RICE UNIVERSITY

DIMENSIONAL COORDINATION
OF INDUSTRIALIZED METAL BUILDINGS

by

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ABSTRACT

DIMENSIONAL COORDINATION OF INDUSTRIALIZED METAL BUILDINGS

by Yee Leung

Dimensional coordination is shown to be a tool which can help to organize different building components manufactured independently into an integrated whole, and to improve flexibility in the use of these products. Modular coordination is defined as the ultimate goal of dimensional coordination.

A review of existing coordination methods shows that the freedom of architectural design would be limited if dimensional coordination problems are approached solely from mathematical points of view. To avoid this, a coordination process is developed to systematically and comprehensively handle the dimensional coordination problem for industrialized buildings.

This coordination process is applied to the metal building industry in Houston to establish a new dimensional system for the industry. This new dimensional system can improve the flexibility and compatibility of the existing metal building products.
DIMENSIONAL COORDINATION OF
INDUSTRIALIZED METAL BUILDINGS
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BIBLIOGRAPHY
1. **INTRODUCTION**

1.1 **Outline of the Study**

Mass production of large prefinished prefabricated building components in the factory ensures significant economical results: reduction of building costs, improved product quality, faster and easier site operations and simplification of design procedures. Inevitably, the degree of building industrialization will continue to increase.

The trend in separating building construction into specialist work-tasks requires clear communications, understanding and discipline. Dimensional coordination is one of the tools which meets these requirements.

Mass production demands reduction of product types; selection of the range of product sizes becomes an essential matter. The selected sizes must be convenient in production, transportation and on-site
assembly, but must as well satisfy functional and aesthetic requirements. The establishment of a product dimensional system to meet these requirements demands a comprehensive and thorough coordination.

The metal building industry is one of the pioneers in producing industrialized building products in the United States. Metal building systems, designed initially for utility and industrial uses, have with improvement and refinement now been extended into other building types.

Texas has long been a major market for metal buildings, and the metal building manufacturers are concentrated in Houston. The port facilities make Houston a major export center for metal building products. The claim "Houston: the Capital of the Metal Building Industry" by Houston Chamber of Commerce is not an exaggeration.

The existing dimensional coordination of these highly industrialized building systems is not well organized. The inability of the various dimensional systems to simultaneously satisfy different architectural requirements constitutes a limitation to further development of the existing metal building industry.

Part I of this study is a theoretical analysis in search of a proper way to handle the dimensional coordination problem for industrialized buildings. Part II is the practical application of the results of Part I to a dimensional system for the metal building industry in the Houston area.
PART I - ANALYSIS
2. ARCHITECTURAL DIMENSIONING

2.1 Dimensions in Architecture

Dimensions are an important part of communications in architecture. Through dimensional systems, design information can be easily communicated among architects, consultants, engineers and specialists, and the building works can be efficiently carried out on site by teams of contractors.
2.2 Determinants of Architectural Dimensions

Dimension is here defined as the magnitude of a linear measurement. When a dimension is associated with an architectural element, certain meanings are perforce involved. 3'-0" is an abstract measurement, but a 3'-0" door represents several architectural meanings: a good passage for one person, a standard width of plywood flush door panel, a suitable size for one man's handling and installation on site. A 3'-0" corridor represents other meanings. Architectural dimensions are associated with one or several architectural meanings; these architectural meanings define the magnitude of the dimension.

The determinants of architectural dimensions can be classified into several categories:

Anthropometrics

The human body is the yardstick of architecture. A standard door head height cannot be less than 6'-8" to allow easy passage. Door knobs must be installed around 3'-2" from ground for convenient operation. If a hand rail is designed for hand grasp, the top width or diameter must be within the range of 3/4" to 3". Human comfort dictates some dimensions, human safety dictates many others. Safe guard railing for instance can not be lower than 3'-6". The relationship of riser (R) and tread (T) of stair must comply with the formula \(2R + T = 23"\) to 25", to ensure trip-free emergency use. As a rule of thumb, buildings for general use should be suitable for the anthropometrics of 95% of the adult population\(^1\). Design for particular users such as children, the handicapped or the aged, calls for special anthropometrical criteria.
Equipment and Activity Requirements

Many buildings are used or occupied by equipment or special objects other than human beings, such as machinery for a factory, or automobiles for a garage. Dimensions are controlled by the installation and operation of these equipments or special objects.

Visual, acoustic and thermal comfort impose additional dimensional restrictions, such as sightline requirement in theater, shape and size for sound effect in concert hall, and wall thickness for cold weather insulation.

Dimensions are also determined by the requirements of athletics, such as basket ball courts, bowling alleys and squash courts.

Building Materials and Products

Size varies from one building product or component to another because of differences in material properties: raw material size, strength, weight, conductivity, expansion, etc. This can easily be seen in a comparison of the dimensional differences of precast concrete panel walls, metal panel walls and masonry walls.

The production equipments and processes also influence the size of building products and components. Consider the panels produced by the metal building manufacturers: panel length is almost unlimited, but panel width is dictated by the rib rolling mill width.

Dimensional tolerance varies with both material and process. Metal products can be more accurately sized than concrete products as metals are of higher strength and ductility, while concrete is so brittle that any dimensional adjustment is totally impossible.

Construction Method

Mechanization induces more restraint to dimensional coordination,
as product size standardization dominates the dimensional system.

Manual handicraft construction on the other hand gives more freedom to
dimensioning, as every building component can be specially constructed.

Transportation and Handling

Transportation and handling methods impose certain dimensional
restrictions to building products. If it is too big it cannot be easily
moved, or at least not far. Dimensions increase in a generalized sequence
as follows:

(1) Manual:

Individual: convenient width four feet, convenient weight
seventy pounds, length about twenty feet.

Two persons or more: weight is the determining factor;
multiply seventy pounds by the number of persons.

(2) Truck and mobile crane: maximum width for truck loading is
double feet, length about fifty-five feet, height eleven
feet six inches². Generally, a mobile crane can lift three
tons up to eighteen feet high, in a radius of stationary
action up to ten feet³.

(3) Train and tower crane: standard freight car size is ten
feet six inches wide by thirteen feet high, maximum length
is ninety feet². Generally, a tower crane with horizontal
jib and travelling saddle can lift seventeen tons up to sixty
five feet high above the crane base with a radius of opera-
tion about fifty feet³.

Proportion and Pattern

Proportion is a concern for the aesthetic relationships of
dimensions. Pattern is the treatment of surfaces for architectural
expression. Both proportion and pattern are dimensional games. The geometrical or architectural criteria expressing proportion and pattern govern dimensions.

Site Condition

The planning dimension may be controlled by the shape and gradient of the site, especially when there are existing structures and special features on-site to be preserved.

Legal requirements

The purpose of any building code is to provide minimum standards and requirements for public safety, health and welfare. The zoning regulations impose area and height restrictions to buildings. Dimensions set up by these codes and regulations often are the starting points for dimensional frameworks.

When the rough dimensions are determined, mathematical methods can be applied to organize these dimensions to form a basic skeleton for the whole design. When the dimensions are well organized, the architectural elements represented by these dimensions should also be in a better organized relationship. To select a suitable dimension to satisfy the requirements of its determinants, and to arrange the dimension in the right context are steps to clarity in architectural design.
2.3 Grouping of Dimensions

There are at least thirty thousand individual parts, materials and equipments in an average house. With at least three dimensions for any individual element, there should be more than one hundred thousand individual dimensions in an average house. These individual dimensions must be simplified and gathered into groups before dimensional organization and adjustment can be carried out. Since architectural dimensions represent the sizes of architectural elements, the best way to group the dimensions is to separate them into groups according to the function of the architectural elements. Within each group, the architectural elements perform similar or related functions; then a dimension criterion can be set up more easily. The following are simple descriptions of five major traditional dimension groups:

Planning

The dimension group for planning is determined by the following:

- requirements of human activities
- vertical and horizontal circulation
- environmental control requirements
- building site conditions
- relationship among buildings
- legal requirements

The planning dimension group governs the division of internal spaces and the distribution points of the service systems. The planning dimensions may also extend into the spaces between buildings when necessary.
Structural

The structural dimension group is set up according to the relationship and positions of structural elements, and varies with the different design method and the materials used. For tall or long span structures or non-rectangular buildings, structural systems always impose strict limitations to dimensions. Also in these cases, due to economical reasons, the structural dimension group often governs other dimensions.

Services

There are several different types of building service systems:
- heating, ventilation and air-conditioning
- liquid and gas supply, and waste disposal
- electrical
- communication

All these systems require continuous supply or distribution lines and ready access for maintenance and repair. The dimensional requirements of these systems are complicated, as their sizes and positions vary greatly with the system.

Aesthetic

The architect's personality is important to dimensional aesthetics. Some architects are fond of simple geometrical compositions of explicit dimensional systems while others pursue sculptural effects without regard for dimensional nicety.

Site Construction

Although the final complete building on site should be identical to that shown in the drawings, for convenience in building processes another new set of dimensions may be required. This supplementary
dimensional system is solely approached from the construction point of view to phase the construction, to provide construction joints and to set up constructional equipments.

Beside these five major dimensional groupings, there are other dimensional groups, such as those of finishing elements, fixtures, and filler components. They are typically governed, however, by one or two of the major groups, and for this reason have not been given detailed discussion.

Contradiction between major dimensional groups is inevitable. Structural dimensions may not fit with planning dimensions and tend to obstruct the continuity of the service dimensions. In every design, the rational elements of structure and planning compete with subjective aesthetics. Sometimes, for site construction, a new dimension group has to be planned. To establish an internal systematic grouping for each dimension group is not an easy task. To coordinate the conflicts between these major groups is even more difficult when there is no mutual basis for communication. The successful coordination of these contradicting dimensional groups is essential to an architectural integration.
NOTES


(4) "Modular Coordination". *ARCHITECTURAL RECORD.* June, 1950, P. 60.
3. **BUILDING INDUSTRIALIZATION**

3.1 **The Changing Building Process**

The logic of building industrialization is simple: transfer as much as possible the building work from manual labor on-site to mechanized and organized processes in controlled environments — the factory. Building industrialization is not only a technical innovation, but a total improvement of the building process.

Manufacture can be divided into four generations, according to the history of building industrialization. Manufacture of basic building materials (glass, brick, steel, etc.) is the first generation; these products require extensive on-site labor. Fabrication of building parts and components (windows, ceiling panels, door frames, etc.) is the second generation; site labor is reduced. The third generation is the assembly of building sub-systems (mechanical equipments, movable
partitions, curtain wall, etc.); little cutting or fitting is needed on-site. The latest generation is the production of complete building systems (metal building industry, mobile home industry); site work is simplified and reduced to a minimum. The role of the manufacturer in the building industry began as a supplier of materials; the manufacturer is now gradually becoming the center of the whole industry. The manufacturer not only produces the building system, but does the major part of the design work and on-site construction as well. The manufacturer may now control the major part of the total process.

Building industrialization simplifies and expedites contractors' work. Large size products with simple assembly methods allow the contractors to use more mechanical equipments to further save on-site labor. As fewer human factors are involved, management becomes easier. The recent trend toward the combination of manufacturer and contractor (e.g. the big home builders) or their close association (as in the metal building industry) contributes more flexibility to the control of both factory and site processes.

For architects and engineers, work procedures are also simplified. As the whole building system is prefabricated in the factory, and on-site assembly methods are pre-designed, traditional working drawings and details are eliminated. Design becomes the arrangement and choice of suitable products. Although some personal freedom in creativity may be constrained, the design work is much simplified. The bidding procedures are also changed. Where sub-systems from several manufacturers are used, pre-design bidding gives more control to the building cost. Traditional continuous site supervision is replaced by periodic inspections and final performance tests. These changes
in working processes in the design professions are now gradually changing
traditional professional practices, especially those of architects.

Building industrialization can also extend the building process
into a new area — growth and change. Standardized products, fewer
joints on site, and simplified erection methods contribute flexibility
and simplification to site construction; and at the same time give higher
potential for future addition or alteration. The rapid development of
science and technology has caused drastic and dynamic changes in human
life. The traditional concept of architecture as a static container
for human activities too often resulted in misfit buildings unable to
change to meet new demands. The extended building process of indus-
trialized buildings should be the best solution to lengthening the
building life span; the building potential for continuous growth and
change meets the changing needs of human activities.

3.2 The Economical Demands of the Products

The basic logic of building industrialization — to reduce on-
site labor and to increase mechanized processes in-factory — developed
from economical demands and opportunities. Substituting factory tech-
niques for individual craftmen on-site saves money and time.

Inside the factory, control is much improved. Products obtained
through specialized refinement achieve a higher degree of quality.
Machines, better than human labor, can accurately perform many complicated duties. Unnecessary waste can be reduced and human errors can be avoided. Moreover, through well-organized production lines, high efficiency can be achieved. If electronic controlling devices are used, sets of programmed operations can be automatically carried out to further substitute human control. Besides, in the factory some special production methods can be performed which are impossible to be carried out on site (such as oven-cured painting). All these lead to the same economical effect: better and cheaper products with efficient production.

The result of building industrialization is mass production of building products: fewer product types in continuous maximum production. Replication, standardization, flexibility and compatibility are four major economically demanding factors for continuous mass production:

Replication --- The continuous reproduction of a few product types.

Machines are tools that can continuously repeat predetermined cycles of activities. The fewer the types, the more effective is the repeated operation.

Standardization --- The setting up of standards for performance, operation, dimension, method of assembly, etc., either locally or nation-wide. These standards are fundamental guidelines to the wide acceptance of the product by users and designers. These standards can help to reduce product types.

Flexibility --- The capability of the products to meet the requirements of changing conditions. Through multi-use of the product, types can be reduced and markets can be widened.
Compatibility — The ability to joint together with other products.

The ability to get along with other types of products which are either by the same or other manufacturer is the prime factor to widened use of the product.

In considering the product system as a whole, each demand must be well satisfied. The building product system must be replicable, standardized, flexible in use and compatible with other products before it can be considered for mass production.

But mass production must have a mass market to ensure the return of the initial capital investment and to allow continuous development. Except in the single case that mass production sustained by government is the only way to meet volume demand, a mass market depends solely on users' wide acceptance. Mass markets can only be established or maintained through one or all of the following:

1. Price reduction — A big price cut over the conventional production method. The users purchase the products for straight economical reasons.

2. New and improved product — A new kind of product or product quality which can not be obtained with conventional production methods (factory oven-cured painting, refrigerated air conditioning).

3. Publicity — The market public is convinced with advertising that it can not do without the product.

Building industrialization has set up new demands on building product systems. Two sets of demand factors, one representing the need of manufacturers to achieve continuous profit and one representing
users need for cheaper and better consumption, must be simultaneously satisfied. Automation, which can be programmed to produce different product sizes in sequence, is one way to balance the variety of user needs and the demand for simplification in production. A complete open system is another; high interchangeability between products of different systems can give more freedom in product use, and thus can increase production.

3.3 Building Industrialization and Dimensional Coordination

Building industrialization is a simplified and extended process. Building works for industrialized buildings are transferred as much as possible from site to factory and from man-labor to machinery. Industrialized products require minimum product types and maximum production. With this new architectural direction, the traditional design approach of made-to-order-design and construction can not be satisfied. New design approaches are required to meet the demands of economy, and to obtain buildings of simple and efficient construction. Systems concepts and performance concepts are key ideas significant to this new design approach.

Building Systems

A building system is an orderly arrangement of all sub-systems in the building. Traditional custom design sometimes constitutes a
building system; but the system is only suitable for one or several related buildings. The industrialized building system must be applicable to many unrelated buildings. A flexible order or discipline must be imposed, so that various combinations of limited parts can be achieved; and each combination must be an integral whole.

**Performance Concept**

Unlike conventional descriptive specification, only the quantitative and qualitative aspects of the products are defined in performance specifications, and the detailed design is left to the manufacturers. A widely accepted standard, which compromises the requirements of all parties concerned, is the basis for the performance criterion. Close linkages are required among different kinds of performance criteria for easy integration of different products.

Dimensions are important to both systems concepts and performance concepts. Through mathematical methods, dimensions can be easily coordinated to form a numerical order to set up the skeleton of the system. Being part of the quantitative standard of the performance criteria, dimensions are the major linkage between different kinds of performance criteria. Therefore, in the design of industrialized buildings, dimensional coordination is the best tool to achieve orderly variety in the designed building from the simple uniformity of the industrialized building products.

Besides this, dimensional coordination can help to achieve the following advantages in the whole industrialized building process:

To reduce product inventory — By carefully coordinating product dimensions, product types can be reduced and the flexibility in use
can be retained.

To control waste, error and tolerance --- Dimensional coordination facilitates the planning of site operations, so that waste and error can be avoided and tolerances can be controlled.

To facilitate communication --- Dimensions are an important architectural communication medium. Coordinated dimensions facilitate the coding of the products and the transfer of information among all parties.

To shorten time --- Time can be saved through the simplification of all stages of work by dimensional coordination, especially design and site construction.

To achieve integrity --- As stated before, contradiction between different building elements can be harmonized by dimensional coordination, thus giving a high level of integrity to the building.

As to open systems, dimensional coordination plays an even more important role; to set up a mutually agreed upon dimensional standard is the first step toward interchangeability.

Dimensional coordination is not only inevitable but indispensable to building industrialization; dimensional coordination is a key to industrialized buildings.

Fig. 3.1 shows the hierarchy of dimensional coordination of industrialized buildings. The higher the degree, the more important is the dimensional coordination.
Fig. 3.1 Hierarchy of Dimensional Coordination.
NOTES


(2) MODULAR COORDINATION (Lectures and Proceedings of a series of Conferences on Modular Coordination held in six cities in Canada, October 17 to November 1, 1967) Ottawa: Canada Department of Industry, 1967.
4. REVIEW OF EXISTING DIMENSIONAL COORDINATION EFFORTS

4.1 Mathematic Basis

Dimensional coordination establishes an orderly relationship among dimensions, so that the dimensions can be flexibly combined in a suitable manner. Mathematical number series are derived from fixed numerical orders, and are useful in formulating a numerical relationship among dimensions. Building construction is an additive process; accordingly, the combination of dimensions in building is also a numerically additive process. Therefore, only those mathematical number series of simple additive or multiple orders are used as bases of dimensional coordination.

Arithmetic series are widely used. The basic form of them is:

\[ L, 2L, 3L, 4L, 5L, 6L, 7L, \ldots \]

When \( L=1 \), the series become the natural number sequence:
1, 2, 3, 4, 5, 6, 7, 8, ..................

When the value of \( L \) increases more series are evolved:

\( L=2; \quad 2, 4, 6, 8, 10, 12, 14, \ldots \)

\( L=3; \quad 3, 6, 9, 12, 15, 18, 21, \ldots \)

\( L=4; \quad 4, 8, 12, 16, 20, 24, 28, \ldots \)

\( L=5; \quad 5, 10, 15, 20, 25, 30, 35, \ldots \)

And so on.

Arithmetic series are in a simple order: fixed increment. The simple rhythm and close adhesion to the natural number sequence are their advantages. Monotony is their major drawback.

Geometric series are another family of mathematical series popular in architecture. The successive term are in a fixed ratio. Their basic form is:

\[
R^0, R, R^2, R^3, R^4, R^5, R^6, R^7, \ldots
\]

When \( R=1 \), all term are equal to 1.

When \( R=2, 3 \) and \( 4 \), the respective series are:

\( 1, 2, 4, 8, 16, 32, 64, 128, \ldots \)

\( 1, 3, 9, 27, 81, 243, 729, \ldots \)

\( 1, 4, 16, 64, 256, 1024, \ldots \)

The geometric series are in a more dynamic relationship. The increment between successive terms becomes very large as the value of \( R \) increases. The application of geometric series to dimensional coordination is therefore confined to several initial terms of low \( R \) value.

The name "geometric" is not accidental; geometric series can be constructed by geometrical methods, even for those values of \( R \) not an integer, such as \( \sqrt{2} \) and \( \sqrt{3} \). When the value of \( R \) is fractional, a mysterious proportional relationship can sometimes be created among the terms.
of the series. The geometric series of fixed fractional ratios were widely adapted in classical architecture for this reason. But for dimensional coordination purposes, as the terms are fractional numbers, they are useless. The famous Fibonacci Series is the only exception.

The Fibonacci Series is not only a geometric series but also an arithmetic series. This series is formed by an additive order: make 1 and 2 the first two terms; the third and succeeding terms are the sum of the preceding two terms. The basic series is:

1, 2, 3, 5, 8, 13, 21, 34, 55, ............

Besides the formation order, another relationship exists: the ratio of the successive terms is approaching the mysterious figure: the Golden Mean \( \frac{1 + \sqrt{5}}{2} = 1.618 \ldots \), which is a proportion governing many geometrical deviations, aesthetic formations and natural phenomena.

Doubling this series, other numbers are included:

2, 4, 6, 10, 16, 26, 42, 68, 110, ............

Fig. 4.1 tabulates the above series for comparison. Numbers which appear often in this table can easily relate to other numbers. They are useful for dimensional coordination. For prime numbers larger than seven their use should be carefully considered, as they are difficult to coordinate with other numbers.
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Fig. 4.1  
Comparison of Series
4.2 Modular Theory and Coordination Methods

To use a convenient size as a basic measurement unit (a module) to organize the dimensions of a building is not a new idea. Many examples of this practice can be found in ancient Western masonry structures and Eastern wooden structures. But to establish a standard basic module for the whole building industry was not attempted until 1936 when the American industrialist, Albert Farwell Bemis, advocated the Modular Theory in his book "Rational Design". He proposed a basic module of four inches.

Modular coordination is the ultimate goal of dimensional coordination. When a basic measurement unit is established, a three dimensional modular system can be set up. Then all building design, manufacture of building products, construction on site and use of the completed buildings can be coordinated to this three dimensional modular system. For architects and engineers, modular design can eliminate the laborious work of calculating dimensions to fractions of an inch. Design and drafting procedures are simplified. Manufacturers can eliminate odd size building products. Cost can be lowered and efficiency can be achieved when fewer standardized sizes are in greater replication. For contractors, modular construction can reduce error, save labor, simplify estimation and expedite on-site works. Modular buildings can also benefit the clients and users by cheaper building cost, better workmanship and flexibility in use. Above all, when the module is closely integrated with the total building process, economical results can easily be achieved.

The modular theory is simple, but the practical application of
modular theory is not so easy. As the basic module has to meet all kinds of building requirements, it is related to all dimensional determinants. Even when this module is defined, to extend it into a three dimensional measurement system to integrate all kinds of dimensional requirements is difficult. In order to conquer these difficulties, much research has been done. Finally, four inches has been chosen as the basic module by most inch/foot countries, and ten centimeters, by most metric countries. For coordination methods, there were many diverse approaches; not all of them based on the chosen basic module. The following are four significant ones:

**Le Corbusier's Modulor**

Le Corbusier's Modulor was an attempt to substitute for the often chaotic measurements of architecture a system of harmonious proportion and human scale. As major proportions of human measurements are close to the Golden Mean ratio, he was able to combine the anthropometrics of a 6'-0" man and the Fibonacci Series into two numbers sets called the Blue Series and the Red Series. The Blue Series is twice that of the Red Series. (see Fig. 4.2). There are at least three significant advantages in this measurement system:

1. The dimensions are mainly in an additive relationship. They can be combined easily.
2. Each combination is in a good and harmonious proportion.
3. Every dimension is in anthropometric conformity.

However, this "Modulor" system has not had wide acceptance. Although Le Corbusier has indicated in his book "Modulor" that this measurement system is designed for universal application, due to lack of consideration for other dimensional determinants (except anthropo-
Measurement Unit: Millimeter

Fig. 4.2 Le Corbusier's Modulor
metrics and proportions), its use is limited. For instance, in brick construction, it is impossible to form, without cutting, the window sill height 86.3 cm (34 in) and the railing height 113 cm (44\frac{1}{2} in), even by a kind of specially manufactured brick (113 is a prime number).

Dominated by the additive relationship, and limited to one proportional family (golden mean ratio), this measurement system constitutes certain restrictions to the designers' freedom.

Moreover, the over-emphasis on the vertical relationship, and lack of consideration of the horizontal relationship in dimensions (even those of anthropometrics) confine its application mainly to vertical surfaces.

**Ezra Ehrenkrantz's Modular Number Pattern**

Ehrenkrantz's modular number pattern\(^2\) is a three dimensional matrix. Each coordinate of this matrix is a mathematical series: as shown in Fig. 4.3a the X coordinate is the first five terms of geometric series of ratio two, i.e. 1, 2, 4, 8, 16; the Y coordinate is the first five terms of the Fibonacci Series, i.e. 1, 2, 3, 5, 8, and the Z coordinate is the first three terms of geometric series of ratio three, i.e. 1, 3, 9. The matrix is generated by multiplication of the three coordinates. By doing so, every number in this matrix is closely related to each other. They are not only of additive relationship, but also in ratios of two, three and golden mean ratio, or the multiples of them. They can combine in many different ways.

Setting the inch or other measure as unit, these numbers become dimensions. This matrix of dimensions can be used as a guide to manufacturers to choose the range of product sizes. Flexible combinations of good proportional relationships can automatically be obtained. For
(a) The Three Dimensional Matrix

(b) Modular Number Pattern in Ascending Order to Show Interval between Successive Terms

Fig. 4.3 Ehrenkrantz's Modular Number Pattern
design work, this matrix can help to achieve a good part-whole relationship. The aesthetic neutrality in each combination allows some freedom for the designer in selection of combinations.

Despite these advantages, one serious drawback exists in this matrix. If we put all dimensions in ascending order as in Fig. 4.3b, the uneven and large intervals between successive dimensions appear in the section between 72" and 144" (over 144", the increment is unreasonable; even Mr. Ehrenkrantz has not taken this section into consideration in his book "Modular Number Pattern"). Therefore, this matrix is only helpful to the design of small building components, such as windows, wall panels, cup boards, etc.

Philip Dunstones' Combination of Number in Building

This study concentrated on the grouping of component sizes. Based on mathematical formulas, the Critical Number Table and the Combigraph were compiled.

Critical Number Table — Critical Number is the number beyond which the combinations of the selected component sizes fill every dimension. As shown in Fig. 4.4, the critical number of three component size can be easily determined. (Such as the critical number for 7, 9, and 10 is 23.)

Combigraph — It is a supplement to the Critical Number Table. The graph can give a total count of all possible combination of three component sizes. Sample of the Combigraph is shown in Fig. 4.5.

This table and this graph are useful to determine modular product sizes and their combinability, but their capability is limited to three linear dimensions only. There is no other usage.
PART OF THE TABLE
OF CRITICAL NUMBERS

RULES
1. PUT COMPONENT SIZES INTO ASCENDING ORDER
2. APPLY AS IN KEY TO FIND CRITICAL NUMBER

KEY
THIS POSITION GIVES CRITICAL NUMBER FOR TWO COMPONENT SIZES \( CN = (a - 1)(b - 1) \)
REMAINING POSITIONS GIVE THE CRITICAL NUMBER USING A THIRD COMPONENT SIZE ACCORDING TO THIS LAYOUT

Fig. 4.4 Sample of Table of Critical Numbers

(From: Combination of Numbers in Building)
Fig. 4.5 Sample of Combigraph

(From: Combination of Numbers in Building)
The grids shown are typical examples of possible modular grids.

**Basic Module Grid**

**Modular Grid with multi-modular square grid superimposed**

(1ft/300mm)

**Modular Grid with multi-modular rectangular grid superimposed**

(2ft x 1ft/600mm x 300mm)

**Modular Grid with multi-modular tartan grid superimposed**

(4in and 2ft 8in/100mm and 300mm)

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*Fig. 4.6 Grid Systems*

* (From: The Coordination of Dimensions in Building)
Procedure, in principle, for calculating the Maximum and Minimum sizes for a modular component.

1. Define the Modular Size \((nM)\) of the component.

2. Define the Minimum Gap \((g)\).

3. Define the Positional Tolerance \((p)\).

4. Define the Manufacturing Tolerance \((t)\).

When the above have been settled, make the following calculations:

5. Determine the Minimum Deduction: 
   \[ g + p + \frac{t}{2} \]

6. Determine the Maximum Size: 
   \[ S = nM - (2g + p) \]

7. Determine the Minimum Size: 
   \[ s = S - t \]

8. Check the Maximum Gap \((G)\): 
   \[ G = g + p + \frac{t}{2} \]

9. Check the Minimum Gap \((g)\): 
   \[ g = \frac{1}{2}(nM - S - p) \]
   and check against 2, above.

Fig. 4.7 Calculation of Tolerance

(from: The Coordination of Dimensions in Building)
Graphical Method

Graphical applications to modular design have been standardized by the Royal Institute of British Architects in 1965 and published in a book called "The Coordination of Dimension for Building". In this book, modular grid line system (Fig. 4.6), tolerance (Fig. 4.7), codings, symbols, terminologies, etc. are established or defined. This standardization can simplify some aspects of modular design and strengthen the communication among all parties in the building industry. However, this book is only compiled as a guide. There is an obvious gap between this graphic standardization and the practical solution to modular coordination methods.

Though based on simple theory, the application of modular coordination is nevertheless complicated. Each of the above four approaches provides but partial solution to this complicated problem. A comprehensive solution is yet to be found.

4.3 Modular Effort

There is always a confusion about the true meaning of Modular Theory as advocated by Albert Farwell Bemis. To individually select a measurement unit as a design module for a building and to repetitively use it in the building as the common denominator of space arrangement, facade treatment and structural system, is only a coordination method. To practise modular coordination, this selected design module must be
commensurate with all detailed dimensions in the building and must also relate to a nation-wide standard measurement unit, which has been mutually agreed to by all parties concerned with the building industry. This standard measurement unit is the starting point of modular coordination.

After the publication of Albert Farwell Bemis' book "Rational Design" in 1936, "Project A62" was authorized in 1939 by American Standards Association (In 1966 succeeded by United States of America Standards Institute) to develop a national basis for coordination of dimensions of building materials and equipment. In 1945, four inches was designated as the basic United States standard module. A book "A62 Guide" was then published to introduce modular detailing and to promote modular coordination. Concrete masonry products began to convert to modular coordination. In 1957, Modular Building Standards Association (M.B.S.A.) was formed to promote modular coordination in the building industry.

Since in the United States the acceptance and application of modular coordination is totally voluntary, the progress, in general, has been very slow and small in volume. A survey by M.B.S.A. in 1959 covering all architectural firms of some size showed that only 11 percent of architects used "Modular Drafting" in their work.

The latest modular effort in United States was the adoption by the United States of America Standards Institute of a basis for horizontal dimensioning in 1968 (Fig. 4.8 and 4.9) and a basis for vertical dimensioning in 1969 (Fig. 4.10 and 4.11).

In Europe, during World War II, a basic module of 12.5 cm was proposed in Germany and a basic module of 10 cm (close to 4 inches) was also proposed in Sweden. After World War II, modular coordination
\[ M = 4'' \text{ Basic Module} \]

**Fig. 4.3** United States Basis for Horizontal Dimensioning

Relationship of Systems Module to Preferred Component

Dimensions and Basic Module
M = 4" Basic Module

Fig. 4.9 United States Basis for Horizontal Dimensioning

Points of Compatibility
A Story Height - 28M, 32M, 36M, 40M, 48M
B Ceiling Height - 20M, 24M, 28M, 32M, 36M
C Floor-Ceiling Sandwich Thickness - 4M, 8M, 12M
D Structural Column Height - 8 + F
E Structural Floor Thickness - 2M, 4M, 6M, 8M
F Ceiling Space Dimension - 2M, 4M, 6M, 8M
G Thickness of Finished Floor

M = 4" Basic Module

Fig. 4.10 United States Basis for Vertical Dimensioning

Preferred Magnitude
$M = 4\"$ Basic Module

Fig. 4.11 United States Basis for Vertical Dimensioning

Combination Systems
drew the attention of many other countries during their post-war construction. In 1955, the European Productivity Agency backed a study on modular coordination in which eleven European countries, Canada and the United States took part. This study recommended a basic module of four inches for inch/foot countries and 10 cm for metric countries.

Because in some European countries modular coordination is mandatory for certain types of government financed projects, and because of the popularity in prefabricated and precasted concrete construction, considerable work on modular coordination has been done.

During the late 1950's and early 1960's, many countries in Asia and Latin America began to adopt modular coordination. They are metric countries, therefore, 10 cm basic module was adopted. In 1965, Great Britian opted for metric conversion, and programmed a full conversion by 1972. In Germany, the 10 cm basic module has also been adopted and used in parallel with the original 12.5 cm basic module. Canada and the United States are the last stronghold for the four inch basic module.

Undoubtedly, 4in/10cm will become a universal basic module for the building industry, at least in the free world. In fact, 4in=10.16cm; there is only 1.6% difference between these two basic modules. Generally in building industry, the dimensional tolerance is fairly large. For small building components, especially those of masonry construction, this small difference can be easily absorbed, and interchangeability is possible. But for large building components, this difference becomes significant. (for instance, there is nearly a one inch difference between 5 feet and 150 cm, both 15 M)

The determination of the 4in/10cm basic modules involved extensive research and study in the early 1940's. For masonry and wooden
construction prevailing at that time, 4in/10cm proved to be small enough for flexibility in design of various buildings, and also large enough for simplification of the sizes of various components. After thirty years of development of building technology, metals and other synthetic materials are now widely used, and human society has changed greatly. Supplementary modules are proposed by various countries, as in Britain, in the form of sub-modules (fraction of the basic module, such as 1/4 basic module = 1 in or 2.5 cm) and multi-modules (multiples of the basic module, as one foot or 30 cm).

As to the latest United States bases of horizontal and vertical dimensions, their degree of acceptance by the building industry is not yet tested. However, we can compare them with Ehrenkrantz's Modular Number Pattern. The more uneven and larger increments in these two bases would certainly limit their application.
NOTES


5. **DIMENSIONAL COORDINATION OF INDUSTRIALIZED BUILDING**

5.1 Dimensional Coordination and Architectural Design

Dimensional coordination is part of the architectural design process. Coordinated dimensions are a framework which can help organize the building elements into an integrated whole, one that avoids chaotic disorganization within a system, that allows orderly variations.

When the building industry was in the handicraft stage, dimensional coordination was an on-site cutting and fitting job. Gradually, draftsmen assumed this responsibility; dimensions were coordinated in the working drawings to avoid on-site cutting and fitting. With the introduction of modular theory, dimensions of major building materials and components could be standardized. Coordination works begun at the planning stage could be carried through the whole design process. Now, with fully developed industrialized building systems, pre-coordinated
dimensions of the products dominate the whole design process.

Although the importance of dimensional coordination has gradually increased, its function must still remain an aid to design, not a dictator. Many coordination approaches violate this principle. Le Corbusier's red and blue series are a dictator to architectural design. With today's ever increasing levels of complexity, existing modular coordination methods tend to over-simplify the design problem and tend to cause environmental misfit.

A new comprehensive approach to dimensional coordination problems is needed. This new approach should be thorough and inclusive; every aspect of each dimension must be considered. It should not be doctrinal; mathematical series and grid line systems should be used only when they are an appropriate application. It should be systematic, but the approach must not over-simplify the dimensional relationship. Instead, the goal must be a set of suitable groupings of dimensions in a hierarchical order.

Only through a thorough examination of the fitness between product dimensions and architectural dimensions can dimensional criteria regarding the use of industrialized building products be established. As to open systems, it is impossible to incorporate products from different manufacturers into a system by simple adaptation of a modular series (such as Ehrenkrantz's modular number pattern) without a comprehensive study in dimensional coordination.
5.2 **Coordination Elements: Dimensional Character, Interaction and Relationship**

The first step in dimensional coordination is to select an initial magnitude for each dimension according to its determinants. Some determinants impose rigid requirements, some set up a loose standard that a wide range of dimensions can satisfy. Dimensions can be classified as follows:

**Fixed** — The dimension can not be changed, such as the dimensions of a standard tennis court and the dimensions of highly standardized industrialized building products (e.g., length of fluorescent tube).

**Adjustable** — The dimension can be changed. Dimensions of this category are useful to coordination as they can be adjusted to fit the fixed dimensions. They can be further classified into two types:

1. **Minimum**: the dimension can only be increased, such as many legal dimensional requirements: exit door width, stair width, etc.

2. **Maximum**: the dimension can only be reduced, such as site dimensions as limits of building dimensions; the permissible span of structural materials; the product size of alterable materials: plywood, glass, etc.

When the dimension can vary within a certain range, for convenience it can be considered either as a maximum by taking its upper limit or as a minimum by taking its lower limit. However, if the range is very small, it should be considered as fixed by taking its optimum magnitude.
The character of a dimension is important to dimensional coordination, as it can indicate the direction of adjustment. Therefore, for coordination purposes, an architectural dimension should be represented by its meaning, its magnitude and its character, e.g. door width, 3'-0", fixed; ceiling height, 9'-0", minimum, etc.

When the initial magnitudes of the dimensions are selected and their characters are classified, the next step is the consideration of their interaction to see whether they are related to each other. The interaction must be considered through the relationship of the associated architectural elements. Since the relationship of architectural elements differs from one design to another, it is impossible to set up a general ruling. However, as a direction, the following is suggested:

Element — The dimensions of the same architectural element will be closely related, such as the width, height and thickness of a door.

Grouping — The dimensions within the same group are generally related, such as the dimensions of elevational elements.

Space — The dimensions of the same space may be related, such as the floor tile size and ceiling panel size in the same room.

Interface — The dimensions at jointing points of elements, groupings and spaces should be related, such as the size of ceiling air diffusers and the size of ceiling panels.

If two dimensions are related to each other, their dimensional relationship must be considered; the interaction is an index of the dimensional relationship. For dimensional coordination, the degree of interaction is not important. A binary system, a simple indication of whether two architectural dimensions have interaction is enough.
An additional categorization is useful:

Part-whole relationship —- One dimension is part of another dimension.

This is the most common relationship, such as door width is part of the whole width of the wall where it is installed.

A window height is part of the floor to floor height. In this case, two dimensions can be related by:
- addition, or
- multiplication

Parallel relationship —- Two dimensions are related to each other in a parallel condition, such as the width and height of a wall.

The length of the downspout and the story height; both are fractions of another dimension, total building height. This relationship can be expressed by one of the following:
- equal
- both related to a common denominator (common module)
- fixed ratio
- fractional parts of another dimension

Mathematical relationship —- The relationship is set up purposely, a special dimensional series, such as:
- Le Corbusier's Modulor
- Ezra Ehrenkrantz's Modular Number Pattern

Special relationship —- The dimensional relationship is set up to meet a special requirement. Such as, for structural reasons, the depth of a beam and its span are in a special relationship.

In a circular building, all elements are governed by the circular formulas.

When these three classifications of dimensional coordination
have been set, the remaining process will be the adjustment of the dimensions according to their character and relationship along their interaction net-work.

5.3 Coordination Process: Interaction Matrix Hierarchical tree and Adjustment

The coordination process must be comprehensive and systematic. Every dimensional relationship between any two interacting dimensions must be considered. From the interaction network of all dimensions, a hierarchical system can be established. The individual dimension can then be adjusted according to its character to suit its relationship with other dimensions. In doing so, the dimensional problem can be handled as a whole, and at the same time, the special problems can be isolated and solved individually.

A two-dimensional matrix of all dimensions is the best tool to systematically consider the interaction between any two dimensions, as shown in Fig. 5.1. The meaning, initial magnitude and character of each dimension should also be indicated in this matrix for easy reference.

On completion of the matrix, the interaction between any two fixed dimensions must be considered immediately. If they can not fit in their required relationship, special adjustment, such as revision of the design, can be carried out at this initial stage.
The interaction between the fixed dimensions cannot be adjusted; they must be excluded for any further consideration.

In order to transform this matrix into a hierarchical system to find out important dimensions, the following rules of hierarchy are established:

1. The hierarchical position of a dimension is determined by its number of interactions with other dimensions; the greater the number, the higher is its hierarchical position. For example, the common module which reacts with all other dimensions should be in the highest hierarchical position.

2. When two dimensions have the same number of interactions,
and they have no direct interaction with each other, they are in the same hierarchical position.

(3) When two dimensions of different character, i.e. one fixed and another adjustable, have the same number of interactions, and they have direct interaction with each other, the fixed dimension has the higher hierarchical position.

(4) When two dimensions of the same character have same number of interactions, and they have direct interaction with each other, the dimension at the right hand side has the higher hierarchical position (This rule is arbitrary, but it simplifies the work. Because of this rule the major dimensions should be arranged in the right hand side of the matrix.).

According to these rules of hierarchy, the interaction matrix can be transformed into a hierarchical tree by the following steps:
Step 1 --- Count the number of interactions of each dimension. Advance the dimensions of greater interaction into a higher hierarchical position according to the rules of hierarchy. Join the advanced dimensions and remaining dimensions by straight lines to replace their interactions in the matrix. Then cancel the replaced interaction in the matrix.

- interaction
- coding and character
- meaning
- initial magnitude

- fixed; no adjustment
- minimum; addable
- maximum; subtractable
- number of interaction

Fig. 5.2a

Transformation Step 1
Step 2 --- Count the remaining number of interactions of each dimension in the new hierarchical position. Advance the dimensions of greater interaction into a higher hierarchical position according to the rules of hierarchy. Then, replace the interactions of the advanced dimensions and remaining dimensions in the matrix by the straight lines in the diagram.

![Diagram showing the transformation step 2 with symbols for interaction, coding and character, meaning, initial magnitude, fixed, no adjustment, minimum, addible, maximum, subtractable, and number of interaction.](image)
Step 3 — Repeat the operation until the whole hierarchical tree is set up.

- interaction

- coding and character

- meaning

- initial magnitude

- fixed; no adjustment

- minimum, addible

- maximum, subtractable

- number of interaction

Fig. 5.2c

Transformation Step 3
Step 4 — Simplification and re-arrangement. In order to avoid the crossing of lines in the hierarchical tree, the position of dimensions can be re-arranged to make the tree express the dimensional relationship more clearly.

Fig. 5.2d

Transformation Step 4
In this hierarchical tree, the dimensions in the higher hierarchical position become controlling dimensions. The interactions become the links between the controlled and controlling dimensions. With the character and initial magnitude of each dimension indicated in the matrix, together with its systematic relationship in the hierarchical tree, there is now sufficient information to start the most important stage of the coordination process --- adjustment.

Adjustment is a trial-and-error work. With the information given above, the range of trial-and-error is much reduced and the work should be much easier.

At first, the dimensional system should be considered as a whole to see:

(1) Whether the 4in/10cm basic module is applicable. If there is no problem in the fixed dimensions, other adjustable dimensions should be no problem also.

(2) Whether a bigger common module (multiplication of the basic module) can be established. If a common module can not be established among all dimensions, it might be applicable for sub-dimensional groups.

(4) Whether the mathematical series and the special dimensional series are applicable.

With these results it is possible to assign trial magnitudes to some or all dimensions, then start individual adjustments. Individual adjustment should be worked together with the drawings, so that the relationship can be easily considered.

In general, the controlled dimension should be adjusted to suit the controlling dimensions. However, as a fixed dimension can not be
adjusted, its controlling dimensions must be adjusted to suit it. Therefore, sometimes, several closely related dimensions, centered around a fixed dimension, have to be adjusted simultaneously. This multi-dimensional adjustment is more difficult than individual adjustment.

When a dimension is related to several controlling dimensions, the adjustment of this dimension must be suitable to several different dimensional relationships. This multi-relationship adjustment is another point of difficulty.

Therefore, the multi-dimensional adjustment and multi-relationship adjustment should be worked out first. The remaining individual adjustments should be much easier. Fig. 5.3 shows an example of adjustment.
After several times of trial-and-error adjustment, an optimum magnitude should be assigned to each dimension to suit its relationship with other dimensions. Then the dimensional framework should be well organized and many dimensional misfits can be avoided.

5.4 Dimensional Coordination of Industrialized Building

Dimensional requirements of industrialized building are two-fold. On the manufacturer's side, the range of product dimensions must be simple and must meet the requirements of production methods, the nature of materials, transportation and handling. On the architect's side, the product sizes must satisfy the needs of the specific uses and aesthetics which vary from one building to another. Coordination work must harmonize the contradiction of the dimensional requirements of these two positions. The comprehensive approach should be useful for these purposes.

Fig. 5.4 shows the steps for the manufacturer to set up the range of product dimensions. The first step is to set up an interaction matrix for all initial product dimensions. Then, this matrix is transformed into a hierarchical tree. At this stage, the manufacturer can consider and adjust the dimensions for his own benefit to select his optimum product sizes. This internal coordination is essential to the simplification of the product types. The second step is to test the
**STEP 1**

**initial magnitude**

**1ST ADJUSTMENT**

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**coding and character**

**meaning**

**STEP 2**

**other building sub-systems**

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**STEP 3**

**dimensional requirements of possible building types**

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**STEP 4**

**mathematical adjustments**

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**interaction matrix**

**hierarchical tree**

**Coordination**

**Process of Product**

**Dimensions**

**Fig. 5.4**
product dimensions against the requirements of other building sub-systems to improve their compatibility. From the possible interactions, the product dimensions can be further adjusted. The third step is to consider the requirements of possible uses. Upon the setting up of the general dimensional requirements of one or several possible building types (such as schools, housing, etc.), the product dimensions can be further adjusted to improve their applicability. The final step is a mathematical adjustment to set up a common module and to improve combinability. The 4in/10cm basic module should be considered first, then other larger common modules. For good combinability, the basic rules are:

Lowness — The smaller the dimensions, the greater will be the combinability.

Togetherness — The closer the product dimensions, the greater will be the combinability.

Common factor — Generally, the best combinability is obtained when all product dimensions are relatively prime, i.e. no common factor other than the common module.

After these several steps of adjustment, the product dimensions should be much improved in every aspect. However, in order to achieve the best result, the final adjusted dimensions can be used as initial dimensions in the interaction matrix, and then the process can be repeated for further improvement. After several cycles, if there is no adjustment necessary, the product dimensions should be in a perfect coordination.

As to the architect's design with industrialized building products, this comprehensive approach is also helpful. According to the nature of the building project and the architect's preliminary idea, the interaction matrix and the hierarchical tree can be set up for all architectural
dimensions, except those dimensions of the industrialized building products, as shown in Fig. 5.5. Then a table is set up to help to systematically consider the interactions between the product dimensions and other architectural dimensions. The dimensional adjustment can now be carried out according to the hierarchical tree and the interaction table. In doing so, the selected magnitude of each architectural dimension should be simultaneously suitable for both related product dimensions and other related architectural dimensions. If a dimensional range can be selected for each architectural dimension, the architect can have more freedom in the choice of the dimensions in design.

As it is impossible to have any adjustment between a fixed architectural dimension and its related product dimensions (also fixed), if a dimensional relationship can not be set up between them, special solutions must be considered, such as a revision of the design to avoid this difficulty or to manufacture a special type of product for this special purpose.

For architects, this coordination process is not only useful for design, but also can help to select the most fit product system for a building project. With this systematic consideration, the dimensional misfit between the industrialized products and the requirements of the project can be easily determined.

This coordination process should work in parallel with design. During the sketch stage, only the major dimensions are considered, so that a preliminary dimensional system can be established. When the design develops in detail, more dimensions are involved. The interaction matrix and the hierarchical tree expand with the design to continuously
interaction matrix

coding and character

meaning

initial magnitude

hierarchical tree

Fig. 5.5
Coordination
Process of
Industrialized
Building
review the dimensional relationship. The most appropriate magnitude can thus be selected for each dimension.

5.5 Conclusion

The above is an attempt to provide dimensional coordination in a comprehensive and systematic way. The theory and method are of simple arithmetic and can easily be worked out by hand. It is believed that by this thorough objective analysis, the existing gap between modular theory and practical application can be bridged.

This method should be useful not only to the study of industrialized building product systems and the design of industrialized buildings, but useful as well to the design of conventional buildings.

This method is in the initial stage of development. Further study and research can certainly improve its effectiveness and increase its capability. Its application is confined not only to the coordination of linear measurements, but may be extended to the coordination of all kinds of dimensions of different units, such as the circulation and service distribution problems of complicated building projects and density and traffic problems in urban planning.
Christopher Alexander has developed in his book "Notes on the Synthesis of Form", a mathematical method to set up a hierarchical tree from a system of binary stochastic variables. (refer Appendix 2 of the book: Mathematical treatment of Decomposition. P.174-191). His approach decomposes the system into a set of sub-systems, so that information transfer between the sub-systems is at a minimum. This method of decomposition has been widely used in solving architectural design problems. However, this method of decomposition allows the separation of links between variables, i.e. breaks up the relationships between them. This is against the basic principle of dimensional coordination, that each relationship must be accounted for. It can not be used for dimensional coordination purposes. Moreover, this method of decomposition is based on complicated mathematical formulas, which can only be worked out by computers. For dimensional coordination purposes, the method should be simple enough to be worked out by hand.

(2) Dunstone, Philip H. COMBINATION OF NUMBERS IN BUILDING.
PART II - APPLICATION
6. METAL BUILDING INDUSTRY IN HOUSTON

6.1 Background: the Metal Industry in Houston

The metal industry has long been rated the third major industry in Houston, after the petroleum industry and the chemical industry. They are closely related; refineries, oilfields, pipeline, petrochemical and chemical plants all have provided a very stable and expanding market for metals. The completion of the Houston ship channel in 1915 provided access to an international metals market, and insured ready supply of raw materials.

Rapid development in the Southwest after World War II gave forceful impetus to post-war expansion of the metal industry. Extensive construction, highway programs, the new ship building industry and fast growth of suburbs consumed all kinds of primary metals and fabricated metal products. Today, after more than 20 years of growth in her metal industry,
Houston has become the Metal Center of the Southwest. In addition to several hundred well established primary and fabricating metal plants, the decision in 1965 by United States Steel Corporation, the nation's biggest steel maker, to build its 14,000 acre Texas Work on Cedar Bayou predicts an even brighter future for the metal industry in Houston.

6.2 The Rapid Maturity of the Metal Building Industry

Founded under the shelter of a mature metal industry, the metal building industry in Houston grew rapidly after World War II from a small annex of the metal industry for fabrication of metal building products to an independent and mature industry.

Fifteen years ago, metal buildings were corrugated tin roof temporary structures and were associated with a dull, cheap and unhabitable image. But, through continuous research under the aid of its mother industry, the metal building industry began to shape up. By the early 1960's, metal buildings had penetrated commercial, educational, recreational and other non-residential areas, and had become a self-contained building system.

Although the rapid maturity of the metal building industry in Houston must be credited to the support of its strong parent metal industry with its technical and financial assistance and its supply of primary materials, other important factors should not be neglected:

(1) A ready market: the fast expansion of the Houston urban
area called for more industrial and commercial facilities.

(2) Frontier attitudes and the semi-tropical climate allowed the acceptance of metal buildings.

(3) A complete transportation system: port facilities and the highway network provide easy access to national and international markets.

(4) The availability of land, machinery and labor made easy the setting up of new plants.

With the maturation of metal building systems and the change of public attitudes toward metal buildings, the manufacturing plants expanded, and computers are now widely used for product quality control and for structural design. These efforts in product and application refinement have gained international recognition, not only for the components themselves, but also for the whole building system.

The Houston Port and easy access to primary materials have made Houston a major metal building export center. With an increase in international trade, manufacturers of other states have set up plants or distribution centers in Houston. This concentration makes Houston the capital of the metal building industry.

According to the Manufacturer Directory of the Houston Chamber of Commerce, there are nineteen established metal building manufacturers in the Houston area. Classified in accordance with their products, about half of them are special manufacturers. They produce either particular building types, such as oil field buildings, aircraft hangars, etc., or major metal building components. The rest are general manufacturers; they produce complete metal building systems. Marketing areas of these manufacturers range from the local Houston area
to International. About half of the general manufacturers carry on international trade. In addition, there are also four distributions in Houston for major manufacturers in other states.

A nation-wide business organization called Metal Building Manufacturer Association (M.B.M.A.) was formed by major metal building manufacturers to promote the metal building business, to improve product quality and to set up industry wide technical, manufacturing and design standards. Out of twenty-six M.B.M.A. members, five are in Houston, and Houston is the only city which has more than one member in this organization.

6.3 Metal Buildings

Metals, especially steel, are good structural materials due to high strength and comparatively light weight. Although widely used as structural materials in all kinds of buildings, metals are generally covered with other materials, not only for protection but also for disguise. But the difficulties of heat and sound insulation, condensation prevention, rust and corrosion protection, and monotony in finishing of steel products have been successfully overcome. Metal sheetings and panels are increasingly accepted as finish materials, especially for the curtain wall of high-rise building.

However, buildings totally constructed in metal were confined until recently to utility and temporary uses because of low weather
resistance. Then some fifteen years ago, jointing techniques and insulation materials began a steady improvement, and environmental control systems became economically feasible for metal buildings. Metal buildings began to be used for purposes other than utility and temporary. This was the turning point of the metal building industry.

Since then, metal buildings have been continuously improved by research and development. It is not an exaggeration to say that 80% of present metal building products did not exist 10 years ago. As stated before, metal building products and construction methods became a self-contained building system. A typical metal building system is shown in Fig. 6.1. Metal building, the result of this industrialization, certainly has some advantages over other types of construction:

- **Economy is the first advantage.** Standardized products and mass-production result in lower prices. Large, simple and lightweight components together with simple assembly methods reduce the on-site labor cost. For an average metal building, the total material and labor cost of the metal parts, including structure and weather enclosure, is only $1.50 to $3.70 per sq. ft. (in comparison to $1.70 per sq. ft. for a 6" concrete slab, labor and materials for the slab only). It must be noted however that the metal structure and weather enclosure represent only 20% to 30% of the total building cost.

- **Saving in time is another important advantage.** Due to standardization and the aid of computers, designs can be prepared within a few hours, and materials production can be completed within a few days. Also, because of dry construction and systematic assembly methods, erection work on site can be completed within a few weeks.

With regard to long span structures, steel is generally the
(a) Major Structural Frame and Secondary Structural Members

(b) Wall and Roof Panels and Accessories

Fig. 6.1 A Typical Metal Building System

(From Stran-Steel Product Manual)
best material. The standard clear spans of metal building systems range up to 170', which is impossible with most other building materials.

Dry construction and standardization constitute another advantage — flexibility. Alteration and extension can easily be carried out in metal buildings; even re-location of the whole building to another site is possible. The growth and change potential is higher in metal buildings than in other industrialized building systems.

Easy maintenance is another advantage of metal buildings over other types of construction. The refinement in finish and jointing methods reduce maintenance to a minimum. Again, dry construction and the standardized product enable maintenance to be easily carried out.

However, in spite of these advantages, there are certain limitations to existing metal building systems:

Single story and sloping roofs are the main reasons for low price, high speed construction, and flexibility in growth and change, but result in a rigid limitation to the use of metal buildings. As mentioned above, the existing metal building systems were developed from utility and temporary structures, which are generally single story. Multi-story metal building systems are indeed rare. No manufacturer in Houston has ever attempted to establish one.

Austerity and what might be called a cold feeling derived from the nature of metal are the main aesthetic objections to the use of metal. The comparative monotony in texture and finish is another cause for the rejection of metal buildings. Also, a high coefficient of thermal expansion prevents easy integration with other materials. All these can explain why metal buildings have seldom been used for residential purposes.
These limitations can be overcome. Perhaps recent expansion of the research departments of some major manufacturers is the first step toward this target.

6.4 Products and Processes

90% of the primary materials of metal buildings are steel. Carbon steel ASTM A36 is used for major members while low alloy steel is used for thin sheets. Sheets and strips less than 1/4" thick which can be ordered in coils are widely used by the metal building industry. Primary materials in this form are not only economical but also suitable for continuous automatic processes. For major structural members materials thicker than 1/4" have to be used. Due to the difficulty in coiling, these thicker materials are delivered in plates of limited length. This is one hindrance to continuous processes in fabrication of main structural members. For economy and flexibility in fabrication, hot rolled members such as I beams, wide flanges, channels etc. are never used.

Metal building products can be classified in four categories (refer Fig. 6.1):

Major Structural Frames
Secondary Structural Members
Wall and Roof Panels
Accessories
Major Structural Frames

All major structural frames are in the form of rigid frames. If possible, for longer spans, interior columns are added. Trusses and space frames, due to their high fabrication labor consumption, are seldom developed by metal building manufacturers.

The cross section of the major structural frame is a built-up 'I' shape. The top and bottom flanges are joined to the web by welding. Welding is usually done on one side only. For transportation purposes, the rigid frames are separated into several linear members, which are joined together on site by bolts.

Production of these major structural frames is a manual labor consumption process. Each component, such as the flange, web, jointing plate, stiffener, etc., is cut from primary materials, mainly steel plates, by a high pressure shearing machine. All holes for bolts and bracing rods are punched.

Fabrication of these components into members is done by welding. Whenever possible, a high speed automatic welding machine is used. Other special welds are completed manually.

The fabricated members are hoisted by conveyors for cleaning and then spray painted with red oxide zinc chromate primer for protection. As these members are always heavy and big in size, storage is difficult. Therefore, most manufacturers seldom have structural members in stock. If the cleaning and painting jobs are properly done, however, there is sufficient protection against rust and corrosion when outside storage is necessary.

Secondary Structural Members

These members have two major functions: to tie the major
frames and to provide support to wall and roof panels. Purlins, girts, end wall columns and eave struts are types of this category. They are fixed to major structural frames and joined together by bolts.

Purlins and girts are Z sections. Z sections have two advantages: they can be stacked together easily, and can be formed by cold roll forming processes.

Primary materials for Z sections are steel strip coils. First, the steel strip is de-coiled and flattened. Then holes are punched and surfaces are cleaned. In the roll forming mill, flat strip can be gradually pressed into a Z shape and then cut into required lengths. Finally, these Z section purlins and girts are conveyed through the painting tunnel and curing oven, and stacked together for storage and delivery to the site.

Production of Z sections is a typically automatic continuous process which is precisely controlled by electronic devices. Only two to three workers are needed to look after the process and store the products.

End wall columns and eave struts are in C sections, as connections have to be made on three sides or two adjacent sides. Since roll forming mills for C sections are complex and expensive, pressing machines are used typically. As pressing must be carried out piece by piece; the production of C section is not a continuous process. More manual labor is needed.

Primary materials for C sections are also steel strip coils, but for structural reasons, thicker steel plate may be used. Primary materials are cut into strips of required dimensions by shearing machines; then holes are punched and surfaces are cleaned. After the
strips are pressed into C shapes by the pressing machine, the painting
and oven-curing process is similar to that for Z sections.

'I' shape end wall columns are used for high end walls. They
are fabricated like major structural members.

Wall and Roof Panels

Primary materials for wall and roof panels are 22 to 26 gauge
metal sheets. Finish is important for external surfaces. The sheets
used to form wall and roof panels are galvanized and sometimes embossed
and textured by the metal manufacturers, and then pre-painted or pre-
coated with synthetic materials by chemical manufacturers before delivery
to the metal building manufacturers in coils.

The production of wall and roof panels from these pre-finished
sheets is comparatively simple. The sheets are pressed by the cold roll
forming machine into a ribbed configuration, and then cut into required
lengths. This is also an automatic and continuous operation. The
ribbed configurations can improve structural properties and appearance.

No holes are pre-punched for wall and roof panels. Holes for
fixing bolts or screws are drilled on-site as needed. Continuous tape
sealers are provided for all joints.

Some manufacturers also manufacture sandwich panels with metal
inner panels in a more elaborate finish or texture. The inside face is
generally of a flat surface with recessed jointing.

Accessories

There are several types of accessories:

(1) Flashings, closures, trims, ridges, etc. to cover the joints
of external panels and edges.

(2) Eave gutters and down spouts for rain water.
(3) Roof ventilators.

(4) Louvers.

These four types of accessories are produced by a pressing and welding process from unfinished sheeting and then treated and painted in the factory to match the color of wall and roof panels.

(5) Doors and frames.

(6) Windows, steel or aluminum.

(7) Insulation.

(8) Sky lights.

(9) Sealers.

Most manufacturers do not produce these last five types of accessories. Specialist manufacturers supply these to the metal building manufacturers.

The above is only a simple outline of the products and processes of the metal building industry. Although the products of all metal building manufacturers are similar, differences in design, detailing, jointing methods and manufacturing equipments cause the product of each manufacturer to become a closed system. There is no interchangeability between products of two different manufacturers. Occassionally, with adjustments, the whole wall and roof panel system can be fixed on another manufacturer's structural system. This is the only flexibility which may be achieved.

In general, production by major manufacturers is well organized. Production is efficient, especially the automatic continuous process which can produce 120 linear feet of product per minute. More over, the whole manufacturing operation a cold process, which has the flexibility of
starting and stopping at anytime. All manufacturers keep only primary materials and accessories in stock, and seldom store large amounts of standard products.

Another important point should be noted. All metal building products are used for structure and weather enclosure only. No manufacturer in Houston has developed an internal partitioning sub-system or any other internal sub-system as part of the whole building system. And none of the existing systems takes the service sub-systems into account. That is to say, the metal building is an empty shell only. Differing from other industrialized building systems, there is no integration of other architectural sub-systems in metal buildings. Again, this can be explained by noting that metal building systems originated from utility and temporary structures. Although the long span column free interior can give some flexibility in interior arrangement, this over-simplified approach can not solve complicated architectural problems. This segregation of architectural elements, associated with other limitations stated in Section 6.3, confines the use of metal buildings to limited functions.

6.5 General Procedure of Building Works

As each metal building manufacturer has his own building system, the erection methods differ from one to another. Therefore, the erection works have to be carried out by specially trained contractors.
These trained contractors are called franchised contractors in the metal building industry. A franchised contractor must also be a licenced contractor as he has to complete building works other than the site assembly of the metal buildings. At the same time, he acts as the business agent of the manufacturer to promote the sales of the metal building products. The extend of a manufacturer's franchised contractor network determines the manufacturers marketing. Generally, a contract or agreement is signed between the manufacturer and the franchised contractor that the franchised contractor can not simultaneously be another manufacturer's franchised contractor, except in a remote area or small town. The franchised contractor is also called by the general public a franchised dealer or a franchised builder.

The manufacturer provides all kinds of assistance to his franchised contractors in addition to the training of erection crews. The manufacturer's professional engineering staff can help the franchised contractor solve special technical problems, and occasionally designs the building footings and finishes the necessary certificates required by the Building Permit Office. Advertising is also the responsibility of the manufacturer to build public confidence in his products. Aside from the sale of products there is generally no other financial relationship between the manufacturer and his franchised contractors.

Based on this franchised contractor system, the procedures of the building process differ from those handled by architects. Fig. 6.2 illustrates several typical types of building processes.

The majority of metal building clients (or buyers) seldom have complicated building programs. With the help of the franchised contractors, the clients can usually find suitable solutions to their
Fig. 6.2 Typical Canon of Building Process

CASE 1

CASE 2

CASE 3

CASE 4

CASE 1

CASE 2

CASE 3

CASE 4
building programs in the standard metal building systems. Upon the client's agreement, the franchised contractor can order the metal building components and organize the building works to be carried out. (as shown in Case 1)

Sometimes, when the client has a special building program, such as heavy loading, long span, large area, etc., he can approach the manufacturer directly or through the franchised contractor. (as shown in Case 2) After the manufacturer finishes the design and production, the erection work will be carried out by the franchised contractor.

In these two cases, since either the manufacturer's professional engineer staff or other engineers can complete the legal procedures for building permits, no architect is involved.

When the client desires some facade treatment, an architect may be involved as consultant to the franchised contractor. As illustrated in Case 3, architects seldom provide direct service to clients.

Only very rarely as in Case 4 will client and architect have a conventional relationship with the metal building manufacturer in the position of specialist supplier. However, the erection works still have to be carried out by the franchised contractors.

To sum up the above, the metal building industry has not only set up a building system, but also created special procedures to carry out building works. This manufacturer-centered building process has simplified the complicated conventional practice of bidding, contracting and supervision. This direct client and contractor/manufacturer relationship reveals two important aspects:

When the product system is simplified into a small amount of standardized parts, the client with a little technical assistance can
easily interpret his building program into a practical design. The pre-engineered big-size product components with typical jointings eliminate the tedious member to member structural calculation, construction detailing and working drawing.

All metal building manufacturers provide long period warranties for their products (ranging from five to twenty years). The simple dry assembly methods enable the immediate replacement of any defective parts or rectification of sub-standard workmanship. Site supervision, therefore, can also be eliminated. Also due to the simplified site assembly methods, high speed in construction can be achieved even without the aid of high level management techniques, (such as C.P.M.).

The above can explain why the traditional architect's roles of professional service to the client and of supervision of the building works can be totally excluded in the whole metal building construction process. The client saves the architect's fee, but without the contribution of the architect, metal buildings are frequently environmental misfits, a loss to both the metal building client and the user, and the metal building industry.

6.6 Architects and The Metal Building Industry

Metal building systems originated from utility and temporary buildings which seldom attract the architects' attention. The growth of the metal building industry from a fabricating branch into a mature
industry is the result of research efforts of engineers and manufacturers; architects have made no significant contribution to this maturation. Even in the whole construction process of metal buildings, architects only play a minor role; and in many cases, architects are totally excluded. This wide gap between the architectural profession and the metal building industry is a great loss to both parties.

With the popularity of metal buildings in industrial and commercial areas, architects lose many job opportunities. Lacking thorough knowledge of metal building systems, architects can not fully utilize the advantages of these highly industrialized building products to broaden their areas of contribution. Also, the efficiency of metal building processes in design, production and on site construction is a challenge to the traditional complicated architectural practice. These well established industrialized systems are a good starting point for those architects who have no experience in building industrialization.

Although the metal building industry is enjoying good business and popularity, further development is constrained. A building system based only on practicability and technological refinement will not successfully form good environment for complex human activities.

Many architects have changed their attitudes toward metal buildings, and have begun to investigate metal building systems. But design information is hard to obtain. Traditionally, there are only two types of manufacturer's information: one for clients and another for franchised contractors. Both of these do not present sufficient information for architects. Moreover, due to rigidity of structural and constructional criteria, and the lack of integration with other building sub-systems, architects find that it is difficult to use metal building systems.
At the same time, many metal building manufacturers have tried to employ architects in their design departments. This has not been successful. On the other hand, manufacturers and their franchised contractors are discouraged by the fact that they are unable to participate in the architects' complicated bidding and contracting procedures. Metal building systems can not bid against conventional construction methods without drastic changes to the architect's design.

As shown in Fig. 6.2, there are only two possibilities for architects in the metal building industry. They can be consultants to franchised contractors to modify the metal building facades for visual comfort. Or they can be consultants to clients to negotiate with the manufacturers for contracts to put up metal buildings to fit clients' requirements.

The following are suggestions to bridge this long-existing gap between architects and metal manufacturers:

**On the architects' side:**

1. The traditional architectural practice should be revised to allow industrialized building systems a fair chance in bidding competition. It is strongly believed that a proper way to handle this matter is the performance concept.

**On the manufacturers' side:**

2. A new two to three story metal building system should be designed from existing products.

3. The existing system should be improved to integrate with building sub-systems.

4. A better communication method should be developed to provide proper information to facilitate architect's design work.
NOTES


(2) "Steelmaker of the Southwest". HOUSTON, August, 1970. P. 17
7.1 General Description and Comparison of Dimensional Criteria of Five Systems

All existing metal building systems are similar; they are designed and manufactured according to the same basic principles. They differ from each other only in detailing. Two building sub-systems are formed from four types of metal building products:

- Structural sub-system — major structural frames and secondary structural members.
- Weather enclosure sub-system — panels and accessories.

In order to facilitate the comparative analysis of the dimensional criteria, the general description of these sub-systems is structured according to the product types and followed by a comparison table of the different systems. The product systems of five manufacturers
are considered:

A & S Steel Buildings, Inc.
Kirby Building System, Inc.
Metallic Building Co.
Stran-Steel Corporation
Butler Manufacturing Co.

All five manufacturers are members of Metal Building Manufacturers Association. The first four are major Houston metal building manufacturers; Butler's manufacturing plant is in Kansas City, Missouri.

There are two reasons to include Butler's products for comparison:
(1) Butler has been recognized as the nation's biggest metal building manufacturer; and (2) Butler's agent is an influential distributor in the Houston area.

**Structural Sub-System**

Rigid frames are the major structural form of this sub-system. Fig. 7.1 shows the relationship of the components. The major rigid frames are arranged in parallel in one direction; they are tied by purlins and girts in the perpendicular direction. End rigid frames are usually replaced by end wall units to provide support for wall panels, doors and windows. Steel cross rod wind bracing is provided between the first two rigid frames to resist wind loads in the direction of purlins and girts.
Purlins — Z shape purlins are widely used. As shown in Fig. 7.2, Z shape purlins allow lapped joints over supports to achieve continuity to increase the span and to reduce deflection. The spacing of purlins has been standardized by all manufacturers to 5'-0" horizontal projection length (i.e. for sloping roof, actual spacing is longer than 5'-0", such as 5'-3/16" for 1 in 12 roof and 5'-3\(\frac{3}{4}\)" for 4 in 12 roof). Purlin thickness is adjusted for roof loading.

The span of purlins is related to three factors: loading, material strength and thickness. The span of purlins governs the spacing of major frames. By adjusting the material thickness and strength for varying loading conditions, all manufacturers individually standardize their purlin spans into a few types.
Fig. 7.2
Lapping Joint of Purlins

Fig. 7.3
(a) Lapping Joint
(b) Fixed to Column by Clips

Fig. 7.4
Eave Strut
### COMPARISON TABLE 1 - Z SHAPE PURLIN

<table>
<thead>
<tr>
<th>FIRM</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>STRAN-STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEPTH</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;, 10&quot;</td>
<td>9½&quot;</td>
</tr>
<tr>
<td>STANDARD SPACING</td>
<td>5'-0&quot;</td>
<td>5'-0&quot;</td>
<td>5'-0&quot;</td>
<td>5'-0&quot;</td>
<td>5'-0&quot;</td>
</tr>
</tbody>
</table>

RANGE OF THICKNESS - 14 TO 16 GAGE

### COMPARISON TABLE 2 - GIRT

<table>
<thead>
<tr>
<th>FIRM</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>STRAN-STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEPTH</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>6½&quot;, 9½&quot;</td>
</tr>
<tr>
<td>MAXIMUM STANDARD SPACING</td>
<td>5'-5½&quot;</td>
<td>4'-7½&quot;</td>
<td>6'-0&quot;</td>
<td>6'-0&quot;</td>
<td>4'-6&quot;(FOR 6½&quot;)</td>
</tr>
</tbody>
</table>

RANGE OF THICKNESS - 14 TO 16 GAGE

### COMPARISON TABLE 3 - EAVE STRUT

<table>
<thead>
<tr>
<th>FIRM</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>STRAN-STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEPTH</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>9½&quot;</td>
</tr>
</tbody>
</table>

RANGE OF THICKNESS - 14 TO 16 GAGE
**Girts** — These are generally of the same cross section as purlins. The major function of girts is to support the wall panels and to transmit the horizontal loading from wall panels to major frames. Girts are joined over supports like purlins, or fixed to columns by clips to save wall space, as shown in Fig. 7.3(a) and (b).

Since Z sections are not designed to be placed horizontally, girts are partly supported by wall panels in the vertical direction. The spacing of girts is closely related to the installation of doors and windows and is at the same time governed by the horizontal wind load and eave height. The spacing of girts is more complicated than spacing for purlins and is not standardized.

**Eave Strut** — These perform the functions of a purlin and a girt and also act as a major tie for rigid frames. Usually, they are butt jointed over supports. Fig. 7.4 shows the typical section of an eave strut and its jointing method with other members. Since eave struts act as connectors of roof panels and wall panels, and as supports to eave gutters, their sections varies with roof slope.

**Major Frame** — All major frames are symmetrical. The shapes of major frames are determined by four factors: eave height, span, bay length and roof slope.

Eave height and span are determined by the design of the building. Bay length is governed by purlin span and is standardized into a few types. Roof slope is also standardized into two gradients: 1 in 12 and 4 in 12. 1 in 12 is the minimum slope of a gable roof allowed by most of the building codes without special water proofing layers. Since a 1 in 12 gradient gives less variation to internal ceiling height, this gradient is widely used in metal buildings, except for special
purposes that require a high 4 in 12 gable roof.

All major frames are designed as hinged arches; a rigid connection between frame and foundation is not required. Only anchor bolts are used for the connection between frame and foundation.

There are four types of major frame (refer illustration of Comparison Tables 4 to 8):

1. **Taper Beam** — Roof slope 1 in 12. The increased depth of beam at midspan helps reduce column moment. The uniform column section and the levelled underside of the beam facilitates installation of internal partitions and ceiling panels.

2. **Rigid Frame** — Roof slope 1 in 12 and 4 in 12. Rigid frames are better structural solutions for long clear spans than taper beams. But the sizes of members vary according to the structural requirement.

3. **Rigid Frame with Interior Columns** — Roof slope 1 in 12. When interior columns are permitted, the span of rafters can be shortened and the structure is more economical. Usually, pipes are used for interior columns.

4. **Width Extension** — Roof slope 1 in 12. Width extensions are half rigid frames, mainly used for additions to existing buildings.

**End Wall Unit** — End wall units are always of light section. Generally, standard girts are used; columns and top rafters are of C sections, except in cases of heavy loading for which built up I sections are used (see Comparison Table 9).

**Wind Bracing** — Wind bracing serves two purposes: to provide rigidity to resist horizontal loadings and to facilitate the alignment of frames.
## Comparison Table 4 - Taper Beam

Roof slope 1 in 12

<table>
<thead>
<tr>
<th>Firm</th>
<th>A &amp; S</th>
<th>Kirby</th>
<th>Metallic</th>
<th>Syran - Steel</th>
<th>Butler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>TB</td>
<td>Space Master</td>
<td>SM</td>
<td>Stran Master</td>
<td>WBF</td>
</tr>
<tr>
<td>Eave Height</td>
<td>10' 12' 14' 16'</td>
<td>10' 12' 14' 16' 20'</td>
<td>10' 12' 14' 16' 20'</td>
<td>10' 12' 14' 16' 20'</td>
<td>9' - 9 3/4&quot; 11' - 9 3/4&quot; 13' - 9 3/4&quot; 15' - 9 3/4&quot;</td>
</tr>
<tr>
<td>Span</td>
<td>24' 30' 40' 50' 60'</td>
<td>30' 40' 50' 60'</td>
<td>20' 24' 30' 36' 40' 50' 60'</td>
<td>20' 24' 30' 36' 40' 50' 60'</td>
<td>24' 32' 40' 50' 60' 70'</td>
</tr>
<tr>
<td>Bay Length</td>
<td>20' 25'</td>
<td>20' 25'</td>
<td>16' 20' 24'</td>
<td>16' 20' 24'</td>
<td>12' 20' 24' 24'</td>
</tr>
</tbody>
</table>
### COMPARISON TABLE 5 - RIGID FRAME

**Roof Slope:** 4 IN 12

<table>
<thead>
<tr>
<th>FIRM</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>STRAN-STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NAME</strong></td>
<td>Rigid Frame</td>
<td>Clear Span Rigid Frame</td>
<td>RF</td>
<td>RF</td>
<td>RF</td>
</tr>
<tr>
<td><strong>Eave Height</strong></td>
<td>10' 12' 14' 16' 20' 25'</td>
<td>10' 12' 14' 16' 20'</td>
<td>10' 12' 14' 16' 20'</td>
<td>10' 12' 14' 16' 20'</td>
<td>9' 9 3/4'' 11' 9 3/4'' 13' 9 3/4'' 15' 9 3/4'' 17' 9 3/4'' 23' 9 3/4''</td>
</tr>
<tr>
<td><strong>Span</strong></td>
<td>20' 30' 40' 50' 60' 70' 80' 90' 100' 120'</td>
<td>30' 40' 50' 60' 70' 80' 100' 120'</td>
<td>30' 40' 50' 60' 70' 80' 100' 120'</td>
<td>30' 40' 50' 60' 70' 80' 100' 120'</td>
<td>20' 24' 28' 32' 36' 40' 50' 60' 70' 80' 120'</td>
</tr>
<tr>
<td><strong>Bay Length</strong></td>
<td>40' 25'</td>
<td>20' 25'</td>
<td>20' 24'</td>
<td>20' 25'</td>
<td>18' 20' 21' 24'</td>
</tr>
</tbody>
</table>

[Diagram of a roof structure with dimensions marked]
## COMPARISON TABLE 6 - LOW RIGID FRAME

### Roof Slope: 1 in 32

<table>
<thead>
<tr>
<th>FIRM</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>STRAN-STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAME</td>
<td>RF</td>
<td>CLEAR SPAN RIGID FRAME</td>
<td>LR</td>
<td>SM (40-60'M)</td>
<td>LRF</td>
</tr>
<tr>
<td>SPAN</td>
<td>20', 30', 40', 50', 60', 70', 80', 90', 100', 120', 130', 150', 170'</td>
<td>30', 40', 50', 60', 70', 80', 90', 100', 120'</td>
<td>40', 50', 60', 70', 80', 90', 100', 110', 120', 130', 140', 150', 170'</td>
<td>24', 32', 36', 40', 50', 60', 70', 80', 100', 120',</td>
<td></td>
</tr>
</tbody>
</table>
# COMPARISON TABLE 7 - RIGID FRAME WITH INTERIOR COLUMNS

*ROOF SLOPE: 1 IN 12*

<table>
<thead>
<tr>
<th>SPAN</th>
<th>BAY LENGTH</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>SHEAR - STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RFC</td>
<td>BEAM &amp; COLUMN</td>
<td>LRM</td>
<td>LR MODULAR</td>
<td>MRF</td>
</tr>
<tr>
<td><strong>EAVE HEIGHT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 SPACING</td>
<td>12', 14', 16'</td>
<td>10', 12', 14'</td>
<td>12', 14', 16'</td>
<td>10', 12', 14'</td>
<td>13'- 9 1/2'</td>
<td>15'- 9 1/4'</td>
</tr>
<tr>
<td>2 SPACINGS</td>
<td>20', 25'</td>
<td>16', 20'</td>
<td>20'</td>
<td>16', 20', 24'</td>
<td>20'</td>
<td></td>
</tr>
<tr>
<td>3 SPACINGS</td>
<td>40', 50', 60'</td>
<td>25', 30', 35', 35'</td>
<td>30', 35', 40', 40'</td>
<td>35', 35 1/2', 35', 40', 40'</td>
<td>40', 50', 60'</td>
<td></td>
</tr>
<tr>
<td>4 SPACINGS</td>
<td>80', 100', 120'</td>
<td>60', 60', 70', 80', 100', 120'</td>
<td>60', 80', 100', 120'</td>
<td>60', 70', 80', 100', 110', 120'</td>
<td>80', 100', 120', 140'</td>
<td></td>
</tr>
<tr>
<td>5 SPACINGS</td>
<td>120', 150', 180'</td>
<td>100', 120', 150', 180'</td>
<td>100', 120', 150', 180'</td>
<td>90', 100', 120', 150', 180'</td>
<td>120', 150', 180', 210'</td>
<td></td>
</tr>
<tr>
<td>7 SPACINGS</td>
<td>180', 240'</td>
<td>180', 240'</td>
<td>180', 240', 300', 360'</td>
<td>240', 300', 360'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAY LENGTH</td>
<td>20', 25'</td>
<td>20', 25'</td>
<td>20', 25'</td>
<td>20', 25'</td>
<td>18', 24'</td>
<td></td>
</tr>
</tbody>
</table>
### COMPARISON TABLE B - WIDTH EXTENSION

**Roof Slope 3 in 12**

<table>
<thead>
<tr>
<th>FIRM</th>
<th>A &amp; S</th>
<th>KIRBY</th>
<th>METALLIC</th>
<th>STEEL-STEEL</th>
<th>BUTLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAME</td>
<td>LEAN-TO</td>
<td>WING UNIT</td>
<td>WING UNIT</td>
<td>WING UNIT</td>
<td>WIDTH EXTENSION</td>
</tr>
<tr>
<td>EAVE HEIGHT</td>
<td>6'-8&quot;</td>
<td>8'-9&quot;</td>
<td>8'-10&quot;</td>
<td>8'-10&quot;</td>
<td>9'-9 3/4&quot;</td>
</tr>
<tr>
<td></td>
<td>9'-6&quot;</td>
<td>10'-9&quot;</td>
<td>10'-10&quot;</td>
<td>10'-10&quot;</td>
<td>11'-9 3/4&quot;</td>
</tr>
<tr>
<td></td>
<td>10'-4&quot;</td>
<td>12'-9&quot;</td>
<td>12'-10&quot;</td>
<td>12'-10&quot;</td>
<td>13'-9 3/4&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14'-9&quot;</td>
<td>14'-10&quot;</td>
<td>14'-10&quot;</td>
<td>15'-9 3/4&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16'-9&quot;</td>
<td>16'-10&quot;</td>
<td>17'-9 3/4&quot;</td>
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<tr>
<td>SPAN</td>
<td>20'-30'-40'</td>
<td>15'</td>
<td>24'-48'</td>
<td>24'-48'</td>
<td>24'-48'</td>
</tr>
<tr>
<td>BAY LENGTH</td>
<td>20'-25'</td>
<td>20'-25'</td>
<td>20'-24'</td>
<td>20'-25'</td>
<td>18'-20'-21'-4&quot;</td>
</tr>
</tbody>
</table>
### COMPARISON TABLE 9 - END WALL UNIT

- **RooF SloPe:** 1 IN 12 OR 4 IN 32
  **According To Major Frame**

- **Standard Column Spacing:** 20'

<table>
<thead>
<tr>
<th>Firm</th>
<th>A &amp; S</th>
<th>Kirby</th>
<th>Metallic</th>
<th>Span-Steel</th>
<th>Butler</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Column</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>7 8&quot;</td>
<td>6 1/2 10&quot;</td>
</tr>
<tr>
<td></td>
<td>10&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Top Rafter</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8&quot;</td>
<td>8&quot;</td>
<td>8&quot; or over</td>
<td>8&quot; 10&quot;</td>
<td>6 1/2 10&quot;</td>
</tr>
<tr>
<td></td>
<td>10&quot;</td>
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</tr>
<tr>
<td></td>
<td>12&quot;</td>
<td></td>
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</tr>
</tbody>
</table>
during erection. Generally, crossed bracing of 1/2" rods is used. Double purlins are provided at the fixing points of roof wind bracing to resist compressive forces (refer Fig. 7.1). If necessary, other types of bracing, such as knee bracings are used.

Flange Bracing — Flange bracing is provided at every second or third purlin or girder, as shown in Fig. 7.5, to prevent buckling of the compressive side of the built up I section.

![Flange Bracing Diagram](image)

**Fig. 7.5 Flange Bracing**

**Special Structures**

Besides the standard structural sub-system, the metal building manufacturers also produce special structural sub-systems, such as small utility buildings of load bearing metal panel wall construction, aircraft hangers, stadium stands, etc. As these structural sub-systems are for limited use, they are not taken for comparison. However, some of these special sub-systems do represent new directions and are worth mentioning:

1. Flat roof buildings — By using zip rib roof panels of interlocking closure top ribs (Fig. 7.6), Kirby's Century Building can lower the roof slope to 1 in 48 gradient. Butler's Landmark
System of beam trusses and bar joists has been widely used for school buildings.

(2) Load bearing wall roof unit — A roof system designed to rest on masonry walls, such as Stran-Steel's LBW Roof System and Kirby's BWC Roof Unit.

(3) Interior girder system — Developed by Stran-Steel. With the provision of a supporting girder, alternate interior columns supporting the rigid frame are eliminated to achieve bigger column free spaces (refer Fig. 7.7).

![Fig. 7.6 Zip Rib Roof Panels](image)

![Fig. 7.7 Interior Girder System](image)

Weather Enclosure Sub-system

Wall and Roof Panels — In addition to weather resistance, the wall and roof panels also brace the purlins and girts, and act as diaphragms to transmit horizontal loads. Panels are generally ribbed for additional rigidity in patterns that give some variety to the outer appearance of the buildings.
Panels are jointed and fixed to purlins and girts by self-tapping screws with neoprene washers for waterproofing. Joints between panels are sealed with a special kind of sealing tape to prevent water and moisture penetration. A special rubber or plastic closure strip is used to close the panel end for weather tightness. Each manufacturer has his own group of trims to enclose the joints at corners and openings, and ridge caps to cover the ridges.

Except for the specially manufactured insulated panels, wall and roof panels are insulated with 1" fiber glass, with a vapor barrier to prevent condensation. Wire mesh is provided to protect and support the fiber glass as shown in Fig. 7.8.

Fig. 7.8 Panel Insulation

Most panels can be used for both walls and roofs. Some manufacturers have developed additional panels solely for walls to give more variety in elevation. Recently, sandwich wall panels with insulation cores, interior lining panels and concealed joints have been developed by several manufacturers. These new sandwich panels are fixed at the
### Comparison Table 10 - Panels

*Panel sections are not to scale; thickness has been exaggerated.*

#### A & S

- **Wall & Roof:**
  - 0.125" WALLOM
  - 0.022" ALUM.
  - 20, 24, 26 GAGE STEEL

#### Kirby

- **Wall & Roof:**
  - 0.125" WALLOM
  - 0.032" ALUM.
  - 24, 26 GAGE STEEL

- **1901 Wall:**
  - 0.125" WALLOM
  - 0.032" ALUM.
  - 24, 26 GAGE STEEL

- **Zip Rib Panel:**
  - FLAT ROOF

#### Metallic

- **Wall & Roof:**
  - 0.125" WALLOM
  - 0.032" ALUM.
  - 24, 26, 28 GAGE STEEL
COMPARISON TABLE 10 - PANELS (CONT'D)

- PANEL SECTIONS ARE NOT TO SCALE; THICKNESS HAS BEEN EXAGGERATED.

STRAN-STEEL

SA: WALL
- 0.072" ALUM.
- 22, 24, 26 GAGE STEEL

SR: WALL & ROOF
- 0.032" ALUM.
- 22, 24, 26 GAGE STEEL

SS: WALL, ROOF, INTERIOR
- 0.032" ALUM.
- 22, 24, 26 GAGE STEEL

SE: WALL
- 20, 22, 24 GAGE STEEL

SL: INTERIOR LINING
- 24, 26 GAGE

SHADOW STRANWALL:
WALL PANEL: INSULATED
26 GAGE BOTH FACE

LINEAR STRANWALL:
WALL PANEL: INSULATED
26 GAGE BOTH FACE
## COMPARISON TABLE 10 - PANELS (CONT'D)

*Panel sections are not to scale; thickness has been exaggerated.*

### BUTLER

<table>
<thead>
<tr>
<th>BUTLER IB WALL &amp; ROOF</th>
<th>0.032&quot; ALUM.</th>
<th>24, 26 GAUGE STEEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.2&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12&quot;</td>
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</tr>
<tr>
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<tr>
<td>12&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96&quot;</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>F - 103 WALL &amp; ROOF</th>
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<th>0.032&quot; ALUM.</th>
<th>24, 26 GAUGE STEEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12&quot;</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>96&quot;</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MONOPAL WALL</th>
<th>INSULATED</th>
<th>24, 26 GAUGE STEEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12&quot;</td>
<td></td>
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</tr>
</tbody>
</table>

**Glass or Other Insulated Panel**

<table>
<thead>
<tr>
<th>BUTLER PANEL WINDOW WALL SYSTEM</th>
<th>EXTRUDED ALUM. FRAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5&quot;</td>
<td></td>
</tr>
<tr>
<td>4.5&quot; to 4.5&quot;</td>
<td></td>
</tr>
</tbody>
</table>

**Hardboard Inner Face**

<table>
<thead>
<tr>
<th>MODULAR WALL INSULATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.032&quot; ALUM. OUTER FACE</td>
</tr>
<tr>
<td>4.5&quot;</td>
</tr>
</tbody>
</table>
top and bottom only, with a clear vertical span up to 14'. Girts are eliminated.

Steel is the primary material for panels, but aluminum is used occasionally. Panels are prefinished by other manufacturers. Two types of panels finish are available, painting and film coating. Generally, painted panels carry a five year guarantee and film coated panels carry a fifteen to twenty year guarantee.

The ribbed panels are rolled and cut to length by an automatic and continuous process. The length of the panel is almost unlimited; any desirable length can be produced. But for transportation and handling purposes, the maximum panel length is kept less than 40'. Panels are lapped over purlins and girts with a lapping length of 10" for 1 in 12 roofs, 6" for 4 in 12 roofs and 4" for walls as shown in Fig. 7.8. As panels are comparatively thin, cutting on site to fit the sloping roof and to fix accessories is a common practice.

Skylight panels of glass fiber reinforced polyester are generally used to replace roof or wall panels when natural daylight is needed. The width and configuration of skylight panels are the same as wall and roof panels. The length is generally in 5' increments. Skylight panels can also be insulated with a double layer panel, with a dead air space inside.

The design of wall and roof panels differs from one manufacturer to another. Comparison Table 10 shows the size and section of the panels of five major manufacturers.

The following accessories are common attachments to weather enclosure sub-systems:

**Ventilator** --- Two types of ventilator are generally available:
Circular Vent — usually 20" or 24" diameter, installed at the ridge.
Continuous Ridge Vent — standard length 10'-0".

Manually operated remote controlled dampers can be provided in the ventilators when needed.

Windows and Louvers — There is no standard size for windows and louvers. They are installed by cutting wall panels on site as required.

Doors — Two types of doors are used in metal buildings: side-hung doors for general use and horizontal or vertical sliding doors for service entrances. Side-hung doors are installed by cutting wall panels on site as required. Sliding doors are fixed to major frames; the sizes of sliding doors generally correspond to the bay width and eave height.

Gutter and Down Spout — The eave gutter is a part of the building system (Fig. 7.4). Both the gutter and down spout are cut and fitted on site to suit different installations.

7.2 Dimensional Misfits

A comparison of the major dimensions of five metal building systems indicates their lack of dimensional coordination; most dimensions derive from structural criteria alone. A study of the structural properties of panels indicates that 5' is an economical span for roof panels, given material strength, thickness and typical roof loadings. The result is a 5' purlin spacing and a 10' span increment (due to
symmetry) for major frames. A similar approach for purlins and girts gives spans of 18', 20', 21', 24' and 25'. A 3'-0" panel is pressed from a 42" wide sheet, which is one of the economical widths of steel sheet rolls. 1 in 12 is the minimum roof slope without adding a waterproofing layer. With an arbitrary 10' basic eave height and a 2' eave height increment, these few dimensions become the bases of the whole dimensional system.

Considering the panel width and the span of major frames, as 5' and 3' are relatively prime to each other, end wall panels are a problem; except when the span of the major frame is a multiple of 3', site cutting and fitting or excessive lapping is inevitable. The span of purlins and girts includes multiples of both 5' (20' and 25'), and multiples of 3' (18', 21' and 24'). The former do not accord with the 3' panel width while the latter do not correspond to the 5' structural module in the other direction. With this problem in mind, Kirby's 30" panel width should be the best among these five metal building systems. By keeping all horizontal dimensions in multiples of 5', Kirby is the only manufacturer who has a consistent horizontal dimensional system. However, the 30" panel has one disadvantage: lack of compatibility with building materials on the 4" basic module, such as brick and block.

Vertical dimensioning is more consistent; all systems are in 2' increments. But 2' does not relate to the 5" vertical increment of roof slope per purlin (5' spacing, 1 in 12 slope). Therefore, in all major frames, no two ridge heights of different spans are of the same dimension. Fig. 7.9 tabulates a few examples for easy reference. The dimensioning of width extensions is another good example. A & S and Kirby, in keeping the span in 5' increments, end up with odd eave
Fig. 7.9 Ridge Heights of Roof Slope 1 in 12

heights which differ from the general standard. The other three manufacturers, in keeping standard eave heights, have spans not multiples of 5'.

Other dimensional misfits in existing product systems are obvious, such as door width and panel width mismatch, window and door height mismatch with the spacing of girts, and the span of girts at end walls mismatch with the span of major frames. Each requires on-site cutting and fitting.

Although light gage members do allow on-site cutting and fitting, these dimensional misfits cause the following disadvantages in the building process:

(1) Increased on-site labor — Many minor labor consuming adjustments have to be carried out on-site.
(2) Increased waste and error — Dimensional misfits inhibit smooth site operations. The chance of costly error is increased, and time and materials are wasted.
(3) Increased difficulty in communication — Ambiguity is introduced into the dimensional system by misfits, and
misunderstanding can result. Information is not effectively transferred.

Comprehensive coordination is the single solution to elimination of dimensional misfits.

7.3 Analysis and Criticism

The production of existing metal building products is mechanized and partly automated; the production processes are effective and flexible. In all metal building factories, only three production lines are needed: built-up I sections, Z and C sections, and panels. These production lines are independent; the production cycles can be repeated as required.

Through the franchised contractor network, each manufacturer has total control of his own market. The direct co-operation of manufacturing and on-site operations, the high speed production and erection, and the long term warranty constitute a high degree of dependability and predictability.

The price of metal building products has been kept low and stable. The erection cost and maintenance cost are low in comparison with other building systems. In term of long span structures, metal building systems are usually the only economical solution.

On the other hand, certain restraints to flexible use of existing systems are inherited with these three special characteristics:
symmetry, sloping roof and single story. In the strict sense, the existing systems only have one-directional planning flexibility; the use of width extensions is not always effective, as the eave height is rigidly governed by the roof slope (Fig. 7.10).

![Diagram of Planning Flexibility](image)

Fig. 7.10 Direction of Planning Flexibility

Aesthetic freedom is also restricted to a small confined area by these three special characteristics. With the exception of Butler and Stran-Steel, many major manufacturers have only one type of panel for the use of both wall and roof. Limited to a one-directional pattern (vertical ribbed configuration), elevational treatment is monotonous and comparatively tasteless.

Compatibility is perhaps the most difficult problem. Even within the same system, site cutting and fitting is unavoidable. As to other sub-systems, no service freeway has been considered and provided for ducts, pipes and wires. Sloping ceilings and the irregularity of the sizes of major frames make the installation of internal partitions
difficult. Ceiling, lighting and air diffusers have to be installed independently, as there is no consideration in the existing structural system for these installations.

The mass market for utility and industrial buildings after World War II which nourished the early age of the metal building industry has been captured and secured. Further extension of the metal building industry will require increased flexibility in aesthetics and planning, and also high compatibility with other building sub-systems. A comprehensive coordination of the dimensional system, although not a total solution will at least increase the flexibility and compatibility of the existing metal building systems.
8. A COORDINATION PROPOSAL

8.1 The Need for an Industry-Wide Dimensional Standard

The individual development of existing metal building systems has led to a diversity in detailing and dimensional criteria. Keen business competition has precluded concern for interchangeability among different systems. Even disregarding, however, the argument for a completely open system, an industry-wide dimensional standard would have these three advantages:

To improve product compatibility — The dimensional criteria of many other building products have been standardized: masonry, timber, ceramic products, ceiling panels, etc. To standardize the dimensional criteria of metal building products would certainly improve compatibility with these building products.

To encourage more effective production of primary materials and purchased
accessories used by the metal building manufacturers —- The standardization of dimensional criteria for metal building products would provide an opportunity for primary material and accessory manufacturers to standardize their product dimensions, and thus encourage their mass production to lower their product price and to improve their product quality.

To widen the market of metal building systems —- An industry wide dimensional system would give more freedom for design with metal building systems in an open bidding process. Tedious comparison of the different systems would be unnecessary, and drastic changes to the architect's design after bidding would be avoided.

Should this industry-wide dimensional system be compatible with the dimensional criteria of other building systems or conventional construction methods, metal building systems could bid against conventional construction methods and other building systems.

Due to the close similarity of the existing metal building systems, a common dimensional standard would not be difficult to achieve. No manufacturer would suffer from inconvenience due to the conversion, as the present production processes are not dimensionally fixed.

In fact, comprising only two sub-systems, the existing metal buildings are not independent building systems. The completion of a functional metal building requires integration of the metal building with other sub-systems. Elimination of dimensional misfits between them is the first step toward this goal.
8.2 A Way to Improve the Flexibility of Planning Dimensions

The existing metal building systems allow only one directional flexibility in planning. The existing classification of major structural members is the main source of this limitation. Except for the width extension, each of the other three types of major structural frames is a symmetrical, stable and self-contained structure. Their combinations are confined to parallel arrangements. The difference in ridge height (refer Fig. 7.9) prevents the combination of structures of different spans without special adjustment. The planning dimensioning is strictly limited.

To release this limitation, the existing classification of structural frames should be revised. The solution is to use half of the whole frame as a unit to allow asymmetrical combinations. Fig. 8.1 shows this new classification system.

The combination of these partial units allows greater variety than current systems. Fig. 8.2 tabulates the possible combination of four half rigid frame units. Fig. 8.3 shows the use of the taper beam as a connection unit and cantilever as an extension unit, generating even more combinations. As shown in Fig. 8.4, several single or combined linear units can be arranged in a parallel position. The variations of the building form are almost unlimited.

Without alteration of the basic structural form and principle, except symmetry, this simple change of the classification concept can release the restrictions to planning flexibility in existing systems. The production of major structural members is a manual process; each member is handled individually. This conversion in classification
(i) CANTILEVER BEAM – ROOF SLOPE 1 IN 22

(a) DOWNWARD

(b) UPWARD

(ii) TAPER BEAM – ROOF SLOPE 1 IN 22

WITH OR WITHOUT COLUMN

(iii) HALF RIGID FRAME – ROOF SLOPE 1 IN 12 AND 4 IN 12

(a) ROOF SLOPE 1 IN 12

(b) ROOF SLOPE 4 IN 12

WITH OR WITHOUT COLUMN

(iv) HALF RIGID FRAME WITH INTERIOR COLUMNS – ROOF SLOPE 1 IN 12

(a) WITH END COLUMN

(b) WITHOUT END COLUMN

Fig. 8.1 A New Classification of Structural Frame
Fig. 8.2  Combination of Half Rigid Frame
Fig. 8.3 Combination with Taper Beams and Cantilever Beams

Fig. 8.4 Variation in Building Form
should have no effect on this existing production system.

The only adverse effect will be the increase of the complexity in structural design. Almost every major manufacturer is equipped with a computer; if the program for each possible combination is prepared, the structural design of these asymmetrical combinations will be no problem.

This new combination method constitutes a two dimensional flexibility in planning. The richness in the variety of form and space can certainly give more freedom for architects to design within the existing metal building systems.

8.3 The Coordination Process

Ridge height is a major dimension of this new classification system. Ridge height, eave height and the span of the half frame unit are specially related: the difference between ridge height and eave height is equal to the product of span and roof gradient. The eave heights and the ridge heights of different half frames must be related in the dimensional system so that different half frames can be combined together easily.

According to the procedures set out in Chapter 5, we can proceed with the coordination process:

Fig. 8.5 tabulates the initial magnitude and character of
twelve major dimensions.

Fig. 8.6 set up the interaction matrix and lists the relationship between any two of the reacting dimensions.

Fig. 8.7 transforms the interaction matrix into a hierarchical tree. The panel width proves to be the controlling dimension.

Adjustment to dimensions is now possible. Three panel widths are tested:

3'-0" (36") --- typical existing panel width.
3'-4" (40") --- a standard 3'-0" door with frame.
4'-0" (48") --- most convenient width which can be handled by one man.

The results of these three adjustments are shown in Fig. 8.8, 8.9 and 8.10. Comparison of these three dimensional systems indicates that a 3'-4" panel width generates the best dimensional system:

(1) Most dimensions are existing dimensions. Less conversion is required.

(2) 5' x 5' can be used as a planning and structural module. The 5' x 5' planning grid has been successfully used in many school building systems, such as SCSD project of California, SEF project in Toronto and SBP project in Florida. Many building materials and sub-systems are produced according to this planning grid. With minor alterations, these building materials and sub-systems can fit the special characteristics of metal building systems. High compatibility is thus achieved.

(3) 20" x 20" has also been used as a planning module for residential buildings. This dimensional system can
<table>
<thead>
<tr>
<th>CODING</th>
<th>MEANING</th>
<th>INITIAL MAGNITUDE</th>
<th>CHARACTER</th>
<th>REMARK</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Panel Width</td>
<td>4'-4&quot;</td>
<td></td>
<td>See NOTE (2)</td>
</tr>
<tr>
<td>K</td>
<td>Panel Horizontal Span and Purlin Spacing</td>
<td>5'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>J</td>
<td>Panel Vertical Span and Girt Spacing</td>
<td>10'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>I</td>
<td>Purlin Span and Frame Spacing</td>
<td>25'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>H</td>
<td>Girt Span</td>
<td>25'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>G</td>
<td>Span of Taper Beam</td>
<td>20'-0&quot;</td>
<td>+</td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>F</td>
<td>Span of Half Rigid Frame (no interior column)</td>
<td>15'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>E</td>
<td>Span of Half Rigid Frame (with interior column)</td>
<td>30'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>D</td>
<td>Spacing of Interior Column</td>
<td>20'-0&quot;</td>
<td>-</td>
<td>Existing Dimensional Criteria</td>
</tr>
<tr>
<td>C</td>
<td>Eave Height (1 in 12 &amp; 4 in 12)</td>
<td>10'-0&quot;</td>
<td></td>
<td>Existing Dimensional Criteria (Depth of Eave Struct Included)</td>
</tr>
<tr>
<td>B</td>
<td>Ridge Height (1 in 12)</td>
<td>11'-3&quot;</td>
<td></td>
<td>Calculated according to the minimum span and eave height</td>
</tr>
<tr>
<td>A</td>
<td>Ridge Height (4 in 12)</td>
<td>15'-0&quot;</td>
<td></td>
<td>Calculated according to the minimum span and eave height</td>
</tr>
</tbody>
</table>

**FIG. 8.5 TABLE OF MAJOR DIMENSIONS**

**NOTES:**

(1) Span of cantilever has no relationship with other dimensions except that it must be a multiple of purlin spacing. Therefore, the exclusion of it in the coordination process is possible.

(2) According to USS Catalog: width of pre-finished steel sheet is available up to 5'-0". 8" have been deducted for corrugation and lapping.

* Coding in this manner allows the basic dimensions to be arranged in the right hand side of the matrix.*
PART-WHOLE RELATIONSHIP

DE — Interior column and total span
AJ, BJ, CJ — Girt spacing and ridge height and eave height
EH, FH, GH — Girt span and frame span (at end wall unit)
DK, EK, FK, GK — Purlin spacing and frame span
HK — Purlin spacing and girt span (at end wall unit)
EL, FL, GL — Panel width and frame span (at end wall unit)
HL, IL — Panel width and purlin span and girt span

PARALLEL RELATIONSHIP

HI — Girt span and purlin span
KL — Panel width and purlin spacing (at end wall unit)

SPECIAL RELATIONSHIP

AC, AF, BC, BE, BF, CE, CF — The difference of ridge height and eave height equals to the product of span and roof gradient.

Fig. 8.6 Interaction and Relationship
The Hierarchical Tree
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
</tr>
</thead>
</table>
| Panel Width              | 3'-0" (36"
| Purlin Spacing           | 4'-6"
| Girt Spacing             | 6'-0"
| Frame Spacing            | 18', 21', 24'
| Girt Span                | 18', 21', 24'
| Taper Beam Span          | 24', 36', 48', 54', 60',     |
| 1/2 R.F. Span            | 18', 27', 36', 45', 54', 60',|
| * 1/2 R.F.C. Span        | 36', 54', 72', 90',          |
| Interior Column Spacing  | 18', 27', 36'                |
| Eave Height              | 10', 11'-6", 13', 14'-6", 16',|
| Ridge Height (1 in 12)   | 11'-6", 12'-3", 13'-0", 13'-9"|
| Ridge Height (4 in 12)   | 16', 19', 22', 25'           |
| Cantilever Span          | 4'-6", 9'-0"                 |

Horizontal Module: 18" x 18"

Vertical Module: 9"

Fig. 8.8 Dimensional System for 3'-0" Panel

* 1/2 R.F.C. --- Half rigid frame with interior columns
<table>
<thead>
<tr>
<th>Dimension</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel Width</td>
<td>3'-4&quot; (40&quot;)</td>
</tr>
<tr>
<td>Purlin Spacing</td>
<td>5'-0&quot;</td>
</tr>
<tr>
<td>Girt Spacing</td>
<td>5'-0&quot;</td>
</tr>
<tr>
<td>Frame Spacing</td>
<td>20', 25'</td>
</tr>
<tr>
<td>Girt Span</td>
<td>20', 25'</td>
</tr>
<tr>
<td>Taper Beam Span</td>
<td>20', 30', 40', 50',</td>
</tr>
<tr>
<td>1/2 R.F. Span</td>
<td>20', 30', 40', 50', 60',</td>
</tr>
<tr>
<td>* 1/2 R.F.C. Span</td>
<td>60', 80', 100',</td>
</tr>
<tr>
<td>Interior Column Spacing</td>
<td>30', 40', 50',</td>
</tr>
<tr>
<td>Eave Height</td>
<td>10', 11'-8&quot;, 13'-4&quot;, 15',</td>
</tr>
<tr>
<td>Ridge Height (1 in 12)</td>
<td>11'-8&quot;, 12'-6&quot;, 13'-4&quot;, 14'-2&quot;, 15',</td>
</tr>
<tr>
<td>Ridge Height (4 in 12)</td>
<td>16'-8&quot;, 20',</td>
</tr>
<tr>
<td>Cantilever Span</td>
<td>5'-0&quot;, 10'-0&quot;</td>
</tr>
</tbody>
</table>

Horizontal Module: 20" x 20" (and 5' x 5')
Vertical Module: 20" (with sub-module 5"

Fig. 8.9 Dimensional System for 3'-4" Panel

* 1/2 R.F.C. --- Half rigid frame with interior columns
<table>
<thead>
<tr>
<th>Dimension</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel Width</td>
<td>4'-0&quot;</td>
</tr>
<tr>
<td>Purlin Spacing</td>
<td>4'-0&quot;</td>
</tr>
<tr>
<td>Girt Spacing</td>
<td>6'-0&quot;</td>
</tr>
<tr>
<td>Frame Spacing</td>
<td>20', 24'</td>
</tr>
<tr>
<td>Girt Span</td>
<td>20', 24'</td>
</tr>
<tr>
<td>Taper Beam Span</td>
<td>24', 32', 40', 48', 56',</td>
</tr>
<tr>
<td>1/2 R.F. Span</td>
<td>16', 20', 24', 32', 40',</td>
</tr>
<tr>
<td>* 1/2 R.F.C. Span</td>
<td>36', 48', 72',</td>
</tr>
<tr>
<td>Interior Column Spacing</td>
<td>24', 36', 48',</td>
</tr>
<tr>
<td>Eave Height</td>
<td>10', 11', 12', 13', 14',</td>
</tr>
<tr>
<td>Ridge Height (1 in 12)</td>
<td>11'-4&quot;, 11'-8&quot;, 12',</td>
</tr>
<tr>
<td>Ridge Height (4 in 12)</td>
<td>15'-4&quot;, 16'-8&quot;, 18',</td>
</tr>
<tr>
<td>Cantilever Span</td>
<td>4'-0&quot;, 8'-0&quot;</td>
</tr>
</tbody>
</table>

**Horizontal Module:** 4' x 4'

**Vertical Module:** 4''

*Fig. 8.10 Dimensional System for 4'-0" Panel*

* 1/2 R.F.C. --- Half rigid frame with interior columns*
certainly fit well with materials and sub-systems manufactured for residential purposes.

(4) 3'-4" is a 2:3 relationship with 5'-0" and is a common internal partition width. The adoption of this dimensional system together with the use of 3'-4" as the basic dimension for internal partitioning can help to integrate the exterior and interior of metal buildings.

(5) 3'-4" is very close to one meter. For international trade, this dimensional system is quite convenient for metric conversion.

The other two dimensional systems do not share these advantages. Although from a mathematical point of view, dimensions of the other two systems are simpler and more closely related, lacking these advantages, they would limit the flexibility of metal building systems.

There are two drawbacks in the dimensional system generated by the 3'-4" panel width:

(1) Vertical dimensions are in 5" increments (5' purlin spacing in 1 in 12 roof gradient) and are not compatible with the 4" basic module. As multiples of 4" and 5" meet at 20" interval, however, by limiting the eave height to 20" increments, this difficulty can be overcome.

(2) In order to fill the gap between the 5'-0" purlin spacing and the 3'-4" wall panel, a 20" half panel is needed.

Generally, a 3'-4" panel can be pressed from 46" steel sheet, which at present is not a common width. However, after standardization of the 3'-4" panel, the price of 46" sheeting will certainly be lowered by high consumption by the whole industry. As an alternative, 3'-4"
sandwich panel has already been produced by Stran-Steel from 42" sheeting (refer Comparison Table 10 of Section 7.1). Rigidity can be achieved with either core or ribs.

In view of the special dimensional relationships created by sloping roofs, the dimensional system generated by a 3'-4" panel width is the best solution. Its adoption as an industry-wide dimensional standard is recommended.

Based on this dimensional standard, a new product dimension system is suggested as follows:

(1) Panel Width : 20", 40"
(2) Purlin Spacing : 5'-0"
(3) Frame Spacing : 20', 25'
(4) Girt Spacing : 5'-0" standard, with special adjustment for door and window opening.
(5) Cantilever Span : 5'-0" and 10'-0"
(6) Taper Beam : (with or without columns)

Roof Slope : 1 in 12

Span : 20', 30', 40', 50', 60'

Eave Height : (with columns)

10', 11'-8", 13'-4", 15', 16'-8", 20'.
### Half Rigid Frame - Roof Slope 1 in 12

![Diagram of a half rigid frame with roof slope 1 in 12.](image)

<table>
<thead>
<tr>
<th>Span</th>
<th>Eave Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>10'</td>
<td>11'-3&quot;</td>
</tr>
<tr>
<td>20'</td>
<td>11'-8&quot;</td>
</tr>
<tr>
<td>25'</td>
<td>12'-1&quot;</td>
</tr>
<tr>
<td>30'</td>
<td>12'-6&quot;</td>
</tr>
<tr>
<td>35'</td>
<td>12'-11&quot;</td>
</tr>
<tr>
<td>40'</td>
<td>13'-4&quot;</td>
</tr>
<tr>
<td>45'</td>
<td>13'-9&quot;</td>
</tr>
<tr>
<td>50'</td>
<td>14'-2&quot;</td>
</tr>
<tr>
<td>55'</td>
<td>14'-7&quot;</td>
</tr>
<tr>
<td>60'</td>
<td>15'-0&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ridge Height</th>
<th>10'-10&quot;</th>
<th>11'-8&quot;</th>
<th>12'-6&quot;</th>
<th>13'-4&quot;</th>
<th>15'-0&quot;</th>
<th>16'-8&quot;</th>
<th>18'-4&quot;</th>
<th>20'-0&quot;</th>
<th>22'-8&quot;</th>
<th>25'-0&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>10'</td>
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<td>50'</td>
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<tr>
<td>60'</td>
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</tr>
</tbody>
</table>
**HALF RIGID FRAME**  —  **ROOF SLOPE 4 IN 12**

<table>
<thead>
<tr>
<th>SPAN</th>
<th>FAVE HEIGHT</th>
<th>RIDGE HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>15'</td>
<td>15'</td>
<td>35'-0&quot;</td>
</tr>
<tr>
<td>20'</td>
<td>15'-8&quot;</td>
<td>26'-8&quot;</td>
</tr>
<tr>
<td>25'</td>
<td>20'</td>
<td>25'-0&quot;</td>
</tr>
<tr>
<td>30'</td>
<td>23'-4&quot;</td>
<td>23'-4&quot;</td>
</tr>
<tr>
<td>35'</td>
<td>25'-0&quot;</td>
<td>26'-8&quot;</td>
</tr>
<tr>
<td>40'</td>
<td>26'-8&quot;</td>
<td>30'-0&quot;</td>
</tr>
<tr>
<td>45'</td>
<td>26'-8&quot;</td>
<td>31'-8&quot;</td>
</tr>
<tr>
<td>50'</td>
<td>30'-0&quot;</td>
<td>31'-8&quot;</td>
</tr>
<tr>
<td>55'</td>
<td></td>
<td>35'-0&quot;</td>
</tr>
<tr>
<td>60'</td>
<td>30'-0&quot;</td>
<td></td>
</tr>
</tbody>
</table>

With or without columns.
## HALF RIGID FRAME WITH INTERIOR COLUMNS - TYPE 'I'

**ROOF SLOPE: 1 IN 12**

### (1) 30' INTERIOR COLUMN SPACING

<table>
<thead>
<tr>
<th>EAVE HEIGHT</th>
<th>11'-8&quot;</th>
<th>13'-4&quot;</th>
<th>15'-0&quot;</th>
<th>16'-8&quot;</th>
<th>20'-0&quot;</th>
<th>25'-0&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 SPACINGS = 60'</td>
<td>16'-8&quot;</td>
<td>18'-4&quot;</td>
<td>20'-0&quot;</td>
<td>21'-8&quot;</td>
<td>25'-0&quot;</td>
<td>30'-0&quot;</td>
</tr>
<tr>
<td>3 SPACINGS = 90'</td>
<td>19'-2&quot;</td>
<td>20'-10&quot;</td>
<td>22'-6&quot;</td>
<td>24'-2&quot;</td>
<td>27'-0&quot;</td>
<td>32'-6&quot;</td>
</tr>
<tr>
<td>4 SPACINGS = 120'</td>
<td>21'-6&quot;</td>
<td>23'-4&quot;</td>
<td>25'-0&quot;</td>
<td>27'-2&quot;</td>
<td>30'-0&quot;</td>
<td>35'-0&quot;</td>
</tr>
</tbody>
</table>

### (2) 40' INTERIOR COLUMN SPACING

<table>
<thead>
<tr>
<th>EAVE HEIGHT</th>
<th>11'-6&quot;</th>
<th>13'-4&quot;</th>
<th>15'-0&quot;</th>
<th>16'-8&quot;</th>
<th>20'-0&quot;</th>
<th>25'-0&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 SPACINGS = 80'</td>
<td>18'-4&quot;</td>
<td>20'-0&quot;</td>
<td>21'-8&quot;</td>
<td>23'-4&quot;</td>
<td>26'-0&quot;</td>
<td>31'-8&quot;</td>
</tr>
<tr>
<td>3 SPACINGS = 120'</td>
<td>21'-8&quot;</td>
<td>23'-4&quot;</td>
<td>25'-0&quot;</td>
<td>27'-2&quot;</td>
<td>30'-0&quot;</td>
<td>35'-0&quot;</td>
</tr>
<tr>
<td>4 SPACINGS = 160'</td>
<td>25'-0&quot;</td>
<td>26'-8&quot;</td>
<td>28'-4&quot;</td>
<td>30'-0&quot;</td>
<td>33'-4&quot;</td>
<td>38'-4&quot;</td>
</tr>
</tbody>
</table>

### (3) 50' INTERIOR COLUMN SPACING

<table>
<thead>
<tr>
<th>EAVE HEIGHT</th>
<th>11'-8&quot;</th>
<th>13'-4&quot;</th>
<th>15'-0&quot;</th>
<th>16'-8&quot;</th>
<th>20'-0&quot;</th>
<th>25'-0&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 SPACINGS = 100'</td>
<td>20'-0&quot;</td>
<td>21'-8&quot;</td>
<td>23'-4&quot;</td>
<td>25'-0&quot;</td>
<td>28'-4&quot;</td>
<td>33'-4&quot;</td>
</tr>
<tr>
<td>3 SPACINGS = 150'</td>
<td>24'-2&quot;</td>
<td>25'-10&quot;</td>
<td>27'-6&quot;</td>
<td>29'-2&quot;</td>
<td>32'-6&quot;</td>
<td>37'-6&quot;</td>
</tr>
</tbody>
</table>
HALF RIGID FRAME WITH INTERIOR COLUMNS - TYPE II

ROOF SLOPE: 1 IN 12

(1) 30' INTERIOR COLUMN SPACING

<table>
<thead>
<tr>
<th>SPAN</th>
<th>EAVE HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11'-3&quot;</td>
</tr>
<tr>
<td>2½ SPACINGS = 75'</td>
<td>20'-0&quot;</td>
</tr>
<tr>
<td>3½ SPACINGS = 106'</td>
<td>20'-0&quot;</td>
</tr>
</tbody>
</table>

RIDGE HEIGHT

(2) 40' INTERIOR COLUMN SPACING

<table>
<thead>
<tr>
<th>SPAN</th>
<th>EAVE HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11'-8&quot;</td>
</tr>
<tr>
<td>1½ SPACINGS = 60'</td>
<td>16'-8&quot;</td>
</tr>
<tr>
<td>2½ SPACINGS = 100'</td>
<td>20'-0&quot;</td>
</tr>
<tr>
<td>3½ SPACINGS = 140'</td>
<td>23'-4&quot;</td>
</tr>
</tbody>
</table>

RIDGE HEIGHT

(3) 50' INTERIOR COLUMN SPACING

<table>
<thead>
<tr>
<th>SPAN</th>
<th>EAVE HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11'-3&quot;</td>
</tr>
<tr>
<td>1½ SPACINGS = 75'</td>
<td>20'-0&quot;</td>
</tr>
<tr>
<td>2½ SPACINGS = 125'</td>
<td>21'-8&quot;</td>
</tr>
</tbody>
</table>

RIDGE HEIGHT
CONCLUSION
9.1 A Review of the Need for Modular Coordination

This thesis has attempted with demonstration in the metal building industry to show that the practical application of modular theory is possible.

Dimensions are the architectural communication media. In addition to this, a well coordinated dimensional system is an essential framework for decisions in structural design and building sub-systems integration. In all of this, modular coordination is critical to the industrialization of the construction process.

Owing to the high complexity of architectural design and building construction, no manufacturer can produce a totally closed system that will satisfy all needs. A completely open system is surely an ultimate goal in building industrialization from both architectural and
economical points of view. Modular coordination is one of the important elements of this target.

The building industry is now at the threshold of both mechanization and automation; the production of panels and Z sections in the metal building industry is a good example. Through automation, certain dimensional freedoms can easily be obtained. In the metal building industry, panel lengths can be precisely set at 1/8" increments. Automation can allow dimensional coordination among various manufacturers without dislocation or hardship in the transition period. Modular coordination can be fully adopted or even enforced along with the development of automation.

In the United States, modular coordination is not common, though it has been twenty-five years since formal acceptance by government and trade groups. Lack of effective promotion is a main source of this unpopularity. But coordination is indispensable to the national economy in this time of extreme stress; a close cooperation of the whole building industry is essential to promote modular coordination.
BOOKS


PERIODICALS

Ehrenkrantz, Ezra D. "Modular Materials and Design Flexibility". ARTS AND ARCHITECTURE. April, 1967.


"Metal Review". PROGRESSIVE ARCHITECTURE. October, 1969.

"Modular Coordination". ARCHITECTURAL RECORD. June, 1950.

"Modular Coordination". ARCHITECTURAL RECORD. September, 1950.


The following articles in HOUSTON magazine published by Houston Chamber of Commerce are arranged in chronological order:

"Houston's Industrial Progress". HOUSTON, April, 1948.

"Importance of Metal Industry Here". HOUSTON, July, 1951.


PRODUCT MANUALS

Product manuals of the following metal building manufacturers:

A & S Steel Buildings, Inc., Houston, Texas.

Kirby Buildings, Inc., Houston, Texas.

Metallic Building Co., Houston, Texas.

Stran-Steel Corporation, Houston, Texas.

Butler Manufacturing Co., Kansas City, Missouri.