total plant demand of 3000 KVA which means that load center unit substations will be used throughout the plants. These will be suspended with the switchgear and motor control centers on platforms at mezzanine
level. The master substation will be outside the plant either in the open air or in a separate power house.

The artificial lighting will be fluorescent and give a level of 50 foot candles on the working plane throughout the manufacturing areas. The power for these will come from the main distribution system either through small suspended transformers or from a single-phase to ground connection which with a 480-volt system gives 277 volts—suitable for high voltage fluorescent light. The uniform level of 50 foot candles is necessary for flexibility; at critical points it will be supplemented by local light at 120 volts. The lighting units should have an upward component of at least 30 per cent to relieve the contrast of the dark ceiling. The lines of units are normally continuous, since this saves the trouble of conduit connections between separate fixtures.

Service Line Distribution

The pipelines required for compressed air, steam, water, etc., will be suspended from the underside of the roof so that their location can be conveniently changed when necessary. The only service lines which cannot be in this position are drains for gravity waste removal from toilets and machines. The floor, which, as was pointed out before, cannot be easily altered, must therefore incorporate permanent trenches with covers, for drain pipes. The trenches should run along column lines at 60-foot centers in each direction because the production lines and thus the machines are normally arranged along column lines. The dimensions should be two feet wide and four feet deep, to allow sufficient fall from one end of the plant to the other. The cover must of course support the full superimposed floor load of 5000 pounds per square foot.

The Scope of a Prefabricated System

A prefabricated structural system designed to meet the requirements outlined here will suit 78 per cent of the factories repre-
presented in the survey. Since the sample was a fairly good cross section of manufacturing industries with only the basic raw material and large-scale process buildings omitted, we can by extrapolating assume that it will be adequate for three quarters of manufacturing industry. The facilities that this outline was compared with are of course those reported in the questionnaire. There is no way of knowing whether the manufacturers involved were using their facilities to the utmost.
APPENDIX 1 - THE QUESTIONNAIRE SURVEY OF EXISTING FACTORIES

Introduction

The purpose of this survey was to establish the basis of present factory design practice in the United States. For this reason the questionnaires were primarily directed at the latest examples, but it was hoped that the number of earlier buildings would be adequate to isolate any distinct trends in design policy which would show the direction of future development.

It was thought that if the buildings containing a particular manufacturing process were compared, it would be possible to discover the important building requirements of that process and by this means the facilities needed for all the processes represented in the sample. From this could be found the scope and range of adaptability required of a multi-purpose factory building.

Selection of the Sample

The number of questionnaires that could be sent out was largely determined by the number of company names and addresses easily available. Since time was short, no pilot survey to predict the response to a questionnaire was made. It was the general opinion of others more experienced in this field that a 20 per cent response was all that could be expected from a questionnaire which took some time and effort to fill out, even if it came from a respected academic institution. Since a hundred answers would be an adequate sample, it was decided that five hundred questionnaires would be enough.

The only way of insuring that the sample included the latest plants was to send the questionnaire to the largest companies on the assumption that they had probably built new plants within the past few years. Three hundred thirty-one of the five hundred names were taken from the 1956 "Fortune" directory of the five hundred largest United States industrial corporations. Oil companies, steel companies, and others involved in similar processes were omitted because their buildings are too specialized to be included in this
survey. The remainder of the sample was picked from the 1956 Poor's Register of Directors and Executives. It included all types of manufacturing, but there was some emphasis on the durable consumer goods industries. To insure that these companies were of a reasonable size, only those employing more than a thousand were used.

The letter accompanying the questionnaire was addressed to the Vice President in Charge of Construction; it asked him to forward the form to the plant engineer of the company's latest plant. The letter also stated that the replies would be confidential and that the company's name would not be used.

A blank copy of the questionnaire is included in this appendix. The questions were designed for the answers to be expected from a homogeneous single-story plant manufacturing and assembling radios, household appliances, cars, etc. As a result, it was difficult for the process industries and those companies with multi-story buildings or with composite plants to answer. In the replies to the questions it was apparent that a pilot survey would have been helpful in designing the questionnaire. Some of the wording was ambiguous; for instance, "bay size", which can mean the dimensions of a manufacturing bay rather than the column spacing. Again the majority of answers to the question "How frequently do you make layout changes?" was subjective--"Frequently", "Seldom", etc. This question should have included a check list of time intervals with the request to check one.

One hundred and nine completed questionnaires have been returned, and the first hundred of these constitute the present sample. This response is better than expected. The distribution by date and the wide variation in size of plant and in the products manufactured is adequate to fulfill the purpose of the survey.

The Figures

The results are plotted on Figures 1 to 23. All the plants are arranged chronologically down the figure, and each occupies the
same line on every sheet. By this means it is possible to compare answers by placing figures adjacent to each other. If there was no answer to a question, the space is left blank. On those figures showing the answer to a question where a trend in design might be expected, the dates when the plants were built are given; and where multi-story construction would condition an answer, these too are marked. In the pocket at the back of this report there is a series of fourteen transparent overlay sheets which select the factories with the same type of manufacturing process or those designed by specialist firms from the rest of the sample.

The Questions and Answers

The first part of the questionnaire is concerned with general questions. The name of the company and the location of the plant were included so that it would be possible to visit the plant in the future, if this were desirable. It also served as a means of checking the information against other references.

The plants are broadly classified by the products manufactured or the type of process on the transparent overlay sheets. The answers in detail are given in Table 1.

The date when the plant was built was essential to see the distribution of the sample and to be able to isolate any trends in design. The duration of construction was included to give some idea of the normal speed of factory building. From Figure 2 it will be seen that this varies appreciably, even when the area of the plant is taken into consideration. The examples built in 1956 and 1957 seem to have been constructed more quickly than the earlier factories.

The name of the architect or engineer was asked for so that it would be possible to pick out those designed by the large specialist firms to see if they were similar and if they differed in any way from the rest. Any architectural or engineering firm which has designed at least two of the sample was considered a specialist
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cash registers, accounting machines</td>
</tr>
<tr>
<td>2</td>
<td>Automobiles</td>
</tr>
<tr>
<td>3</td>
<td>Heavy-duty trucks</td>
</tr>
<tr>
<td>4</td>
<td>Lubricant application equipment</td>
</tr>
<tr>
<td>5</td>
<td>Phonograph records</td>
</tr>
<tr>
<td>6</td>
<td>Electrical appliances</td>
</tr>
<tr>
<td>7</td>
<td>Pharmaceutical chemicals</td>
</tr>
<tr>
<td>8</td>
<td>Belts, buckles, etc.</td>
</tr>
<tr>
<td>9</td>
<td>Automotive trim</td>
</tr>
<tr>
<td>10</td>
<td>Electric, gas, and water controls</td>
</tr>
<tr>
<td>11</td>
<td>Cameras and projectors</td>
</tr>
<tr>
<td>12</td>
<td>Electronic and communication equipment</td>
</tr>
<tr>
<td>13</td>
<td>Frozen concentrates</td>
</tr>
<tr>
<td>14</td>
<td>Agricultural implements</td>
</tr>
<tr>
<td>15</td>
<td>Men's shoes</td>
</tr>
<tr>
<td>16</td>
<td>Bread</td>
</tr>
<tr>
<td>17</td>
<td>Shoes</td>
</tr>
<tr>
<td>18</td>
<td>Baby foods</td>
</tr>
<tr>
<td>19</td>
<td>Printing magazines</td>
</tr>
<tr>
<td>20</td>
<td>Home appliances</td>
</tr>
<tr>
<td>21</td>
<td>Portable pneumatic and electric tools</td>
</tr>
<tr>
<td>22</td>
<td>Upholstered furniture</td>
</tr>
<tr>
<td>23</td>
<td>Corrugated cartons</td>
</tr>
<tr>
<td>24</td>
<td>Clothes dryers</td>
</tr>
<tr>
<td>25</td>
<td>Machine tools</td>
</tr>
<tr>
<td>26</td>
<td>Aircraft parts</td>
</tr>
<tr>
<td>27</td>
<td>Office equipment</td>
</tr>
<tr>
<td>28</td>
<td>Automobile locks</td>
</tr>
<tr>
<td>29</td>
<td>Paper cups and containers</td>
</tr>
<tr>
<td>30</td>
<td>Boilers and associated products</td>
</tr>
<tr>
<td>31</td>
<td>Cotton cloth finishing and sewing</td>
</tr>
<tr>
<td>32</td>
<td>Synthetic detergents</td>
</tr>
<tr>
<td>33</td>
<td>Synthetic detergents</td>
</tr>
<tr>
<td>34</td>
<td>Chemical cellulose</td>
</tr>
<tr>
<td>35</td>
<td>Conveyors</td>
</tr>
<tr>
<td>36</td>
<td>Arc welding machines, motor generator sets</td>
</tr>
<tr>
<td>37</td>
<td>Cameras</td>
</tr>
<tr>
<td>38</td>
<td>Oil well pumping equipment</td>
</tr>
<tr>
<td>39</td>
<td>Meat and meat products</td>
</tr>
<tr>
<td>40</td>
<td>Radios</td>
</tr>
<tr>
<td>41</td>
<td>Radios, television sets</td>
</tr>
<tr>
<td>42</td>
<td>Gas lift trucks</td>
</tr>
<tr>
<td>43</td>
<td>Carpet</td>
</tr>
<tr>
<td>44</td>
<td>Frozen concentrates</td>
</tr>
<tr>
<td>45</td>
<td>Women's shoes</td>
</tr>
<tr>
<td>46</td>
<td>Outdoor lighting fixtures and equipment</td>
</tr>
<tr>
<td>47</td>
<td>Cosmetics, drugs</td>
</tr>
<tr>
<td>48</td>
<td>Plastic packaging</td>
</tr>
<tr>
<td>49</td>
<td>Machine tools</td>
</tr>
<tr>
<td>50</td>
<td>Brakes and valves</td>
</tr>
</tbody>
</table>
Table 1 (cont'd)

<table>
<thead>
<tr>
<th>51</th>
<th>Road machinery</th>
<th>76</th>
<th>Warehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>Cooking utensils</td>
<td>77</td>
<td>Air conditioning equipment</td>
</tr>
<tr>
<td>53</td>
<td>Mufflers and tail pipes</td>
<td>78</td>
<td>Knitwear</td>
</tr>
<tr>
<td>54</td>
<td>Ice cream</td>
<td>79</td>
<td>Optical frames</td>
</tr>
<tr>
<td>55</td>
<td>Carbonated drinks</td>
<td>80</td>
<td>Fibre ribbons</td>
</tr>
<tr>
<td>56</td>
<td>Chewing gum</td>
<td>81</td>
<td>Wallboard and plaster</td>
</tr>
<tr>
<td>57</td>
<td>Warehouse (refrigerated)</td>
<td>82</td>
<td>Floor tile</td>
</tr>
<tr>
<td>58</td>
<td>Die casting and machining aluminum parts</td>
<td>83</td>
<td>Paper containers</td>
</tr>
<tr>
<td>59</td>
<td>Surgical sutures</td>
<td>84</td>
<td>Polyethylene bags</td>
</tr>
<tr>
<td>60</td>
<td>Warehouse</td>
<td>85</td>
<td>Machine parts</td>
</tr>
<tr>
<td>61</td>
<td>Engine parts (aircraft)</td>
<td>86</td>
<td>Corrugated boxes</td>
</tr>
<tr>
<td>62</td>
<td>Airframes</td>
<td>87</td>
<td>Cigars</td>
</tr>
<tr>
<td>63</td>
<td>Pigment</td>
<td>88</td>
<td>Shoes</td>
</tr>
<tr>
<td>64</td>
<td>Photographic goods</td>
<td>89</td>
<td>Aluminum products</td>
</tr>
<tr>
<td>65</td>
<td>Plastic parts</td>
<td>90</td>
<td>Automatic controls</td>
</tr>
<tr>
<td>66</td>
<td>Automotive stampings</td>
<td>91</td>
<td>Steel strapping</td>
</tr>
<tr>
<td>67</td>
<td>Shirts</td>
<td>92</td>
<td>Soup</td>
</tr>
<tr>
<td>68</td>
<td>Surgical sutures</td>
<td>93</td>
<td>Transformers</td>
</tr>
<tr>
<td>69</td>
<td>Heating and air conditioning equipment</td>
<td>94</td>
<td>Rodenticides</td>
</tr>
<tr>
<td>70</td>
<td>Wool fabrics</td>
<td>95</td>
<td>Oil well drilling tools</td>
</tr>
<tr>
<td>71</td>
<td>Fabrics</td>
<td>96</td>
<td>Aluminum castings</td>
</tr>
<tr>
<td>72</td>
<td>Pharmaceuticals</td>
<td>97</td>
<td>Building products</td>
</tr>
<tr>
<td>73</td>
<td>Semi-conductors</td>
<td>98</td>
<td>Plumbing products</td>
</tr>
<tr>
<td>74</td>
<td>Polyethylene foam</td>
<td>99</td>
<td>Diesel engines</td>
</tr>
<tr>
<td>75</td>
<td>Air conditioning equipment</td>
<td>100</td>
<td>Arms, ammunition, industrial tools</td>
</tr>
</tbody>
</table>
firm for this purpose. The names and the position on the graphs of the examples designed by these firms are given in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Firm</th>
<th>Positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austin Company</td>
<td>10, 11, 24, 35, 36, 42, 73, 93, 99</td>
</tr>
<tr>
<td>Giffels and Vallet</td>
<td>12, 39, 72</td>
</tr>
<tr>
<td>Albert Kahn Associates</td>
<td>26, 56, 66</td>
</tr>
<tr>
<td>Lockwood Greene Engineers</td>
<td>71, 75, 92</td>
</tr>
<tr>
<td>Bechtel Corporation</td>
<td>32, 33</td>
</tr>
<tr>
<td>Shaw, Metz and Dolio</td>
<td>41, 53</td>
</tr>
<tr>
<td>Indenco Engineers</td>
<td>49, 55</td>
</tr>
</tbody>
</table>

The fifteen plants designed by the first three firms agree completely with the estimate of one sixth or one seventh of the total plant construction mentioned elsewhere\(^1\).

Plan

Since it is impossible to gain anything but a very general picture of the horizontal layout of a plant from a questionnaire, this section was primarily aimed at discovering the vertical disposition of employee facilities.

The number of people employed in the plant is another way of stating its size. It is a key figure for arriving at the density of population which may determine the vertical layout. The density in terms of square feet per person and the percentage of car park capacity to the total number employed is shown in Figure 3.

The area of manufacturing space and the area of warehouse space is plotted on Figure 1, where those examples which have no room for expansion are also indicated. Very few plants do not have room to expand, and most of these are early examples which have presumably expanded to the limit of their site in the densely built up areas where old factories are generally situated.

There appeared to be some confusion in the terms describing the location of offices. "Offices within factory" was intended to mean completely enclosed within the manufacturing building and "adjacent outside" a block with a common wall with the factory. Since most

\(^1\) W. A. Allen, "Modern American Factory Design", D.S.I.R., U.K.
respondents checked the "within factory" space, which is not a common arrangement, it would suggest that they reserved "adjacent outside" for a detached office building. This answer, together with the location of toilets and locker rooms and the use of separate level access ways, is shown in Figure 4.

The answer to the line assembly-shop assembly question gives some idea of the horizontal organization within the factory. This too will affect the placing of toilets and the arrangements for access. For instance, by comparing Figures 4 and 5, it can be seen that the plants having separate level access primarily use line assembly.

The aisle spacing was included because it was thought that this in conjunction with the power used per unit area and the spacing between utilization buses would give some indication of the machine density, which it is believed is an important factor in determining the efficiency of a plant. The aisle widths and spacing are shown on Figure 6.

The frequency of layout changes is one of the most important questions in the questionnaire, as it determines the flexibility required of the structure. Unfortunately, most of the answers were indefinite, but an attempt has been made to plot both actual time interval and the subjective description, on Figure 7.

Structure

Most of the factories described in the questionnaire were single-story, as was expected. In the later half of the sample (after 1955) only five multi-story plants are represented as against twelve from the earlier section. This confirms the well known trend toward single-story buildings. The single-story description includes mezzanines and part basements, and multi-story two or more complete floors. In some cases of composite plants, both were checked and the answer was corrected on the basis of other information given. The effect of multi-story construction is most noticeable in bay sizes and the allowable floor loading.
The details of the structure, framing material, roof deck, wall materials, and floor finish are shown on Figure 8.

The bay size and the clear interval height are the two dimensions which control the adaptability of a factory building. For large products such as aircraft, this is clearly evident. For small products with overhead handling or high stacking, the height may be the limiting dimension. In both questions where two dimensions were given, the limiting or smaller one was used. The bay size is shown chronologically on Figure 9 and as a percentage of the sample on Figure 10. The clear internal height is plotted on Figure 11.

It is surprising that only about half the factories represented in the sample had any provision for hanging loads. It was thought that this was almost universal practice in American factories. Of the remainder, thirty stated that they had no provision, while the rest did not answer the question. On Figure 12 it was necessary to add another way of answering this question, since twelve replies were given as weight per square foot of floor area. On this figure the size of the dot indicates the number of examples with a certain load hanging capacity and the small sub-figures the number of panel points per span. The normal provision is 1000 or 2000 pounds at panel points and up to 1000 pounds anywhere.

Figure 13 shows the allowable live floor loading. It is plotted on a contracting scale because in some single-story examples the loading is solely determined by the soil conditions, and if these are good, the figures are very high.

Only one respondent had any provision for moving machinery requiring special foundations. This was an automotive press shop where some changes are made annually. Normally it appears that if there is heavy machinery, it is seldom moved without drastic construction work.

Except for easily removable walls, continuous lintels, etc., and in one instance permanent underfloor trenches 60 feet o.c. for utility distribution, there were no interesting answers to the question "Any other structural provision for flexibility?"
The overhead daylighting arrangements (Figure 14) show one of the clearest trends; in this case to do away with it. In the latest examples there is some indication that it may be coming back into use. Some of these answers stated that the overhead lighting was by glass reinforced translucent plastics which presumably avoid the maintenance disadvantages of glass and industrial sash.

The side lighting does not show such clear trends. From 1952 on, about a quarter of the sample has no window area at all, but this is not dominant.

Fire Precautions

The questions in this section are based on an article in "Architectural Forum"\(^1\) which described the fire precautions taken in the new G.M. and Ford Motor Company plants since the serious G.M. Livonia Plant fire of 1953. It was expected that there would be a significant increase in the use of heat vents and fire curtains and walls after that date. From the answers given, this is not the case.

Heat vents are openings in the structure, usually in the roof, which either open automatically or by hand when there is a fire, to allow superheated air to escape, which prevents the fire spreading. The hot air is contained in one area by fire curtains or walls. Fire curtains are incombustible barriers normally extending from the underside of the roof to the bottom of the trusses or lower but which do not reach the floor and interfere with the production layout. Fire walls are complete barriers with fire doors over the openings. In many cases these are only around the hazardous points—furnace rooms, heat-treating areas, etc.

All the information given in the completed questionnaires is shown on Figure 15.

Power Distribution

This is an important and complex subject but one which has little

1. Architectural Forum, September, 1955
effect on the structure of the building. It will be covered in more detail in a later appendix to this report. The details of the power distribution of the plants included in the sample are shown on Figure 16.

The total plant demand in KVA/1000 sq. ft. is shown on Figure 17. This is helpful in giving some idea of the machine density, since it shows the amount of power the various industries use.

The means of secondary power distribution is shown on Figure 18. It is divided almost equally between busduct and cable in conduit. If the frequency of layout change graph is compared with this figure, it will be seen that those plants which have frequent changes use busduct, which allows more freedom in locating machines.

The dimension between utilization buses (or the equivalent), the point from which the supply is taken directly to the machine, is also a measure of the flexibility of a plant, since, if it is small, the machines may be easily relocated without long conduit runs. The distance should also be compared with plant demand and aisle spacing to arrive at machine density. This dimension is plotted on Figure 19.

The type of lighting and the level is manufacturing areas is indicated on Figure 20. The average level is approximately 40 foot candles. There are no distinct trends toward any one type of lighting, but mainly fluorescent is used.

Heating and Ventilating

This is one of the few services provided by the building which changes appreciably for various processes. Thus a precision instrument manufacturer will have completely filtered air and probably accurate humidity control and cooling, while for a cardboard box plant humidity control only will be necessary. This graph should therefore be read in conjunction with the overlay sheets which select plants by process. For the majority of plants the heating is by unit heaters and the ventilation by exhaust fans, the air being brought in through the unit heaters. This informa-
tion is shown on Figure 21.

Materials Handling Equipment

The percentage of various materials handling equipment used was a difficult question to answer, but it was the only way of finding how much of this equipment is supported by the structure and how much is free. The left column on the questionnaire is structure-mounted equipment and the right free-moving. Figure 22 shows the answers that were received to this question. The almost universal use of fork lift trucks, which require adequate clear internal height for efficient stacking, will be apparent.

Costs

Against better advice these questions were included because it was hoped that some idea of the ratio between capital and maintenance charges and total production costs would be obtained. This would give some idea of the efficiency of the plant; for example, if the building costs were low compared to the total production costs, the plant would be more efficient than if they were high. Unfortunately, since the percentages depend on the accounting procedure of the company and on the age of the building, no consistent answers were received.

Furthermore, it was thought that if the ratio of building costs to production costs could be obtained together with an increase in productivity, it might be possible to see how sound a venture it would be to build a new plant after the old one was obsolete but not inadequate. In many cases the reported increase in productivity is startling, but most of it must be due to the new and better machinery which was installed at the same time. The increase in productivity and the answers to the other questions when they were given are shown on Figure 23.

Whether the building was owned or rented by the company is marked on Figure 1 together with the areas. Only the very smallest plants were rented.
Inadequacy of Building Services

It is difficult to imagine that in a hundred factories only nine different plant engineers found any fault with the services provided by the building. The complaints were as follows:

- Heating and ventilating (3);
- Power distribution (2);
- Provision for hanging loads (1);
- Internal height and bay size (1);
- Building too small (1);
- No room for expansion (1).
Frequency of Layout Changes

- Weekly
- Monthly
- Continuously
- Frequently
- 4/Year
- Often
- 1/Year
- Not Often
- Seldom
- 2/Yrs
- Rarely
- 5/Yrs
- 10/Yrs
<table>
<thead>
<tr>
<th>Material Type</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-story</td>
<td>MTE</td>
</tr>
<tr>
<td>Concrete</td>
<td>CRT</td>
</tr>
<tr>
<td>Steel</td>
<td>STE</td>
</tr>
<tr>
<td>Other</td>
<td>OTH</td>
</tr>
<tr>
<td>Roof deck</td>
<td>Rdk</td>
</tr>
<tr>
<td>Material</td>
<td>Mat</td>
</tr>
<tr>
<td>Concrete</td>
<td>CRT</td>
</tr>
<tr>
<td>Steel</td>
<td>STE</td>
</tr>
<tr>
<td>Other</td>
<td>OTH</td>
</tr>
<tr>
<td>Roof deck</td>
<td>Rdk</td>
</tr>
<tr>
<td>Material</td>
<td>Mat</td>
</tr>
</tbody>
</table>

**Legend:**
- **MTE:** Multi-story
- **CRT:** Concrete
- **STE:** Steel
- **OTH:** Other
- **Rdk:** Roof deck
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference
- **Mat:** Material
- **Ref:** Reference

Note: The table continues with similar entries for different materials and sections.
Average Distance between Utilization Bus (or equivalent)
<table>
<thead>
<tr>
<th>% of area filtered</th>
<th>% of area with humidity control</th>
<th>% of area cooled</th>
<th>% of air changes per hour</th>
<th>% max. recirculation</th>
<th>% means of heating</th>
<th>% means of ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>